Adaptive Fuzzy Variable Structure Control for Permanent Magnet Linear Servo System

Haijun Sun*, Weiwei Yin*
School of Information and Control Engineering, Liaoning Shihua University, Fushun Liaoning 113001, China
*Corresponding author e-mail: sun_hai_jun@163.com, *85095349@qq.com

Abstract. In order to improve the immunity of AC permanent magnet linear servo system to parameter perturbation, end effect and load resistance, an intelligent sliding mode variable structure control scheme based on adaptive neuro-fuzzy inference system ANFIS is proposed. The adaptive neuro-fuzzy inference system ANFIS is introduced into the traditional sliding mode variable structure control to weaken the inherent chattering of sliding mode control and eliminate the end effect of permanent magnet linear synchronous motor. The simulation and experimental results show that the intelligent sliding mode variable structure control method based on ANFIS is simple, has good dynamic performance and good robustness.

1. Introduction
Permanent-magnet linear synchronous motor (PMLSM) has obvious advantages over traditional rotary motor drive in accuracy, rapidity and durability. However, because the load is directly connected with the motor actuator, the load variation and external disturbance will directly affect the performance of the servo system. At the same time, the pulsating thrust generated by the inherent end effect of PMLSM will affect the stability and control accuracy of the system. The parameter perturbation of PMLSM under various states will have a negative impact on the performance of servo system. Traditional PID control is unable to adapt the requirements of AC linear servo system driven directly by high performance [1].

The advantages of rapidity, robustness and simplicity are sliding mode variable structure control (SMVSC). By forcing the structure of the system to change purposefully in the dynamic process, the motion of the system can be achieved and maintained sliding on the predetermined sliding mode line, thus making the system invariable to uncertain parameters, parameter changes, inaccuracy of mathematical description and external disturbances. The ideal sliding mode control has infinite switching frequency and unlimited control quantity, so it’s sliding mode is smooth, but it can not meet the above two requirements in the actual system. Moreover, the system lags behind in time and space. The discontinuity of sliding mode switching control will cause chattering phenomenon of the system, that is, the state trajectory is not sliding along the sliding mode line, but on the sliding mode line. Chattering affects the dynamic and static performance of the direct drive servo system, increases the energy loss, and even affects the stable operation of the system.

In this paper, a sliding mode control strategy based on adaptive neuro-fuzzy inference system ANFIS for linear permanent magnet motors will be presented. ANFIS introduces the knowledge model composed of the control experience and knowledge of relevant controllers or experts with fuzziness into
the control system as a rule, and describes the fuzzy concepts and relations of process variables and control roles by means of fuzzy mathematics. Fuzzy relation uses fuzzy logic to make inferential decision, and obtains the control quantity of process and the behavior of control system. The direction and amplitude of sliding mode switching control are adjusted in real time by ANFIS system. Without affecting the robustness and fast tracking performance of the system, the chattering intensity is greatly weakened by smoothing the motion state of the system across the sliding mode line as smoothly as possible. Thus, the dynamic and static performance and control precision of the direct drive servo system are improved.

2. Mathematical Model of AC Linear Servo System

AC permanent magnet linear synchronous motor (PMLSM) is a thrust device that directly converts AC power into linear motion. The magnetic field oriented vector control technology is used in the current inner loop of the system, which makes the current vector of the mover and the magnetic field of the stator orthogonal in space, and makes the demagnetization component $i_d=0$ of the current of mover. The simplified mathematical model of the system is [2]:

$$F_e = K_f i_q = \frac{\pi}{\tau} \Phi_f i_q$$  \hspace{1cm} (1)

$$F_e = K_f i_q = M \frac{dv}{dt} + Bv + F_L$$  \hspace{1cm} (2)

$$L = \int_0^t v dt$$  \hspace{1cm} (3)

In the formula, $M$ is the mass of the mover; $B$ is the viscous friction coefficient; $v$ is the linear velocity of the mover; $F_L$ is the load resistance; $F_e$ is the electromagnetic thrust; $K_f$ is the thrust coefficient; $L$ is the mechanical displacement of the mover; $\Phi_f$ is the effective flux of the permanent magnet; $\tau$ is the pole distance.

When there are parameter fluctuations and external disturbances in AC linear servo system, the model of the system is established.

$$F_e = (M + \Delta M) \frac{dv}{dt} + (B + \Delta B)v + F_L + F_d = M \frac{dv}{dt} + Bv + f$$  \hspace{1cm} (4)

In the formula, $f = \Delta M \frac{dv}{dt} + \Delta Bv + F_L + F_d$ is defined as generalized perturbation. $\Delta M$, $\Delta B$ is the offset of the parameters $M,B$; $F_d$ is the equivalent resistance produced by the end effect of PMLSM.

3. Sliding Mode Variable Structure Control Block Diagram of AC Permanent Magnet Linear Servo System Based on ANFIS

![Diagram of intelligent sliding-mode variable structure control based on ANFIS for AC linear servo system](image)

**Figure 1.** Diagram of intelligent sliding-mode variable structure control based on ANFIS for AC linear servo system
The virtual frame part in Fig. 1 is a sliding mode variable structure controller of AC permanent magnet linear servo system based on ANFIS. The output of the controller is composed of the output $u_{eq}$ of the sliding mode controller (SMC) and the output $\Delta u$ of the ANFIS controller.

