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MODELING AND PRECISION CONTROL OF PERMANENT MAGNET LINEAR MOTORS

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Abstract: Permanent magnetic linear motors(PMLMs) are easier to accelerate and achieve higher precision than rotary motors. Hence, they have a broad range of applications in the manufacturing industry and other motion control fields. Owing to the structural variation, however, the models of permanent magnet linear motors and rotary motors are different. As a result, their motion control systems shall also be different. In order to efficiently control a PMLM, the control system model of the PMLM is built in the paper. Unlike rotary motors, PMLMs are more sensitive to various force disturbances due to the absence of gears. Based on the simplified system model, feed forward compensation method using an intelligent I/O module is proposed to compensate the disturbances. The simulation results show that the disturbances are suppressed with the intelligent I/O module.

Keywords: linear motors, motion control, neural networks, feed forward compensation.

1. INTRODUCTION

Permanent Magnet linear Motors (PMLMs) are easier to accelerate and to achieve higher precision than rotary motors. This is attributed by the advantage that PMLMs do not require transformation from rotary to linear motion (Chen and Cheng, 2005; Chung, *et a.l*, 2006). Therefore, it is greatly valuable to investigate and develop the control system of PMLMs.

Permanent magnet synchronous linear motors (PMSLMs) are among the most widely used PMLMs because of their simple structure and high-quality performance. In the paper, permanent magnet synchronous linear motors are studied as example. In order to efficiently control a PMLM, accurately modeling of the PMLM is necessary and vital. Many papers have investigated the model of PMLM, but the built models are too generalized and thus incompetent to precisely control a PMLM. Pierre Philippe Robet (Robet, *et al.*, 1998) modeled a Pulse Width Modulated (PWM) inverter as an amplifier and a delayer. Barahanov N. (Barahanov and Ortega, 2000) modeled the frictional forces. However, only parts of the model of PMLM are integrated. Kay-Soon Lowand and K.K.Tan (Lowand and Keck, 2003; Tan, 2003) modeled PMLM, but the frictional forces and force ripple are not being considered nor precisely modeled.

PMLMs are known to be more sensitive to various force disturbances due to the absence of gears. Therefore, it is critical to suppress various disturbances to ensure the high performance of PMLM. The frictional forces and force ripple are two major disturbances for the control system of PMLM. Unfortunately, the model of the force ripple is complex and difficult to be analyzed and compensated. Gerco Otten (Otten, *et al.*, 1997) proposed a learning feedforward controller, but the used online neural network is often unreliable in practice. So in the paper, an improved offline Back Propagation (BP) neural network is proposed to approximate it.

In order to analyze the control system more accurately, the model of PMLM system is further simplified. Based on the simplified model, feed forward compensation method using an intelligent I/O module is proposed to realize the disturbance compensation.

The objective of the research paper is to develop an effective control system for PMLMs. The rest of the paper is organized as follows: Section 2 presents the built models of the armature, PWM inverter, the force and the force ripple. Section 3 illustrates the application of the model, based on which the feed forward compensation method using intelligent I/O module is proposed. Section 4 shows the simulation results. Finally, Section 5 presents the conclusions.

2. MODEL of PMLM SYSTEM

M inverter tunes the output voltage and the magnet field generates the thrust force. The major force disturbances include the frictional forces, the force ripple and the load.

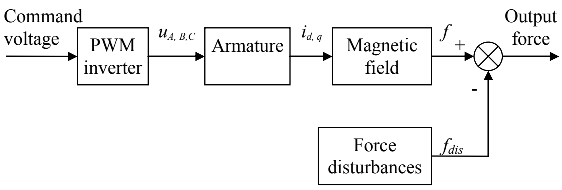


Fig.1 Structure of PMLM System

2.1 Model of the armature

Currents and voltages of PMLMs are analyzed in the d-q coordinate by using vector control algorithm. Since the currents in this coordinate is being considered as a composition of field magnet and torque parts which resembles DC motors, the currents can therefore be easily decoupled.

