Adaptive Control of Permanent Magnet Linear Synchronous Motor using Wavelet Transform

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Abstract: The problem is improving the positioning precision of a permanent magnet linear synchronous motor (PMLSM). Thus, this paper presents the design and realization of an adaptive dither to reduce the force ripple in PMLSM. A composite control structure is used, consisting of three components: a simple feed-forward component, a PID feedback component and an adaptive feed-forward compensator (AFC).
Especially adaptive feed-forward component cancel out detent force using wavelet transformation. Computer simulation results verify the effectiveness of the proposed scheme for high precision motion trajectory tracking using the PMLSM

Keywords: Permanent magnet linear synchronous motor (PMLSM), Feed-forward compensator (AFC), Detent force, Wavelet transform, Adaptive control.

1. INTRODUCTION

Recently, a complicated transport system is demanded in the field of factory automation for the reduction of labor in a large-scale factory. Linear synchronous motor (LSM), linear induction motor (LIM) and linear pulse motor (LPM) were studied for the transport system. Because it is among the electric motor drives, permanent magnet linear synchronous motors (PMLSM) are probably the most naturally akin to application involving high precision motion control.

The increasingly widespread industrial applications of PMLSMs in various industrial field, precision metrology and miniature system assembly are self-evident testimonies of the effectiveness of PMLSMs in addressing the high requirements associated with these application areas.

The main benefits of a PMLSM include the high force density achievable, low thermal losses and, most importantly, the high precision and accuracy associated with the simplicity in mechanical structure. Unlike rotary machines, linear motors require no indirect coupling mechanisms as in gear boxes, chains and screws coupling. This greatly reduces the effects of contact-type nonlinearities and disturbances such as backlash and frictional forces, especially when they are used with aerostatic or magnetic bearings. However, the advantages of using mechanical transmission are also consequently lost, such as the inherent ability to reduce the effects of model uncertainties and external disturbances.

Therefore the reduction of these effects, either through proper physical design or via the control system, is of paramount importance if high-speed and high precision motion control is to be achieved. A significant and well-know nonlinear effect in the dynamics of the PMLSM is the phenomenon of force ripple arising from the magnetic structure which exhibit characteristics that are position and velocity dependent. This is also shown in Fig. 1.

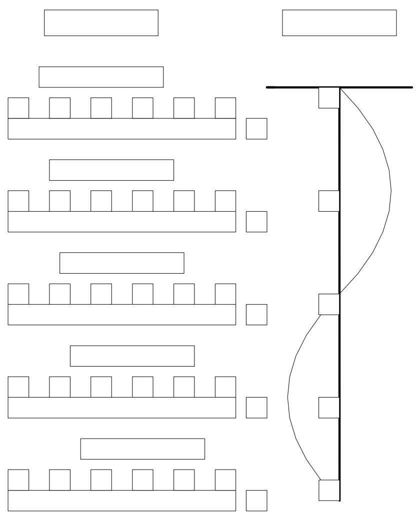

Fig. 1 Detent force produced by the interaction between a permanent magnet and the steel teeth of the primary

1.1 Detent force reduction - Hardware

In [1], [2], and [3], the four methods to reduce detent force were studied and analyzed. The methods are adjusting the width of permanent magnet, varying the shape of armature teeth, relocating the permanent magnet, and adjusting the width of permanent magnet and relocating the permanent magnet at the same time. However this method is demanded design of detail and complexity machinery.

1.2 Detent force reduction - Software

In [4], H_∞ optimal feedback control is used to provide a high dynamic stiffness to external disturbances. In [5], a neural-network feed-forward controller was proposed to reduce positional inaccuracy due to reproducible and slowly time-varying disturbances. Yao and Tomizuka given by [6] proposed an adaptive robust control approach and applied it subsequently to high speed, high accuracy motion control of machine tools. In [7], radial-basis function is used as part of a composite control scheme to reduce errors arising from nonlinear uncertain remnants which were not considered in the linear control. In [8] iterative learning control is used, targeted at applications involving repeated iterative operations. In all these works, while the efforts were geared towards the compensation of nonlinear uncertainties, there has been no explicit modeling of the ripple force phenomenon, and consequently, no direct approach to attempt to suppress these force.

