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Permanent Magnet Linear Synchronous Motor Drive Using Nonlinear Control

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Abstract

The conventional linear controllers such as PI, PID can no longer satisfy the stringent requirement placed on high performance drive applications. These controllers are sensitive to plant parameter variation and load disturbance. Considering the lumped uncertainties with parameter variations and external disturbance for an actual PMLSM drives, a Non Linear control technique is proposed an Adaptive Back Stepping Sliding Mode Control(ABSMC). The proposed Non-linear control scheme is valid to compensate the lumped uncertainty with parameter variations and external disturbance for PMLSM drives. The system performance is evaluated by Matlab/simulink. The Result is compared with the result obtained by PI controller.

1. Introduction

Permanent magnet linear synchronous motors (PMLSMs) have been widely used for industrial robots, machine tools, semiconductor manufacturing equipment, automatic inspection machines etc. The main features of PMLSM are high force density, low losses, high dynamic performance and most importantly, high positioning precision associated with mechanical simplicity. However, since mechanical transmission devices are eliminated, the effects of model uncertainties such as parameter variations and external perturbation in PMLSM drives are directly transmitted to the load. In order to achieve high positioning precision in spite of the effects, some appropriate control strategies must be adopted in PMLSM drives.

An adaptive back stepping sliding mode control (ABSMC) scheme which combines both merits of adaptive back stepping control [7-8] and sliding mode control [9], is proposed to control mover position of PMLSM. Considering the lumped uncertainty with parameter variations and external disturbance for the actual PMLSM drives, the lumped uncertainty can be observed by an adaptive uncertainty observer and considered to be a constant during the observation. Digital processing is feasible in practice since the sampling period of the observer is short enough comparing with the variation of the lumped uncertainty.

The simulated results show that the proposed scheme is valid to compensate the lumped uncertainty with parameter variations and external disturbance for actual PMLSM drives.

2. Modelling of PMLSM

Neglecting the longitudinal end effect, the mathematical model of PMLSM under the d-q rotating coordinate is written in [1]

$$v_d(t) = Ri_d + \frac{d\psi_d}{dt} - \omega\psi_q \qquad (1)$$

$$v_q(t) = Ri_q + \frac{d\psi_q}{dt} + \omega\psi_d \qquad (2)$$

Where d & q axis flux linkages are given as:

$$\psi_d = L_d i_d + \psi_{PM}$$

$$\psi_q = L_q i_q$$

Where ψ_{PM} is the flux linkage of the permanent magnet.

Thrust force of PMLSM:

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

Where p=No. of Pair Poles, τ = PM pole pitch

The relation between ω (angular synchronous speed) & Linear velocity:

$$\omega = \frac{\pi}{\tau} v_{lin}$$

The motion equation of PMLSM is described as follows:

$$F_e = M\dot{v} + Dv + F_L \qquad (4)$$

Where M is the total mass of moving elements, D represents the viscous coefficient; F_L stands for the external disturbance force.

3. ABSMC Control Scheme

Design of ABSMC controller

Considering a practical PMLSM drives with parameter variations and external force disturbances, let

$$\dot{d} = v \tag{5}$$

$$\dot{v} = (A_m + \Delta A)d + (B_m + \Delta B)U + CF_L \tag{6}$$

Where d is position, v is velocity, $C = -1/\overline{M}$, $A_m = -\overline{D}/\overline{M}$, $B_m = K_F/\overline{M}$, ΔA and ΔB are the uncertainties introduced by the variations of system parameters M and D respectively, $U = i_q$ is control input to the motor drive system. Reformulating (6), then

$$\dot{v} = A_m d + B_m U + F \tag{7}$$

In (7), F is called the lumped uncertainty, defined as

$$F = \Delta A d + \Delta B U + CF_L \tag{8}$$

The lumped uncertainty F can be observed by an adaptive uncertainty observer, the control objective is to design an ABSMC system for the output d in (6) to track precisely the reference trajectory d*. We assume d* and its first two derivatives $\dot{d}^*, \ddot{d}^*$ are all bounded functions of time. The proposed ABSMC system is described as follows.
For the position tracking objective, the tracking error is defined as