However, the output three-phase voltages and currents are described in a-b-c coordinate, so the coordinate transformations, namely Clark and Park transformations are needed. The coordinate transformation from a-b-c to d-q coordination can simply be written as

$$\mathrm{P} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \tag{1}$$

Typically, the current control loop uses a scheme that the field current i_d is controlled to be zero, and then the voltage equation is described by

$$u_d(t) = -\frac{2\pi}{p \cdot d} \dot{x} L \cdot i_q(t) \tag{2}$$

$$u_q(t) = k_e \dot{x} + R i_q(t) + L \frac{d i_q(t)}{dt} \tag{3}$$

where u_d and u_q are the d and q axis terminal voltages; i_d and i_q are the field and torque currents, respectively; p is the

The servo control system of a PMLM is nonlinear, strongly-coupled and multi-variable. Its complete model composes of a PWM inverter, an armature, a force model and a force disturbance model as shown in Fig.1. The armature transforms voltage to current, and then generates the magnet field reacting with the permanent magnet. Thus, it is a key component in the energy conversion from electrical to mechanical form. The PW
number of pole pair; R is the winding resistance; L is the inductance; d denotes the pole pitch; k_e is the coefficient of the back electromotive force and x is the displacement of PMLM.

In Equation (3), $k_e \dot{x} = E_f$ represents the back electromotive force. Suppose $T_a = L/R$ and $K_a = 1/R$, we can then acquire the transfer function from the q-axis voltage to the q-axis current

$$\frac{I_q(s)}{U_q(s) - E_f(s)} = \frac{K_a}{T_a s + 1} \tag{4}$$

2.2 Model of Pulse Width Modulated Inverter

A PWM inverter (Robet, *et al.*, 1998) is composed of an amplifier and a delayer. For a three-phase inverter shown in Fig.2, the PWM output phase voltage is

$$u_A = U_A \sin(\omega_0 t + \varphi) = \frac{K U_d}{2} \sin(\omega_0 t + \varphi) \tag{5}$$

where U_d is the PWM input DC voltage; K is the tuned coefficient; ω_0 is PWM output angle frequency, and φ is the output phase offset.

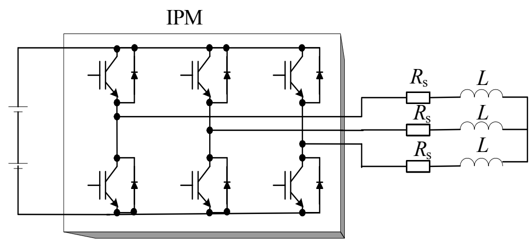


Fig.2 Principle Diagram of the Three-phase Inverter

So the amplified coefficient is

$$K_{inv} = \frac{\frac{K U_d}{2}}{U_s} = \frac{U_d}{2 U_\Delta} \tag{6}$$

where U_s is the amplitude of the sinusoidal component of PWM input control voltage and U_Δ is the amplitude of triangle carrier wave voltage. Thus, we can consider the PWM inverter to be an amplifier coefficient plus a delay.

The delay of PWM inverter is generated by modulated comparators, power switches and the deadbeat controllers. And it is less than half of the carrier wave period. So we can consider the delay as

$$T_{PWM} = \frac{1}{2}(f_\Delta)^{-1} \tag{7}$$

where f_Δ is the frequency of the triangle carrier wave. Then the transfer function of the PWM inverter is

$$G_{PWM}(s) = U_A / U_s = K_{inv} e^{-T_{PWM} s} \tag{8}$$

The transfer function can be translated to be first-order

$$G_{PWM}(s) = \frac{K_{inv}}{1 + T_{PWM} s} \tag{9}$$

The output of the PWM inverter is a three-phase voltage $u_{A,B,C}$, but from Equation (8), we can see that transfer function (9) can also be applied in the d-q coordinate.

2.3 Model of the force

The magnetic field of armature and that of PMLM reacting against each other generate the electromagnetic force. The thrust force drives the carriage to accelerate. The generated thrust force (Tan, 2003) can be described by

$$f(t) = k_f i_q(t) \tag{10}$$

$$f(t) = m\ddot{x} + f_{load}(t) + f_{fric}(\dot{x}) + f_{ripple}(x) + f_n(t) \tag{11}$$

where $f(t)$ and $f_{load}(t)$ are the thrust force and applied load, respectively; $f_{fric}(\dot{x})$ is the frictional forces; $f_{ripple}(x)$ is the force ripple; $f_n(t)$ is the unknown force disturbances; m is the mass of the carriage and k_f is the force coefficient.