4. Sliding Mode Controller Design
The system state variable is set to $x_1(t) = L - L = e$, $x_2(t) = \dot{x}_1(t)$, $u(t) = i_q(t)$. From equation (3) and equation (4), the equation of state of the system can be obtained as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{M} \\ 0 & -\frac{B}{M} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ K_f/M \end{bmatrix} u + \begin{bmatrix} 0 \\ -1/M \end{bmatrix} f$$

(5)

The switching function of sliding mode variable structure control is designed to enhance the adaptive ability of $S(X)$ for the system in different speed stages of acceleration $-dx_2/dt>0$, constant speed $-dx_2/dt=0$ and deceleration speed $-dx_2/dt<0$ [3].

$$S(X) = \begin{cases} \frac{c_1 x_2^2}{2} + (x_1 - x_{10}) & -dx_2/dt > 0 \\ x_2 - x_{20} & -dx_2/dt = 0 \\ c_2 x_1 + x_2 & -dx_2/dt < 0 \end{cases}$$

(6)

In the formula, $c_1$ is the acceleration constant; $x_{10}$ is the initial position error; $x_{20}$ is a preset velocity constant; $c_2$ is a constant greater than zero. When the system parameters remain unchanged and are not disturbed by external disturbances and proportional switching control strategy is adopted, the control quantity $u_{eq}$ is:

$$u_{eq} = \sum_{i=1}^{2} \lambda_i x_i$$

(7)

Considering the existence of generalized disturbances $f$ in the system, set to $\Delta u = \Psi \text{sgn} S(X)$ as a compensated control quantity for disturbances. Therefore, the design control strategy is as follows:

$$u = u_{eq} + \Delta u = \sum_{i=1}^{2} \lambda_i x_i + \Psi \text{sgn} S(X)$$

(8)

In the formula: $\lambda_1 = \begin{cases} \alpha_1, & x_1 S > 0 \\ \beta_1, & x_1 S < 0 \end{cases}$; $\lambda_2 = \begin{cases} \alpha_2, & x_2 S > 0 \\ \beta_2, & x_2 S < 0 \end{cases}$

The corresponding stage $u_{eq}$ is calculated according to the generalized sliding mode condition. $S(X)$ ($dS(X)/dt)<0$ Because the generalized disturbance of the system is difficult to measure, the calculation of $\Delta u$ is realized by ANFIS system.

5. Fuzzy Neural Network Model Structure of Sliding Mode Variable Structure Control Based on ANFIS
ANFIS adaptive neuro-fuzzy inference system has the advantages of easy insertion of human-like rules and expert knowledge into the fuzzy system, and has the advantages of learning, optimizing and connecting structure of the neural network [4, 5]. The Mamdani type [6] fuzzy system, which conforms to the habits of human thinking and language expression, has some disadvantages that are not conducive to mathematical analysis. Therefore, this paper constructs ANFIS system by using Takagi-Sugeno type
fuzzy system, which has the characteristics of simple calculation and is conducive to mathematical analysis.

Figure 2 shows the model structure of sliding mode variable structure control fuzzy neural network based on ANFIS. It is a five-layer feed forward fuzzy neural network [7], which contains 25 control rules, and each layer has a clear meaning.

The first level: the justification of input state variables, the node (or) is the specific value of state variables; $A_i$ (or $B_j$) is a fuzzy variable related to the node function value, and the input state variable (or) corresponds to the fuzzy set $A=\{PB, PS, ZO, NS, NB\}$ (or $B=\{PB, PS, ZO, NS, NB\}$); it is the membership function value of the fuzzy set $A$ and the membership function value of the fuzzy set $B$.

$$o_{Ai} = \mu_{A_i}(x_1) , o_{Bj} = \mu_{B_j}(x_2) , i=1,2,3,4,5$$ (9)

The second layer is the control rule layer, which calculates the excitation intensity of each rule and outputs as follows

$$o_{2ij} = \mu_{A_i}(x_1)\mu_{B_j}(x_2) , i=j=1,2,3,4,5$$ (10)

The third level is to normalize the incentive intensity and calculate the contribution of each rule. The output is as follows:

$$o_{3ij} = \frac{o_{2ij}}{\sum\sum o_{2ij}} , i=j=1,2,3,4,5$$ (11)

Layer 4: Each node in this layer is an adaptive node. The structure of the model is as follows:

IF $x_1$ is $A_i$ AND $x_2$ is $B_j$ THEN $o_{4ij}=o_{3ij}f_{ij}=o_{3ij}(px_1+qx_2+r_j)$ .The following is not a fuzzy quantity.