In this paper, we consider the design and realization of an adaptive dither to suppress the force ripple phenomenon associated with servo mechanisms with a more specific view towards application to PMLSM.

A composite control structure is used, consisting of three components: a simple feed-forward component, a PID feedback component and an adaptive feed-forward compensator (AFC). The first two components are designed based on a dominant linear model of the motor. In particular, the feedback control uses a PID structure and the PID parameters are tuned using a LQR approach to achieve optimal motion trajectory tracking. uncompromising on the maximum force achievable. AFC generates a dither signal with the motivation to eliminate or suppress the inherent force ripple, thus facilitating smooth precise motion while uncompromising on the maximum force achievable. AFC dither signal refer to the disturbance of Wavelet transformed.

Finally, we propose a composite controller comprising of three components in this paper; *i) feedback component*, *ii) feed-forward component*, *iii) adaptive feed-forward component (AFC) generating an adaptive dither si*gnal. The proposed controller is also useful for precision control of permanent magnet linear motors which exhibit simple and tuning the controller requires only simple step or pulse tests.

2. MACHINE MODEL OF PMLSM

The machine model of a PMLSM can be described in synchronous rotating reference frame as follows

$$v_q = R_s i_q + p\lambda_q + \omega_e \lambda_d \quad (1)$$

$$v_d = R_s i_d + p\lambda_d + \omega_e \lambda_q \quad (2)$$

where

$$\lambda_d = L_q i_q \quad (3)$$

$$\lambda_d = L_d i_d + \lambda_{PM} \quad (4)$$

$$\omega_e = P\omega_r \quad (5)$$

and v_d, v_q are the d, q axis voltages; i_d, i_q are d, q axis currents; R_s is the phase winding resistance; L_d, L_q are the d, q axis inductances; ω_r is the angular velocity of the mover; ω_e is the electrical angular velocity; λ_{PM} is the permanent magnet flux linkage; P is the number of primary pole pairs and p denotes the differential operator. Moreover, we know that the following equations

$$\omega_r = \pi v / \tau \quad (6)$$

$$v_e = Pv = 2\tau f_e \quad (7)$$

where v is the linear velocity; τ is the pole pitch; f_e is the electric frequency. The developed electromagnetic power is given by

$$P_e = F_e v_e = 3P[\lambda_d i_q + (L_d - L_q) i_d i_q]\omega_e / 2 \quad (8)$$

Thus, the electromagnetic force is

$$F_e = 3\pi P[\lambda_d i_q + (L_d - L_q) i_d i_q] / 2\tau \quad (9)$$

and the mover dynamic equation is

$$F_e = Mpv + Dv + \omega(t) \quad (10)$$

where M is the total mass of the moving element system; D is the viscous friction and iron–loss coefficient; $\omega(t)$ is the external disturbance term. In equations (4), (7), (8) and (9), if i_d =0, the d-axis flux linkage λ_d is fixed since λ_{PM} is constant for a PMLSM and the electromagnetic force F_e is then proportional to i_q^* which is determined by closed-loop control. The resulted force equation is given by [9]

$$F_e = 3\pi \lambda_{PM} i_q / 2\tau \quad (11)$$

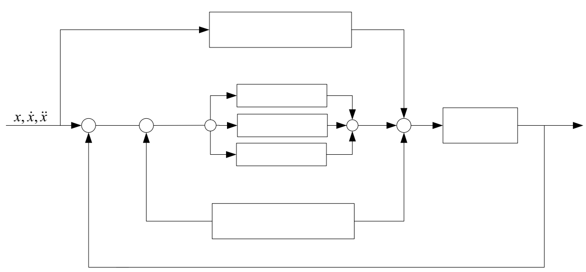

Fig. 2 Block diagram of the proposed control scheme for PMLSM

A 3 tier composite control structure is adopted with the configuration as shown in Fig. 2. The PMLSM servo drive can be simplified to a control system block diagram as shown in Fig. 3.