The frictional force includes Coulomb, viscous, and static components. It is often estimated by the following LuGre model (Barahanov and Ortega, 2000)

$$f_{fric}(\dot{x}) = \left[f_c + (f_s - f_c) e^{-(\dot{x}/\dot{x}_s)^2} \right] \cdot \mathbf{sgn}(\dot{x}) + B\dot{x} \tag{12}$$

where f_c is the minimum level of Coulomb friction; f_s is the minimum level of the static friction; $\dot{x}_s$ is the lubricant parameter determined by empirical experiment, and B is the viscous frictional coefficient. The viscous force is dominant among the three frictional force components. Therefore, Equation (12) can be simplified as follows:

$$f_{fric}(\dot{x}) = B\dot{x} \tag{13}$$

For the control system of PMLM, the frictional forces and the force ripple are two most important disturbances. When a PMLM runs in high speed, the frictional force is dominating, while in low speed, the force ripple is dominant (Brandenburg and Bruckl, 2000).

Since the force ripple is incredibly complex, obtaining the transfer function from torque current to position becomes a difficult task. Simply ignoring the effect of the force ripple would not work because this method would result in big errors. In the case that the force ripple can be compensated, we can derive the transfer function from Equations (10), (12) and (13)

$$\frac{X(s)}{I_q(s) - I_1(s)} = \frac{k_f}{(ms + B)s} \tag{14}$$

where $i_1(t)$ denotes the torque current equivalent to the force disturbances other than viscous frictional force

$$i_1(t) = \frac{1}{k_f}(f_{load}(t) + f_{fric}(\dot{x}) + f_{ripple}(x) + f_n(t) - B\dot{x}) \tag{15}$$

2.4 Model of the Force Ripple

The force ripple arises from cogging and reluctance forces present in the structure of PMLM. Typically, the force ripple is a sinusoidal function of the position of PMLM. However, it is difficult to be fully described by an accurate equation because of its strong nonlinearity and high-order harmonious components (Zhu, *et al.*, 1997). Fortunately, the model of the force ripple can be approximated by an improved BP neural network controller (Zhang, *et al.*, 2007). In the designed controller, a second-order Levenberg-Marquardt (LM) algorithm (Hagan, *et al.*, 1994) is adopted to improve the convergence performance of BP neural network. A momentum part is added to the BP neural network to filter the noises of training samples and achieve faster convergence speed.

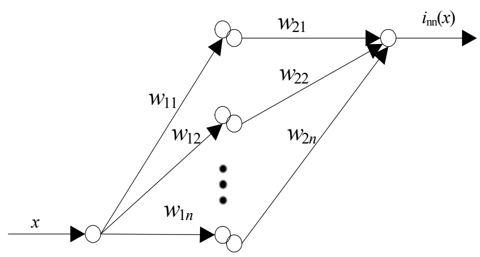


Fig.3 Structure of BP Neural Network

Fig.3 shows the designed neural network controller, in which a three-layered network is chosen, the input of the neural network is the position of the carriage x and the output is the torque current corresponding to the force ripple at the position $i_{nn}(x)$.

According to the currents equivalent to the force ripple, the finally approximated force ripple is derived

$$f_{nn}(x) = k_f \cdot i_{nn}(x) \tag{16}$$

In the end, the current control loop of PMLM is built according to the transfer functions described by Equations (4), (9), (14) and the approximated force ripple, which is shown in Fig.4a. In the current control loop, a PID controller is used to realize the close loop control. $i_{nn}(x)$ is the compensated torque current equivalent to the force ripple. PID controller is used to tune the torque current. k_c is the feedback coefficient of the detected torque currents and K_{PWM} is the amplified coefficient of PWM inverter. And K_{PWM} can be expressed as

$$K_{PWM} = K_{inv} / \sqrt{2} \tag{17}$$

3. PRECISION MOTION CONTROL SYSTEM BASED ON FEEDFORWARD COMPENSATION

3.1 Simplified model

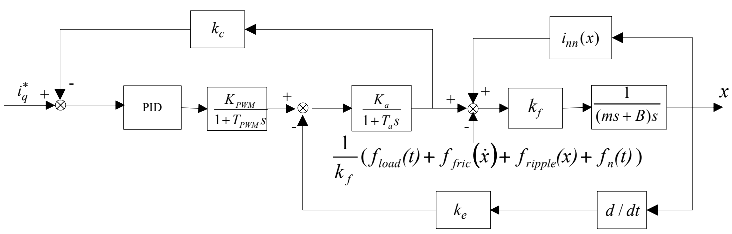
In order to analyze the control system of PMLM more conveniently, we can simplify the model of the current loop shown in Fig.4a.