$$e_1 = d - d^* \tag{9}$$

The derivative of e_1 is

$$\dot{e}_1 = v - \dot{d}^* \tag{10}$$

Define stabilizing function

$$\alpha_1 = -k_1 e_1 + \dot{d}^* \tag{11}$$

where k_1 is a positive constant. The first Lyapunov function is chosen as follows

$$V_1 = \frac{1}{2} e_1^2 \tag{12}$$

Define $e_2 = v - \alpha_1$, then the derivative of V_1 is

$$\dot{V}_1 = e * \dot{e} = -k_1 e_1^2 + e_1 e_2 \tag{13}$$

The derivative of e_2 is described as follows

$$\dot{e}_2 = A_m v + B_m U + F + k_1 e_1^* - \ddot{d}^* \tag{14}$$

Define Lyapunov function

$$V_2 = V_1 + \frac{1}{2} s^2 \tag{15}$$

Take the sliding surface

$$s = k e_1 + e_2 \tag{16}$$

Using (13) and (14), the derivative of (15) can be expressed as

$$\dot{V}_2 = \dot{V}_1 + s\dot{s} = e_1 e_2 - k_1 e_1^2 + s\dot{s}$$

$$= e_1 e_2 - k_1 e_1^2 + s(k\dot{e}_1 + \dot{e}_2)$$

$$\begin{aligned} &= e_1 e_2 - k_1 e_1^2 + s[k(e_2 - k_1 e_1) + \\ &A_m(e_2 + \dot{d}^* - \alpha_1) + B_m U + F - \ddot{d}^* + \dot{\alpha}_1] \end{aligned} \tag{17}$$

According to (17), BSMC law is taken as

$$\begin{aligned} U = B_m^{-1}[&-k_1(e_2 - k e_1) - A_m(e_2 + \dot{d}^* - \alpha_1) - \\ &\overline{F}\operatorname{sgn}(s) - \ddot{d}^* - \dot{\alpha}_1 - h(s + \beta \operatorname{sgn}(s))] \end{aligned} \tag{18}$$

where h and β are all positive constants. Substituting (18) into (17), then

$$\begin{aligned} \dot{V}_2 &= -k_1 e_1^2 + e_1 e_2 - hs^2 - h\beta|s| + Fs - \overline{F}|s| \\ &= -k_1 e_1^2 + e_1 e_2 - hs^2 - h\beta|s| - [\overline{F}|s| - Fs] \\ &= -e^T Q e - h\beta|s| - [\overline{F}|s| - Fs] \le 0 \end{aligned} \tag{19}$$

Where $e^T = [e_1 e_2]$

$$Q = \begin{bmatrix} k_1 + hk^2 & hk - \frac{1}{2} \\ hk - \frac{1}{2} & h \end{bmatrix} \tag{20}$$

In practical applications, since the lumped uncertainty F is unknown, its bound is difficult to obtain, therefore, an adaptive law is proposed to adjust the value of the lumped uncertainty $\hat{F}$.The following Lyapunov function is chosen

$$V_3 = V_2 + \frac{1}{2\lambda} \tilde{F}^2 \tag{21}$$

where $\tilde{F} = F - \hat{F}$, λ is a positive constant. Take the derivative of V_3

$$\begin{aligned}\dot V_3 &= \dot V_2 + \frac{1}{\lambda}\tilde F\dot{\hat F} \\ &= e_1e_2 - k_1e_1^2 + s(k\dot e_1 + \dot e_2) - \frac{1}{\lambda}\tilde F\dot{\hat F} \\ &= e_1e_2 - k_1e_1^2 + s[k(e_2 - k_1e_1) + \\ &\quad A_m(e_2 + \dot d^* - \alpha_1) + B_mU + F - \ddot d^* + \dot\alpha_1] - \\ &\quad \frac{1}{\lambda}\tilde F(\dot{\hat F} - \lambda s)\end{aligned} \tag{22}$$