The output of this layer is: $o_{4ij}=o_{3ij}f_{ij}=o_{3ij}(px_1+qx_2+r_j)$

Layer 5: Calculate the final output of all rules:

$$y = \sum\sum o_{4ij} = \sum\sum o_{3ij}f_{ij}$$ (12)
6. ANFIS System Training

The parameters of the fuzzy inference system are adjusted according to the given error criterion by using the mature parameter learning algorithm in the neural network, so that the model can continuously approach the training data: \( P \) is the parameter set of ANFIS, \( X_i \) is the input vector of ANFIS, \( y_i, y(X_i, P) \) are the corresponding values and the predicted values respectively. And there are \( N \) sets of training data. The training error index of ANFIS network is defined as the sum of squares. The following expressions:

\[
E = \sum_{i=1}^{N} (y_i - y(X_i, P))^2
\]

Levenberg’s LM algorithm is used to calculate the training error index \([8]\). This method has good convergence and fast calculation speed. After learning and training, test data are used to verify the correctness and validity of the model.

7. Simulation and Experimental Research

Aiming at the AC permanent magnet linear synchronous motor servo system with air configuration, the sliding mode variable structure controller based on ANFIS and the traditional sliding mode variable structure controller are simulated and validated by using MATLAB simulation software. Sampling period is \( T=0.5\text{ms} \), and system parameters are as follows:

\[
M=11.0\text{kg}, B=8.0\text{N} \cdot \text{s/m}, K_f = 28.5\text{N}/A, F_{en} = 100\text{N}, v_n = 1.0\text{m/s}
\]

7.1. Simulation of Load Disturbance and Parameter Perturbation

For the convenience of simulation, the system is set \( L^* \) to 2m, which mainly considers the speed response. From equation (4), it can be seen that the generalized disturbances
\[ f = \Delta M \frac{dv}{dt} + \Delta Bv + F_L + F_d \] include load resistance, friction resistance, pulsating thrust caused by end effect, and equivalent resistance caused by variation of system parameters (mass of the mover and coefficient of viscous friction). Therefore, the response performance of the system can be investigated by adding \( F_i \) for different load resistance.

Fixed load resistance \( F_L = 50 \) \( N \) is added to \( t=0.4 \) \( s \). Fig. 3 (a) (b) (c) are the simulation curves of PI control, traditional sliding mode control and sliding mode control based on ANFIS. As can be seen from Figure 3, the speed drop and overshoot in PI control are the largest, while the speed in sliding mode control based on ANFIS is almost unaffected.

![Figure 3](image-url)

(a) PI control (b) Traditional sliding mode Control (c) Sliding mode control based on ANFIS

**Figure 3.** Speed responses of the servo system with constant disturbance

When time-varying load resistance \( F_L = 30 \sin (25t) \) \( N \) is added, the speed response simulation curves of each control strategy are shown in Fig. 4 (a) (b) (c). It can be seen that PI control algorithm has little effect on time-varying resistance disturbance, and the hardness and control performance of speed are very poor. Traditional sliding mode variable structure control (SMVSC) has strong adaptability to time-varying torque disturbances, which embodies the advantages of SMVSC that is insensitive to parameter perturbations and external disturbances. The sliding mode control based on ANFIS weakens the inherent "chattering" of sliding mode variable structure control and has strong robustness to disturbance.

![Figure 4](image-url)

(a) PI control (b) Traditional Sliding Mode Control (c) Sliding Mode Control Based on ANFIS

**Figure 4.** Speed responses of the servo system with disturbance

The system parameter perturbation occurs when the dynamic mass of one of the servo system parameters \( M \) is doubled to its rated value. The simulation curves of PI control and sliding mode control based on ANFIS are shown in Fig. 5. At the same time, the velocity response curves before and after the perturbation are given, which are marked by 1 and 2.
It can be seen that when the system parameters are perturbed, PI control cannot adapt obviously, and the velocity curve is overshoot. The sliding mode control based on ANFIS basically coincides with the two curves before and after the system parameters are perturbed. The results show that the fuzzy sliding mode control has a strong anti-perturbation ability to the system parameters.

7.2. Experimental Verification
To verify the proposed control strategy, DSP TMS320LF2407A is used to implement the control algorithm and 3/2 phase change of current and voltage. The experimental object is a self-developed air-configurable permanent magnet linear synchronous motor with the same parameters as in the simulation. Algorithms implemented in DSP include traditional sliding mode control and sliding mode control based on ANFIS (shown in the virtual box in Figure 1), which are switched by external switches. The velocity response curve at a given position of 0.5 m is shown in Fig. 6. Figure 6 (a) is the traditional sliding mode control speed response curve, and Figure 6 (b) is the sliding mode control speed response curve based on ANFIS. It can be seen that sliding mode control based on ANFIS has better dynamic and static performance.

8. Conclusion
The simulation results show that the sliding mode control strategy based on ANFIS proposed in this paper for AC linear servo system is effective. It has incomparable superiority in PI control and traditional sliding mode variable structure control. It has strong robustness to system parameter perturbation and disturbance, and eliminates thrust fluctuation caused by end effect. At the same time, it also improves the dynamic and static performance of servo system. The design method of the control strategy is simple, the algorithm is simple and easy to implement.

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