Research of controller of Permanent magnet linear synchronous motors via model predictive direct thrust control

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Abstract: How to achieve high-precision control is the core issues of the linear motor research. To solve this problem, this paper proposes a new control algorithm. on the one hand, through the sliding mode control for the unknown torque observations, in the process of observation, select a specific based function to approximate the sign function in order to eliminate the jitter of the vicinity of the switching surface; On the other hand, the use of model predictive control method (Model Predictive Control) to achieve the torque compensator track to achieve the velocity and displacement tracking. The constant sampling time of the model predictive control in the new method can effectively avoid the problems that the number of switching per unit time of the inverter can't be expected.

Keywords: Permanent magnet synchronous linear motors; sliding mode control; model predictive direct thrust control.

1. Introduction

Linear motor technology is widely used in CNC machining, industrial production and so on due to the advantages of simple structure, fast response. Displacement tracking control of linear motor is a core issues of the linear motor applied research. The linear motor mostly used displacement tracking control method: PID control, adaptive control, direct thrust control, sliding mode control, preview control, fuzzy control, neural network control. The MPC current tracking technology developed in recent years, has the advantages of fast dynamic response and high tracking accuracy, the algorithm is simple, model predictive control sampling time constant, can effectively circumvent the direct thrust control sampling time is not a constant problem. Kennel R. et al [1, 2] used generalized predictive control method, established linear controller based on Controlled Autoregressive Integrated Moving Average Model (CARIMA) by data analysis, and used in motor control.

Based on the above analysis, the authors proposed a new method of sliding mode model predict direct thrust control. In the new approach, on the one hand, to observe the unknown torque in the observation process by sliding mode control, select a specific function approximation sign function to eliminate jitter in the vicinity of the switching surface. On the other hand, using model predictive control to achieve the torque compensator to achieve precise control of speed and displacement. The method is an improvement for the conventional direct torque control method, the sampling time is constant, reducing the technical requirements of the inverter.

2. Mathematical Model of the PMLSM

Mathematical Model of the PMLSM as follows:

$$\begin{cases} u_d = R_a i_d + L_d \dfrac{di_d}{dt} - \dfrac{\pi}{\tau} v_m L_q i_q \\ u_q = R_a i_q + L_q \dfrac{di_q}{dt} + \dfrac{\pi}{\tau} v_m L_d i_d + \dfrac{\pi}{\tau} v_m \psi_f \\ F_e = \dfrac{3}{2}\dfrac{\pi}{\tau}[\psi_f i_q + (L_d - L_q) i_d i_q] \end{cases} \tag{1}$$

Where u_d and u_q are the d–q voltages; i_d and i_q are the d–q currents; L_d and L_q are the d–q axis inductance. R_a is phase winding resistance of the stator; v_m is mechanical speed of the rotor; ψ_f is permanent magnet flux linkage.

The mover dynamic equation of the PMLSM is

$$F_e = F_l + B \cdot v_m + M \frac{dv_m}{dt} \tag{2}$$

where F_e is the output electromagnet thrust, M is the mass of moving inertia, B is the friction factor and F_l is the external disturbance term.

It can be seen that the basic characteristics of the permanent magnet linear synchronous motor like with permanent magnet synchronous motor, it is a high-order, nonlinear, strong coupling of multi-variable drive control system, and therefore it is the actual dynamic mathematical model is a complex high-order differential equations, it is difficult to accurate solution for their model. Therefore, in the actual application is often simplified into a simple second-order differential equations.

3. Linear motor controller study

In this paper, the sliding mode model to predict direct thrust control method with constant sampling time, and the advantages of easier to realize in the engineering applications. Its control block diagram is shown in Figure 1 : the reference displacement and the actual displacement as input of sliding mode control, whose output is the reference thrust and reference flux, reference thrust、reference flux、estimate the flux and estimates thrust as inputs of the direct thrust model predictive control. the output of Model predictive control is the switching state of the voltage source inverter. Finally voltage source inverter output voltage to the linear motor.

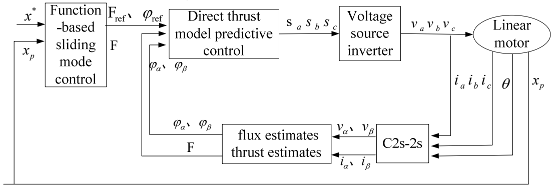


Figure 1. Linear motor SMMP-DTC control block diagram

3.1 Research on sliding mode controller

The linear motor has strong nonlinearity and uncertainty, There is no any the buffer of the middle part, the transformation of the any parameters in the control system will seriously affect the static performance and dynamic performance of the control system of linear motor. sliding mode variable structure control apply to nonlinear and uncertainties of the linear motor. This control method through switch of the control force to make the system state sliding along the sliding surface, the system invariant by parameter perturbation and external interference.