According to (22), an ABSMC law can be proposed

$$\begin{aligned}U = B_m^{-1}[&-k_1(e_2 - k_1e_1) - A_m(e_2 + \dot d^* - \alpha_1) - \\ &\hat F + \ddot d^* - \dot\alpha_1 - h(s + \beta\,\mathrm{sgn}(s))]\end{aligned} \tag{23}$$

An adaptive law is designed

$$\dot{\hat F} - \lambda s \tag{24}$$

Stability Proof

Substituting (23) and (24) into (22), then

$$\dot V_3 = -e^TQe - h\beta|s| \le 0 \tag{25}$$

where Q is a positive symmetric matrix in (20).Let

$$W(t) = e^TQe + h\beta|s| \tag{26}$$

Then

$$\int_0^t W(\tau)d\tau = V_3(e_1(0), e_2(0)) - V_3(e_1(t), e_2(t)) \tag{27}$$

Since Lyapunov function $\dot V_3 \le 0$ is stable, $V_3(e_1(0), e_2(0))$ is bounded and $V_3(e_1(t), e_2(t))$ is non-increasing and bounded. The following result is obtained

$$\lim_{t\to 0}\int_0^t W(\tau)d\tau < \infty \tag{28}$$

Since $\dot e_1$ and $\dot e_2$ are all bounded, according to stability theorem, e_1 and e_2 are also bounded. Therefore, $\dot W(t)$ is bounded. $W(t)$ is uniformly continuous. According to Barbalat's lemma[11], the following result can be obtained

$$\lim_{t\to 0} W(\tau) = 0 \tag{29}$$

When $t \to \infty$ e_1 and e_2 converge to zero, that is

$\lim_{t\to 0} d(t) = d^*$ and $\lim_{t\to 0} v(t) = 0$

Therefore, the control system is asymptotically stable even if the lumped uncertainty exists.

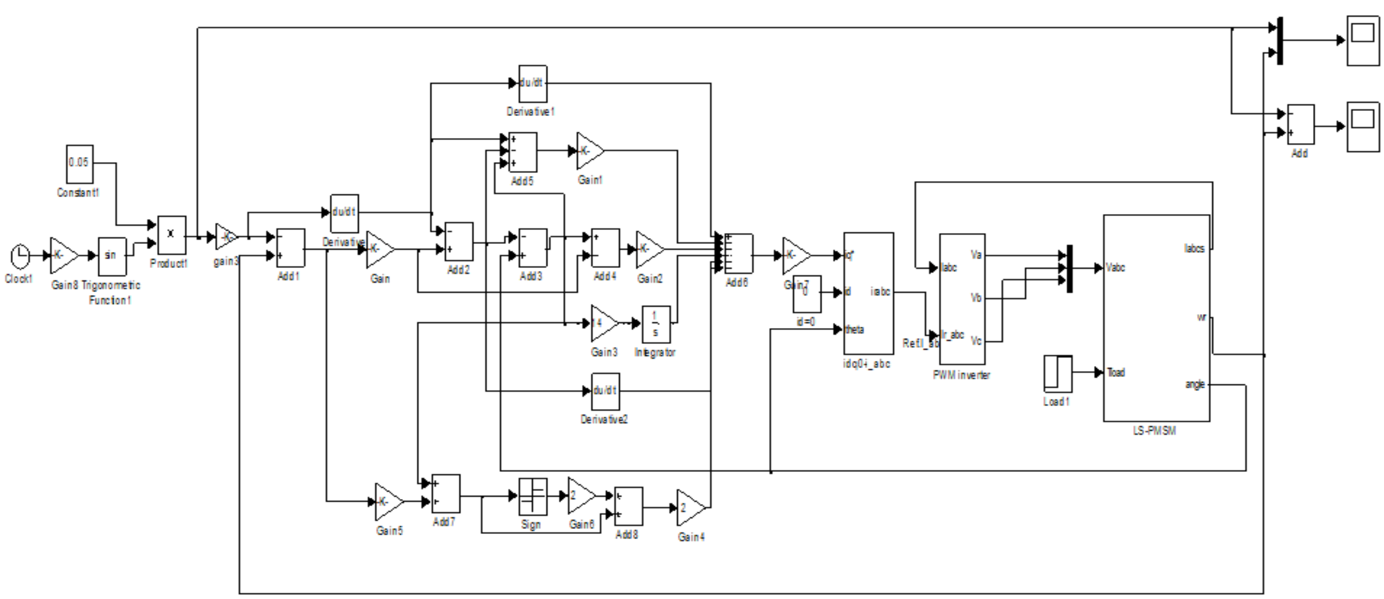
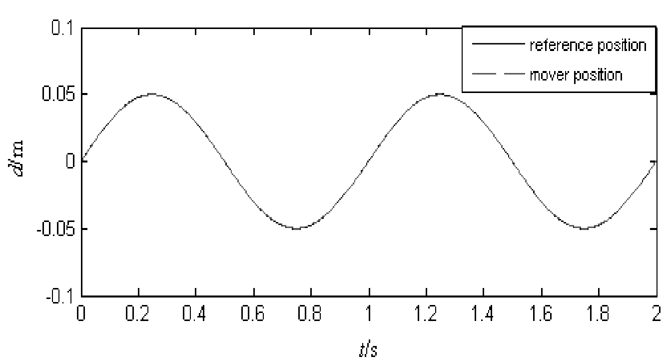