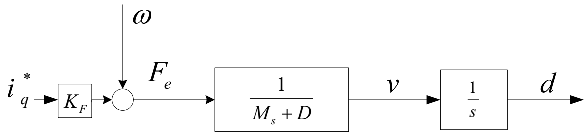

Fig. 3 PMLSM servo drive

where

$$F_e = K_F i_q^* \tag{12}$$

$$K_F = 3\pi P \lambda_{PM} / 2\tau \tag{13}$$

$$H_p(s) = \frac{1}{Ms+d} = \frac{b}{s+a} \tag{14}$$

Moreover, K_F is the thrust coefficient, i_q^* is the command of thrust current, and *s* is the operator of Laplace transform.

3. CONTROLLER DESIGN

The dynamics of a PMLSM can be the following equations:

$$u(t) = k_e \dddot{x}(t) + Ri(t) + L\frac{di(t)}{dt} \tag{15}$$

$$i(t) = \frac{1}{k_f} f(t) \tag{16}$$

$$f(t) = m\ddot{x}(t) + f_{load}(t) + f_{fric}(t) + f_{ripple}(\dot{x}, x) + f_n(t) \tag{17}$$

where

- $u(t)$: time-varying motor terminal voltage;
- $i(t)$: the armature current;
- $x(t)$: the motor position;
- $f(t)$: the developed force;
- $f_{load}(t)$: the applied load force;
- $f_{fric}(t)$: the frictional force;
- $f_{ripple}(t)$: ripple force;

Also, $f_n(t)$ includes other uncertainties and disturbances in the system.

From eq. (12) – eq. (14), we can represent the following equation

$$\begin{aligned} u(t) &= k_e \dot{x}(x) \\ &+ \frac{R}{k_f}\{m\ddot{x}(t) + f_{load}(t) + f_{fric}(t) + f_{ripple}(\dot{x}, x) + f_n(t)\} \\ &+ \frac{L}{k_f}\{m\dddot{x}(t) + \frac{d}{dt} f_{load}(t) + \frac{d}{dt} f_{fric}(t) \\ &+ \frac{d}{dt} f_{ripple}(\dot{x}, x) + \frac{d}{dt} f_n(t)\} \end{aligned}$$

Neglecting all of uncertainties and nonlinearities.

$$u(t) = k_e \dot{x}(x) + \frac{Rm}{k_f}\ddot{x}_d + \frac{Lm}{k_f}\dddot{x}_d \tag{18}$$

3.1 Design of Feed-forward and feedback component

From eq. (18), the feed-forward component (FFC), which is realized as an inverse of the model for fast response, is therefore designed as follow:

$$u_{FFC}(t) = k_e \dot{x}(x) + \frac{Rm}{k_f}\ddot{x}_d + \frac{Lm}{k_f}\dddot{x}_d \tag{19}$$

The feedback control employs a simple PID controller as given following equation

$$u_{PID} = k_p e(t) + k_i \int_0^t e(t)dt + k_d \dot{e}(t) \tag{20}$$

where k_p, k_i and k_d are the three-term controller gains, respectively, and $e = x_d - x$ denotes the error signal.

3.2 Design of adaptive feed-forward component First part

Wavelet transformation is using for pick out the detent force from output signal.

A. Scalar function

Exist next equation $\phi_{D;m}(t) = \lim_{l\to\infty} \phi_{D;m}^{(l)}(t)$, $\phi_{D;m}(t)$ called daubechies scaling function. Daubechies's mother wavelet is defind as follows:

$$\phi_{D;m}(t) = \sum_{k=-K+1}^{l} (-1)^k p_{1-k} \phi_{D;m}(2t - t)$$

Then, the next equation is defined by

$$|s_0(e^{-j\omega/2})|^2 := f_0(\sin^2(\frac{\omega}{4})) = \sum_{k=0}^{m-1} \binom{m+k-1}{k} \sin^{2k}(\frac{\omega}{4})$$

$$|s_0(e^{-j\omega/2})|^2 = \frac{a_0}{2} + \sum_{k=1}^{m-1} a_k \cos(\frac{k\omega}{2})$$

Thus coefficient $\{a_k | k = 0, 1, \cdots, m-1\}$ can be described as follows:

$$a_k = (-1)^k \sum_{l=0}^{m-k-1} \frac{1}{2^{e(k+l)-1}} \binom{2(k+l)}{l} \binom{m+k+l-1}{k+l}$$

4. SIMULATION RESULTS

In the experimental results use of a PMLM (JTM10-0420), the input and output signals of considered system are shown in Fig. 4 and Fig. 5, respectively. The measurement results for detent force of PMLM using wavelet transformation are shown in Fig. 6 – Fig. 15, respectively.