Consider the system: $\dot{x} = Ax + \mathrm{B}u + f(t,x)$ (3)

where $x \in R^n$ ， $A \in R^{n\times n}$ ， $B \in R^{n\times n}$ ， $u \in R^{n\times 1}$ ，If there exists $g(t,x) \in R^{n\times 1}$ ， such that $f(t,x) = Bg(t,x)$ ， n>m and B have the full rank and (3)meets the demands of the matching conditions.

By(2),The dynamics of the PMLSM can be represented by the following second-order differential equation:

$$F_e = M\ddot{x} + B\dot{x} + F_{\mathrm{L}} \tag{4}$$

where x is the position output and $\|\mathrm{F_L}\| \le \mathrm{E}$ is the bounded external uncertainty and disturbance term that may comprise dry and viscous friction, as well as any other unknown forces. Here, $\|\mathrm{F_L}\|$ is satisfy the matching conditions of formula (3). It can be seen that the robustness of the SMC method makes this intensive approach suitable for use in a motor control system[5].

formula (4) can be written as:

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{B}{M} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{1}{M} \end{bmatrix} (u - F_L) \tag{5}$$

where: $x_1 = x_p, \dot{x}_1 = x_2$ ， and， $u = F_e$ is control input.

In this paper ,we selected shift tracking error as the system state variables:

$$e = x^* - x_{\mathrm{p}} \tag{6}$$

Where, x* is reference displacement; x_{p} is actual displacement. PMSLM system error equation:

$$\dot{\mathrm{e}} = \dot{r} - \dot{x}_1 = \dot{r} - x_2 \tag{7}$$

$$\ddot{e} = \ddot{r} - \dot{x}_2 = \ddot{r} + \frac{1}{M}\left[B\dot{r} - \dot{B} + F_L\right] - \frac{1}{M}u \tag{8}$$

This paper select sliding surface: $\mathrm{s} = \mathrm{c}e + \dot{e}$ (9)

Where, c is a positive real number.

Using sliding mode equivalent control method to achieve Sliding mode control of linear motor:

$$u = u_{eq} + u_s \tag{10}$$

u_{eq} is sliding equivalent control system parts, namely, required the control amount when the sliding surface and all of the uncertain part is the zero, i.e. the average value of switch control;

$$u_{eq} = M\left[\ddot{r} + \frac{B}{M}x_2 + c\dot{e}\right] \tag{11}$$

u_s is sliding mode switching control part, the system state towards the sliding surface by the high-frequency switching control, and slide into steady-state status along the lines of the sliding mode, in order to limit and compensation uncertainty of the servo control system.

$$u_s = k\,\mathrm{sgn}(s) \tag{12}$$

Where, k is the scale factor of switching, $\mathrm{sgn}(s)$ is the sign function, It can be obtained $S\dot{S} < 0$ that existence conditions and capacity conditions of the sliding mode by Lyapunov stability theorem. In order to ensure at any point in the phase plane tends reached Sliding line with in a limited time, the switching control must be above conditions. By the formula (8), (9), (10), (11) and (12) can be solved the selection scope of the scale factor:

$k > \dfrac{F_{L\max}}{M} + \varepsilon$ ， Where, $F_{L\max}$ is maximum generalized disturbance. ε is a positive real number.

Based on the above principle, to build linear motor matlab simulation model of the sliding mode control [6].

3.2 The sliding mode control of the linear motor based on the function

In this paper, based on function instead of sign function sgn (s), can greatly weaken the speed control system buffeting phenomenon. Its function is expressed as[9]:

$$\alpha = \frac{2}{1 + e^{-f \cdot s}} - 1 \tag{13}$$

Where, f is a positive real number, so that:

$$u = u_{eq} + \alpha K \tag{14}$$

3.3 The linear motor model predict direct thrust control

The optimizer based cost function as nonlinear model predictive control method [7]. This method will begin the initial value through the system model to predict the predicted outputs, and then compared the predicted value with a reference value to obtain the future errors. The prediction error based on the cost function and other constraints optimizer to calculate future input. The next sampling time system model through past inputs and outputs and the predicted future input state to re-calculate the output state, so the cycle.