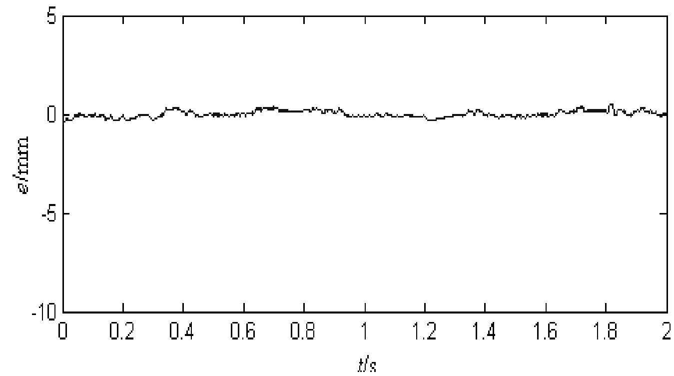
Fig.1 Simulation diagram of PMLSM ABSMC

4. Simulation Results

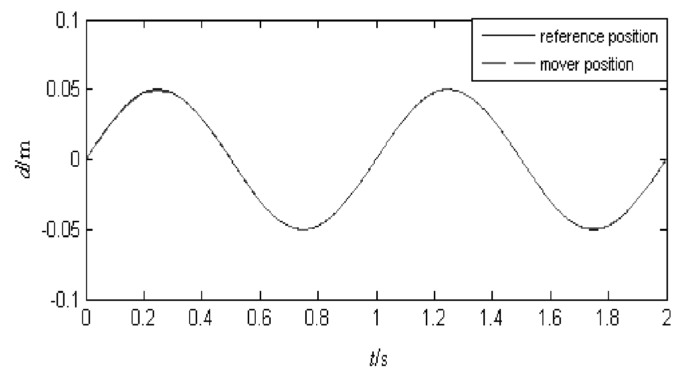
To show the validity of theory analysis and investigate the effectiveness of proposed scheme, simulation is carried out for a PMLSM drive. The diagram of PMLSM ABSMC system is described in Fig.1.The normal values of PMLSM parameters, resistance Rs=2.785Ω, inductance L=8.5e-3H, number of pole the pairs P=2, total mass of the moving element system Mn=2.78kg, viscous friction coefficient Dn=36N/s. The reference position command of PMLSM is given, d*=0.05sin2πt m, and position command of Step was also applied(response shown in Fig.4 and Fig.5). The uncertainties introduced by parameter variations and external perturbation in the drive are set the following values, M=3Mn, D=2Dn, F_L =200N. The parameters of the ABSMC are chosen as k=1000, k_1=500, h=2, λ=14, β=2. In order to avoid the chattering phenomena, the switch function of sliding mode control laws in (18), (23) is replaced by saturated function in simulation. The lumped uncertainty bound $\overline{F}$ is taken 0.2, which is a trade off between the limitation control efforts and the possible perturbed range of parameter variation and external disturbance. The simulation results of ABSMC drive are depicted in Fig.2. To further demonstrate the best control performance of ABSMC drive, the simulation results of PI controller under same conditions are also given in Fig.3.From the simulated results; the mover position tracking is subject to parameter variations and external disturbance in Fig.3(c). Conversely, robust tracking performance is obtained in Fig.2(c) under the occurrence of lumped uncertainties. Compared with the BSMC in Fig.3 (d), the position tracking error of ABSMC is less than ±5μm.The proposed scheme can confront the influence of parameter variations and external disturbance effectively, mainly owing to online adaptation for lumped uncertainty. It is shown that the ABSMC can track precisely reference command in the case of existing lumped uncertainty with parameter variations and external perturbation.