First, the back electromotive force E_f can be ignored because the response of the velocity is much smaller than that of the current.

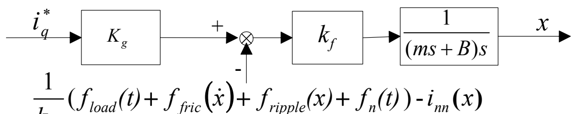
Second, the electrical dynamics and the PWM inverter are simplified as gain coefficients because the electrical dynamics is several times faster than the mechanical dynamics.

Furthermore, the current control loop can be simplified as a gain coefficient. The gain coefficient can be derived as follows

$$K_g = K_{PC} \cdot K_a \cdot K_{PWM} \tag{18}$$



a) Current Control Loop of PMLM



b) Simplified Current Control Loop of PMLM

Fig.4 Simplification of the Current Control Loop of

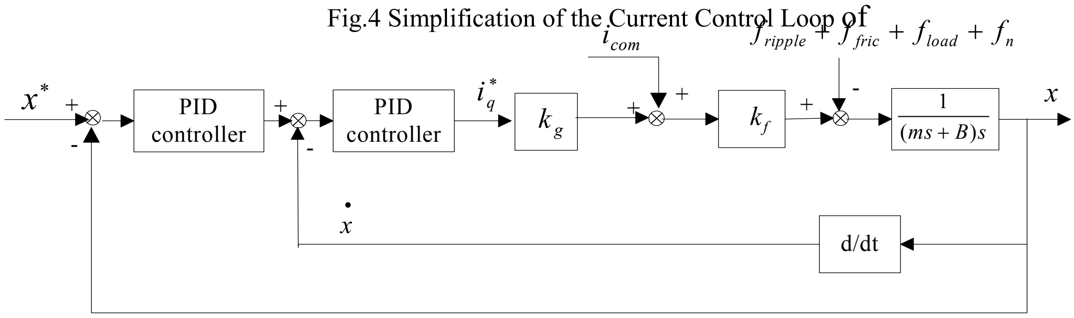


Fig.5 Precision Control System of PMLM

where K_{PC} is the proportional gain of the current control loop. The current control loop can be simplified as shown in Fig.4b.

3.2 Proposed disturbance compensation method

Based on the simplified structure of the current control loop, the control system of PMLM can be analyzed more easily. Considering the position and velocity control loop, the whole control system is designed as Fig. 5.

Now we analyze the static control error. The static control error of the linear motor system is generated due to the force disturbances and the error is

$$e_{ssn} = -\frac{N(s)}{(ms+B)s + G_1(s)\cdot K_g \cdot K_f \cdot s + G_1(s)\cdot G_2(s)\cdot K_g \cdot K_f} \quad (19)$$

Where $G_1(s)$ and $G_2(s)$ are the transfer functions of velocity and position loop, repectively. $N(s)$ is the force disturbances

$$N(s) = f_{load}(t) + f_{fric}(\dot{x}) + f_{ripple}(x) + f_n(t) \quad (20)$$

To improve control precision, a force compensator(Tan, 2003) is proposed to suppress the force disturbances. The force compensator is a disturbance observer, but this method often failed to compensate the force disturbances. In fact, the position of PMLM is the actually measured parameter, and the velocity and acceleration values are achieved by calculating the differential of the position. So noises do exist in the velocity and acceleration signals, which affect the compensation effect of the disturbance observer, especially when a PMLM runs in low speed. Another disadvantage of the method is that the errors of the mathematical model of control system affect the disturbance observer.

In the paper, feed forward compensation method is applied. In this method, the load or the force disturbances are measured and added to the expected torque current i_q^*, then the disturbances are compensated and the high gain of current loop can be used to improve the control precision.

Among the force disturbances, the viscous force $B\dot{x}$, the force ripple $f_{ripple}(x)$ and the load $f_{load}(t)$ are three most important force disturbances. According to Equation categories (10)-(16), the force disturbances can be classified into two kinds according to the input parameters:

- $f_{fric}(\dot{x})$ and $f_{ripple}(x)$ are the function of velocity and position, and they have small variation once a linear motor is selected
- $f_n(t)$ is the function of time and needs to be online measured.

Fig.6 shows the structure of the force disturbance compensator, where $f_{load}^{'}$ is the load measured by force sensors and is compensated by inputting compensation currents according to the measured results. $f_{fric}(\dot{x})$ and $f_{ripple}(x)$ are calculated by the measured position and velocity.