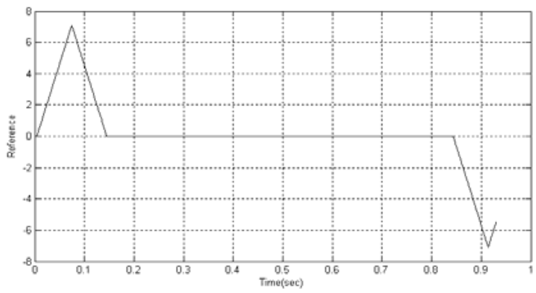

Fig. 4 System input

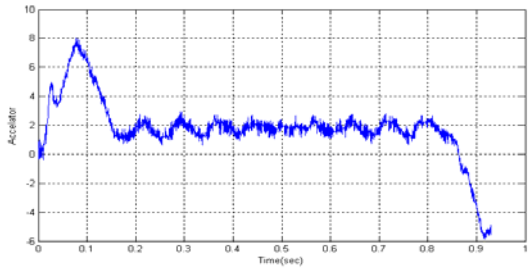

Fig. 5 System output

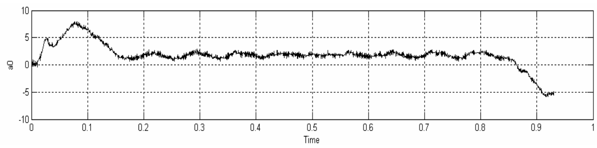

Fig. 6 Coefficient a_0

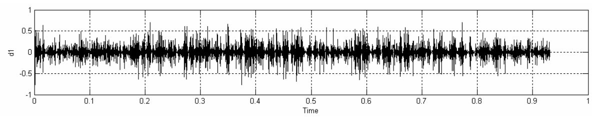

Fig. 7 Wavelet level 1

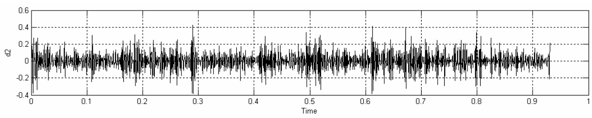

Fig. 8 Wavelet level 2

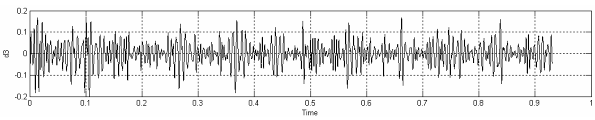

Fig. 9 Wavelet level 3

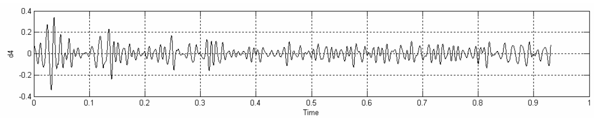

Fig. 10 Wavelet level 4

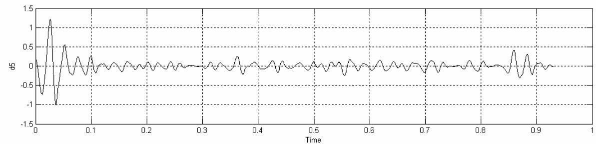

Fig. 11 Wavelet level 5

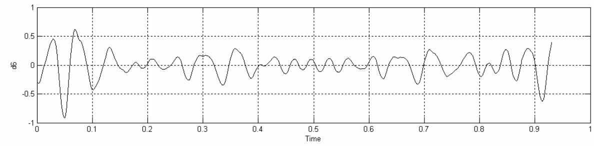

Fig. 12 Wavelet level 6

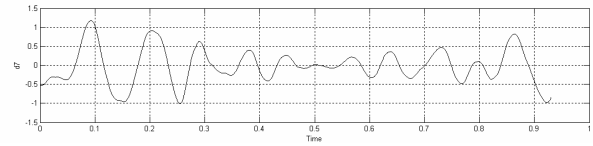

Fig. 13 Wavelet level 7

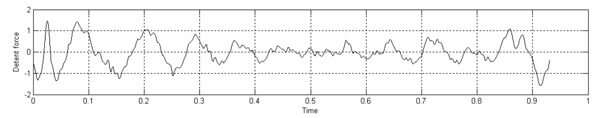

Fig. 14 Detent force

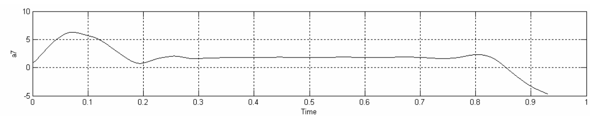

Fig. 15 The cancellations of disturbances

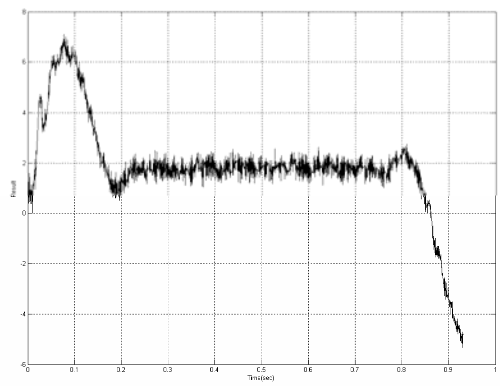

Fig. 16 An actual signal of detent force using wavelet transformation

5. CONCLUSION

This paper has presented the development of a composite controller comprising of three components (a feedback component, a feed-forward component and an adaptive feed-forward component (AFC) generating an adaptive dither signal. The controller is especially useful for precision control of permanent magnet linear motors which exhibit significant force ripples. The proposed scheme is simple and tuning the controller requires only simple step or pulse test.

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REFERENCES

[1] Seok Myeong Jang, In Ki Yoon, Sung Ho Lee, Do Hyun Kang, and Yeon Ho Jeong, "Analysis of Detent Force Reduction Method in a permanent Magnet Linear Synchronous Motor," *KIEE International Trans. on EMECS*, Vo. 12-b, No. 1, pp. 1-6, 2002.