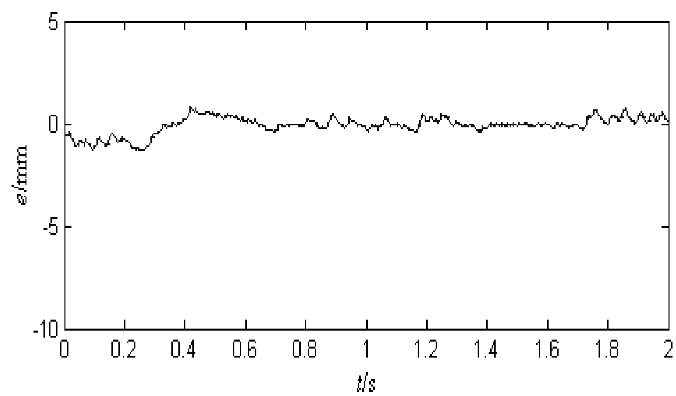
(a) Mover position (M=Mn, D=Dn, F_L =0)



(b) Position error (M=Mn, D=Dn, F_L =0)

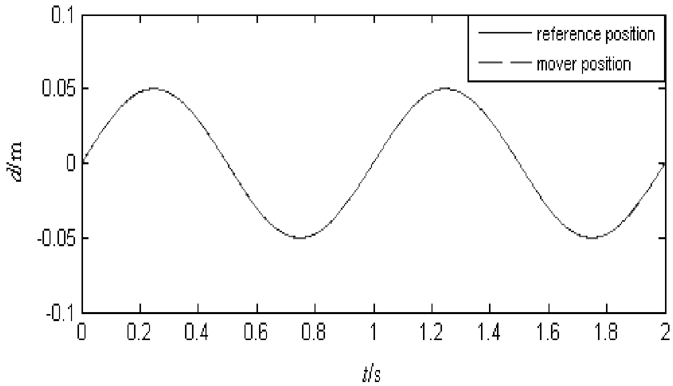


(c) Mover position (M=3Mn, D=2Dn, F_L =200N)

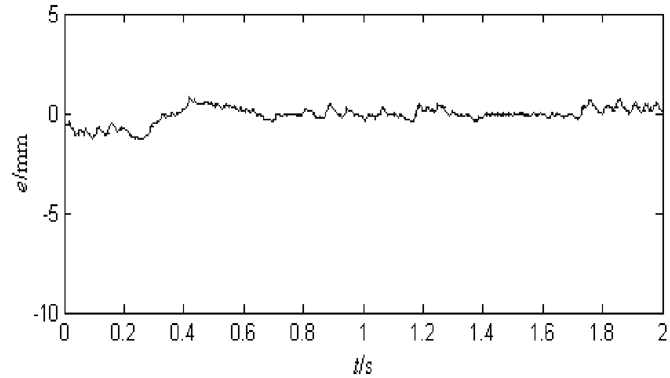


(d) Position error (M=3Mn, D=2Dn, F_L =200N)