$$s_a = \begin{cases} 1, if & s_1 \quad on \quad and \quad s_4 \quad off \\ 0, if & s_1 \quad off \quad and \quad s_4 \quad on \end{cases}$$

$$s_b = \begin{cases} 1, if & s_2 \quad on \quad and \quad s_5 \quad off \\ 0, if & s_2 \quad off \quad and \quad s_5 \quad on \end{cases}$$

$$s_c = \begin{cases} 1, if & s_3 \quad on \quad and \quad s_6 \quad off \\ 0, if & s_3 \quad off \quad and \quad s_6 \quad on \end{cases}$$

The vector expression: $s = \frac{2}{3}(s_a + a s_b + a^2 s_c)$ (15)

Where, $a = e^{j\frac{2\pi}{3}}$。

Load voltage: $v = V_{dc} s$ (16)

Future reference thrust and reference flux can be respectively given from the current thrust value and the flux value and the last thrust value and flux values by second-order extrapolation [5].

$$\mathrm{F}_{ref} = 3 f_{ref1} - 3 f_{ref2} + f_{ref3} \tag{17}$$

$$\varphi_{ref} = 3\varphi_{ref1} - 3\varphi_{ref2} + \varphi_{ref3} \tag{18}$$

Where, F_{ref1}, φ_{ref1} are the current values, F_{ref2}, φ_{ref2} are the values of the last time, F_{ref}, φ_{ref} are the values of the last two sample time.

The expression of the linear motor in the two phase static coordinates:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = R \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + p \begin{bmatrix} L_\alpha & 0 \\ 0 & L_\beta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} -\phi_f w_e \sin\theta \\ \phi_f w_e \cos\theta \end{bmatrix} \tag{19}$$

According to the principles of direct force and model predictive control can know that: In the stationary coordinate $\alpha - \beta$, the discrete magnetic chains within the k+1 sampling interval can be expressed as:

$$\begin{cases} \varphi_\alpha(k+1) = \varphi_\alpha(k) + [u_\alpha - R i_\alpha(k)] T_s \\ \varphi_\beta(k+1) = \varphi_\beta(k) + [u_\beta - R i_\beta(k)] T_s \end{cases} \tag{20}$$

So winding flux vector:

$$\varphi_s(k+1) = \sqrt{\varphi_\alpha{}^2(k+1) + \varphi_\beta{}^2(k+1)} \angle \tan^{-1}\left(\frac{\varphi_\beta(k+1)}{\varphi_\alpha(k+1)}\right) \tag{21}$$

in the stationary coordinate $\alpha - \beta$, the force of the linear motor within the k+1 sampling interval can be expressed as:

$$F_e(k+1) = \frac{3\pi}{2\tau}[\varphi_\alpha(k+1) i_\beta(k+1) - \varphi_\beta(k+1) i_\alpha(k+1)]$$

The general expression of the thrust can be expressed as:

$$F_e(k+1) = k_s \left|\varphi_s(k+1)\right| \times \sin\delta(k+1) \tag{22}$$

Where, $k_s = \frac{3}{2}\frac{\pi}{\tau}\frac{1}{L_d}\varphi_f$

This paper set g function in order to flux and thrust can be achieved good tracking:

$$g_1 = \left|\varphi_{ref} - \sqrt{\varphi_\alpha^2(k+1) + \varphi_\beta^2(k+1)}\right| \tag{23}$$

$$g_2 = \left|F_{ref} - [F(k) + k_s(u_\beta - R i_\beta) T_s]\right| \tag{24}$$

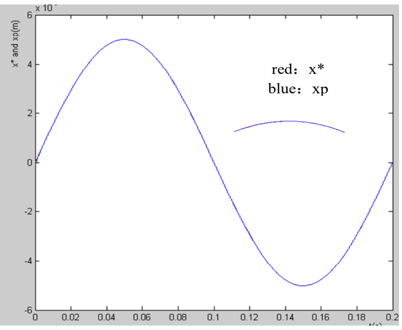
$$g = a * g_1 + b * g_2 \tag{25}$$

Where, a、b is respectively flux estimation and thrust estimated weight coefficient. It can be calculated the most appropriate a、b value according to the proposed method [8].

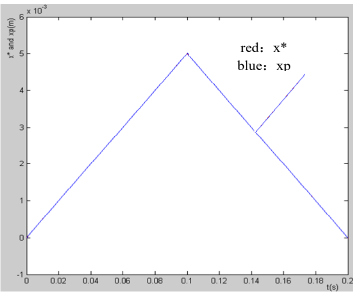
The g function is set, so that the minimum value of the function g conducted inverter switch is selected so that a current can track known current, thereby a good tracking of the displacement of a given signal.