In order to realize the compensation, the intelligent I/O module shown in Fig.7 will be developed. Using the scheme, compensation current i_{com} can be automatically derived by an I/O module with written program. The written program is designed based on fixed functions of position and velocity. The measured force disturbances are mainly detected by a high speed force sensor. In the end, the compensation current is added to the command torque current of servo system.

With the compensation, the force disturbances are deduced and the static control error will be reduced to

$$e_{ssn}^{'} = \frac{k_f \cdot i_{com} - N(s)}{(ms+B)s + G_1(s)\cdot K_g \cdot K_f \cdot s + G_1(s)\cdot G_2(s)\cdot K_g \cdot K_f} \quad (21)$$

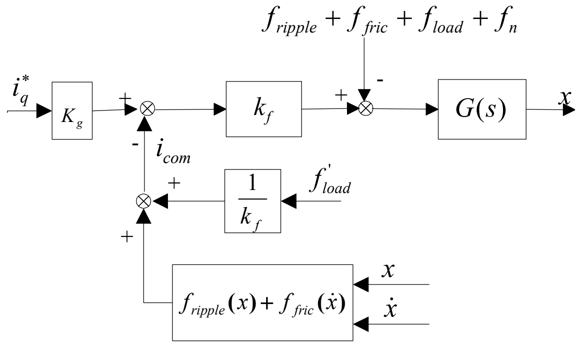


Fig.6 Structure of the Feed Forward Compensator

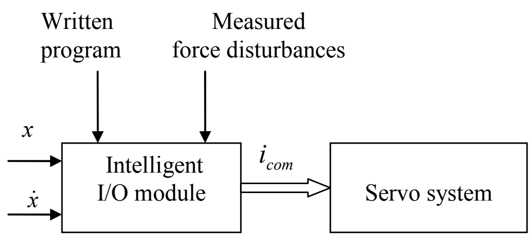


Fig.7 Designed I/O Module

4. SIMULATION RESULTS

In order to verify the built model and the motion control system design, an application example is provided. The control object is a PMLM with a linear encoder whose resolution is 1μm.

The parameters of the PMLM system are listed as follows:

- Mass of carriage $m = 9$ Kg
- Frictional coefficient $B = 2.12$ N·s/m
- Winding resistance $R = 1.25\ \Omega$
- Winding inductance $L = 5.25$ mH
- The amplitude of the sinusoidal component of PWM input control voltage $U_s = 15$ V
- The PWM input DC voltage $U_d = 254$ V
- The frequency of the triangle carrier wave, $f_\Delta = 10$ kHz

The feedback coefficient of detected torque currents $K_c = 6.1*10^5$ A

According to Ziegler-Nichols method, the proportional coefficient of current control loop is acquired as $K_{pc} = 0.06$. The amplification coefficient of the PWM inverter is

$$K_{PWM} = K_{inv} / \sqrt{2} = 254/(\sqrt{2}*2*15) = 5.99$$

The force coefficient $k_f = 11.34$ N/A

PID parameters are acquired by Ziegler-Nichols method. Fig.8 shows the step response of position using the system shown in Fig.5 with 50N random force disturbance exists. We can see that the position errors exist when no disturbance compensation is used, at the same time the response speed will be lowered. While using the feedforward compensation, the errors are suppressed.

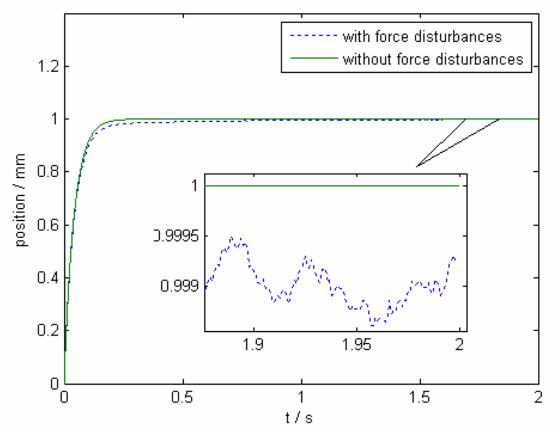


Fig.8 Step Response of Position Signal with and without Disturbance Compensation

5. CONCLUSIONS

In the paper, the model of PMLM system is built. Based on the model, the control system of PMLM is analyzed and the designed I/O module is designed to suppress the force disturbance. Simulation results show that using the designed I/O module, the errors are suppressed.

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