[2] T. Yoshimura, H. J. Kim, M. Watada, S. Torii, and D. Ebhara, "Analysis of Reduction of Detent Force in a Permanent Magnet Linear Synchronous Motor," *IEEE Trans. on magnetics*, Vol. 31, No. 6, pp. 3728-3730, 1995.

[3] Ju Lee, Hyung Woo Lee, Yon Do Chun, Myoung Ho Sunwoo, and Jung Pyo Hong, "The Preformance Prediction of Controlled-PMLSM in Various Design Schemes by FEM," *IEEE Trans. on Magnetics*, Vol. 36, No. 4, pp. 1902-1905, 2000.

[4] D. M. Alter and T. C. Tsao, "Control of Linear Motor for Machine Tool Feed Drives: design and implementation of H_∞ optimal feedback control," *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 118, pp. 649-658, 1996.

[5] G. Otten, T. Vries, J. Amerongen, A. M. Rankers, and E. W. Gaal, "Linear Motor Motion Control using a Learning Forward Controller," *IEEE/ASME Trans. on Mechatronics*, Vol. 2, No. 3, pp. 179-187, 1997.

[6] B. Yao and M. Tomizuka, "Adaptive Robust Control of SISO Nonlinear Systems in a Semi-Strict Feedback Form," *Journal of Automatica*, Vol. 33, No. 5, pp. 893-900, 1997

[7] K. K. Tan, S. N. Huang, H. F. Dou, S. Y. Lim, and S. J. Chin, "Adaptive Robust Motion Control for Precise Trajectory Tracking Applications," *ISA Trans.*, Vol. 40, No. 1, pp. 57-71, 2001.

[8] K. K. Tan, T. H. Lee, S. Y. Lim, and H. F. Dou, "Learning Enhanced Motion Control of Permanent Magnet Linear Motor," *Proc. of the 3rd IFAC International Workshop on Motion Control*, pp. 397-402, 1998.

[9] F. J. Lin, C. H. Lin, and C. M. Hong, "Robust Control of Linear Synchronous Motor Servodrive using Disturbance Observer and Recurrent Neural Network Compensator," *IEE Proc. of Electrical Power Applications*, Vol. 147, No. 4, pp. 263-272, 2000.