4. Simulation realization based on direct thrust control and sliding model predictions

Using simulation software, and established a permanent magnet synchronous linear motor displacement control system simulation model based on the fuzzy sliding mode and model predict direct thrust control. The selected permanent magnet synchronous linear motor parameters: resistance R = 4.6 Ω, L_d = 0.0035 H, L_q = 0.0035 H; permanent magnet flux ψ_f = .618794 Wb; thrust coefficient k_f = 48.6, the pole pair number p = 2, τ = 0.06 m, load mass M = 1.5Kg, viscosity coefficient B = 120 N • m • s. Sliding parameter c = 2000, k = 600, f = 90; A = 100; B = 1; sampling time is 10us, load torque F_d = 10 N, cogging is estimated in accordance with the sine function $F_{ripple} = 10\sin(\frac{\pi}{\tau}x)$: where x is a straight line the displacement of the motor.

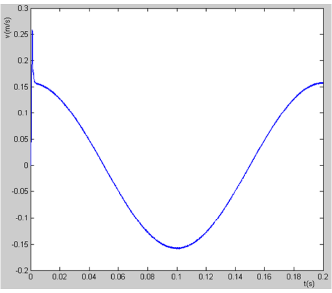


(a) Sine wave tracking figure

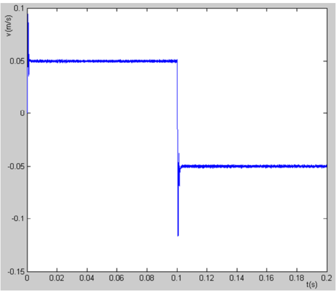


(b)Triangular-wave tracking figure

Figure 2 Displacement tracking diagram of the linear motor the direct thrust predict model

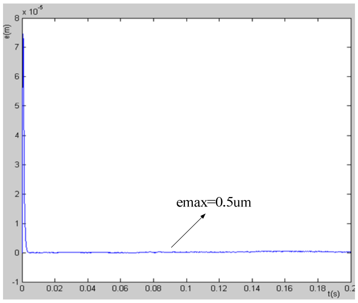


(a) Sine wave tracking velocity figure

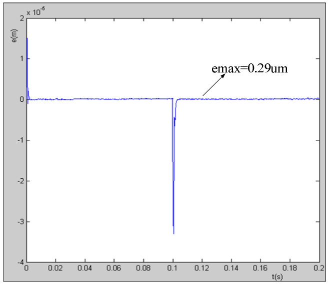


(b) Triangular-wave tracking velocity figure

Figure 3 Velocity tracking diagram of the linear motor the direct thrust predict model

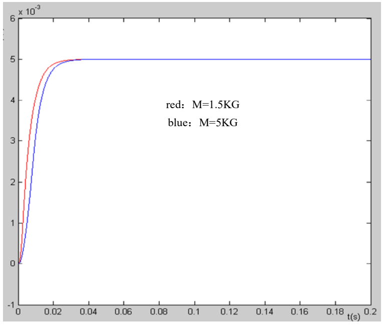


(a) Sine wave tracking error figure

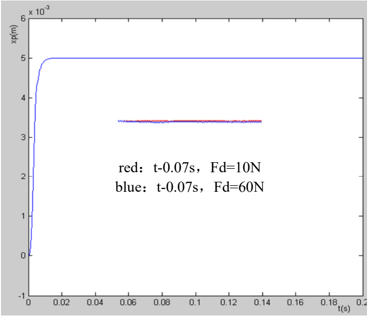


(b) Triangular-wave tracking error figure

Figure 4 Displacement tracking error diagram of the linear motor the direct thrust predict model