Fig.2.The results of ABSMC drive

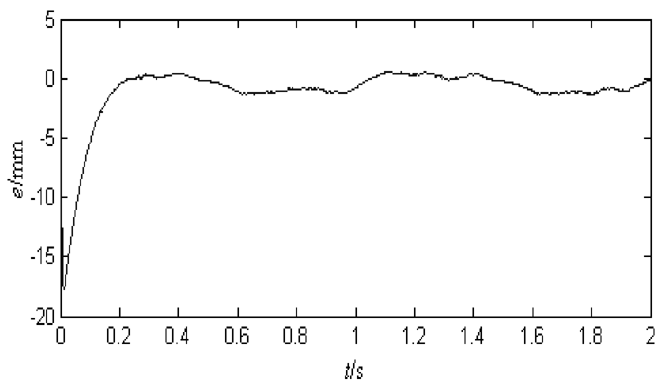


(a) Mover position (M=Mn, D=Dn, F_L =0)

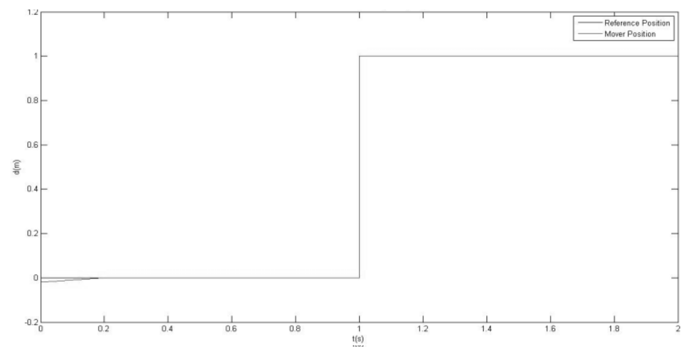


(d) Position error (M=3Mn, D=2Dn, F_L =200N)

Fig.3.The results of PI control drive

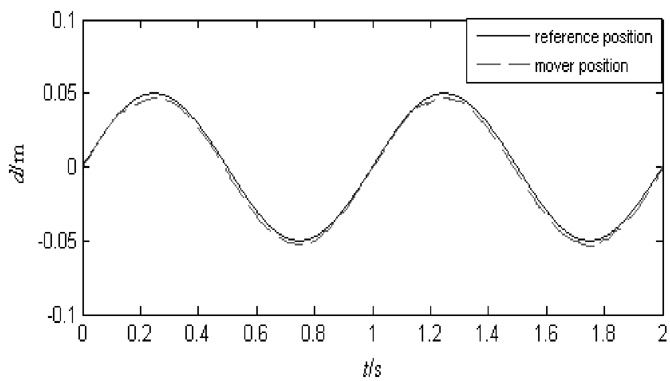


(b) Position error (M=Mn, D=Dn, F_L =0)

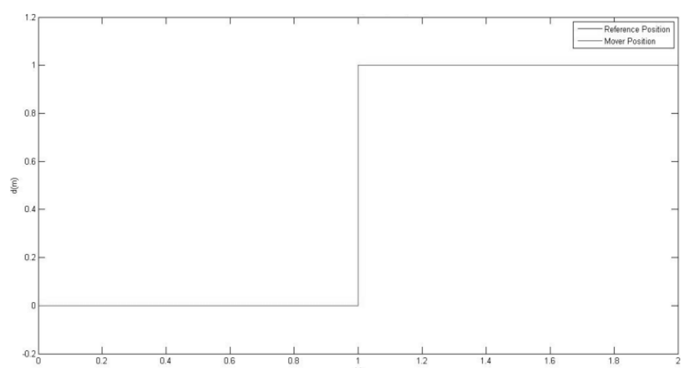


Mover position (M=Mn, D=Dn, F_L =0)

Fig.4. The result of PI control drive for Step Command



(c) Mover position (M=3Mn, D=2Dn, F_L =200N)



Mover position (M=Mn, D=Dn, F_L =0)

Fig.5: The result of ABSMC control drive for Step Command

5. Conclusion

Implementation of ABSMC system for the mover position control in PMLSM drives has been particularly demonstrated. This paper also demonstrated the design, stability analysis.

A simple adaptive law to adjust the lumped uncertainty in real time was proposed to relax the requirement for the bound of lumped uncertainty.

The effectiveness of the proposed control scheme has been confirmed by simulation and is robust with respect to motor parameter variations and external perturbation.

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