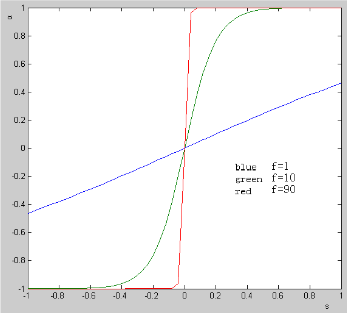


a. Linear motor rotor quality changes

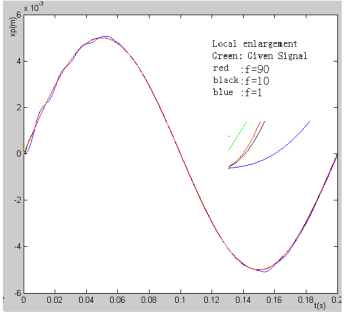


b. Linear motor load changes

Figure5.Displacement tracking figure



(a)Function when different f



(b) Displacement tracking figure when different f

Figure 6. Linear motor displacement tracking map when different f values

The first case: when a given signal types, respectively, a sinusoidal signal $x_p = 0.005\sin(10\pi t)$ m, triangular signal (when $t = \begin{bmatrix} 0 & 0.1 & 0.2 \end{bmatrix}$, $x_p = \begin{bmatrix} 0 & 0.005m & 0 \end{bmatrix}$), The simulation result shown in Figure 2, Figure 3 and Figure 4, The simulation results indicate that the new method of based predictive control track all kinds of displacements of linear motor, and its tracking accuracy is high, the tracking error can reach 0.5um level tracking effect in the sampling period of 10us, and comparison with Yi-Sheng Huang[9] proposed based on the function of the sliding mode direct thrust control, its accuracy is improved by an order of magnitude.

The second situation: When the mass M of the linear motor transform, it can be seen that the response characteristics of the tracking control process will not have a significant impact by the simulation results of Figure5(a) when its quality changed greatly.

Third case: when the load of the linear motor system due to the influence of the external environment, from Figure 5(b) shows, When uncertain load varied from 10N to 60N, the response will not be affected as long as the load does not exceed the maximum of the controller design, this paper, the new control method can better track its displacement.

Fourth case: when f of the function $\alpha = \frac{2}{1+e^{-f.s}} - 1$ transform ,it can be seen by the simulation results of Figure 6, when f from the change from 0 to 100 ,the sinusoidal displacement tracking simulation results can be seen, the larger the value of f, its tracking better higher accuracy.

5. Summary

This article put forward sliding mode model predicts direct thrust control system, for shortcomings of the linear motor nonlinearities and uncertainties as well as the control cycle non-constant of the traditional direct torque control, the number of switching inverter in unit time is not expected, complex frequency components .which control performance has been improved and perfected. The model predicts direct thrust control using discrete control design, to solve the problem SVPWM control assumes that the system as a continuous system. Moreover, the sampling time of the model predictive control constant, reducing the requirements of the computing unit and the implement unit. On the one hand, sliding mode control of function-based to meet the linear motor nonlinear and uncertainties requirements. The other hand, the model predicts direct thrust control algorithms, software and hardware are simple, fast dynamic response, constant control cycle, the control system makes the project easier to realize, lay the foundation for widely using of the direct thrust control. In summary, model predictive direct thrust control system opened up another new direction for linear motor, provides the foundation and help for the latter part of the experimental study.

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References

1. Kennel R., Linder A., Linke M, et al. Generalized predictive control (GPC)-ready for use in drive applications. IEEE, 2001: 1839-1844 vol. 1834.
2. Linder A., Kanchan R., Kennel R., Stolze P. Model-Based Predictive Control of Electric Drives. Cuvillier. 2010.
3. Zhu Xiaodong, Cheng Zhiping, Jiao Liucheng, et al.permanent magnet linear synchronous motor simulation model study. Mining Machinery. 2006, 34 (7): 84-87.
4. Wang Fuzhong, Wang Xudong,Jiao Liucheng, et al.synchronous motor electromagnetic force angle and the maximum thrust control strategies. Coal Society. 2001, 26 (3), p. 307-312.
5. Y. S. Huang and C. C. Sung, et al. Implementation of sliding mode controller for a linear synchronous motor based on direct thrust control theory. IET Control Theory Appl. 2010, p. 1–13.
6. Liu Jinkun sliding model variable structure control MATLAB simulation. Beijing: Tsinghua University Press, 2005.
7. José Rodríguez, Jorge Pontt, César A. Silva, et al. Predictive Current Control of a Voltage Source Inverter. IEEE transaction on industrial electronics. vol. 54, NO. 1, february, 2007.
8. S. Alireza Davari, Davood Arab Khaburi, and Ralph Kennel, et al. An Improved FCS–MPC Algorithm for an Induction Motor With an Imposed Optimized Weighting Factor. IEEE transaction on industrial electronics, vol. 27, NO. 3, march 2012.
9. Yi-Sheng Huang, Cheng-Chung Sung, et al. Function-Based Controller for Linear motor Control Systems . IEEE transaction on industrial electronics, vol.57, NO. 3, march, 2010.