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Iterative Learning Control for Linear Motor Motion System

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***Abstract*- Linear motors have some inherent nonlinear factors, and these nonlinear factors make it a challenging task to control the linear motor motion system precisely. Iterative learning control can construct current control input with the help of the historical control information, and it does not depend on detailed model of the controlled system. Based on the thought of iterative learning control and PID control, an iterative learning controller incorporated with PID was designed and applied to linear motor motion systems. PID controller was used as a feedback controller to stabilize the system, and the ILC controller was used as a feedforward controller to improve the control precision. Simulation results show that a high performance controller is designed according to the iterative learning control theory. It can also compensate the nonlinearity of the system.**

Index Terms –linear motor, Motion system, Iterative learning control.

I. INTRODUCTION

Ever-increasing demands on higher productivity and better product quality in advanced manufacturing industries, such as the semiconductor and precision engineering industries, have continued to motivate and stimulate the development of high-speed and high-precision motion control systems. Among the various electric motor drive systems, linear motors are probably the most naturally akin to applications requiring high speed and high precision. The main features of a linear motor include high force density achievable, low thermal losses, more exact positioning, longer life, less maintenance, fewer moving parts, high positioning precision and accuracy associated with the mechanical simplicity.

However, the achievable performance of linear motors is unavoidably limited by various disturbances. The more predominant nonlinear effects underlying a linear motor system are the various friction components (Coulomb, viscous, and stiction) and force ripples (detent and reluctance forces) arising from imperfections in the underlying components. Because of the direct-drive principle behind the operation of a linear motor, this parasitic force ripple has significant effects on the position accuracy achievable and it may also cause oscillations and yield stability problems, particularly in the presence of operating at low velocities or with a light load. Due to the typical precision position requirements and low offset tolerance of their applications, the control of these systems is particularly challenging since conventional proportional integral derivative (PID) control usually may not suffice in these application domains. To achieve high-precision motion control, some efforts have been made toward more advanced control of linear motor motion systems [1-4]. A zero-phase filtering-based iterative learning control was proposed in [5] and an iterative learning controller based H_∞ approach were proposed in [6].

For high precision linear motor motion control, friction and ripple force disturbances are major challenges to the controller design. The accurate modelling of the whole system is extremely time consuming and cost-inefficient. Therefore, the practical problem is to control the linear motor efficiently with a limited amount of modelling work. Iterative learning control (ILC) requires less model information. Just as humans learn skills by trial and errors, the ILC system learns the dynamics of a system by repeated trials. ILC can construct current control input with the help of the historical control information, and it does not depend on detailed model of the controlled system.

According to the thought of ILC, an ILC controller used in linear motor motion systems was designed on the basis of PID control. PID controller is used as a feedback controller to stabilize the system, and the ILC controller is used as a feedforward controller to improve the convergence and tracking speed.

II. THE MODEL OF PMLM

The linear motor considered in the paper is designed by Philips to perform linear motions with high accuracy for applications such as scanning and pick-and-place tasks. Fig. 1 depicts a block diagram model of the motor, showing explicitly the various exogenous disturbance signals presented. The measurement available is the translator's position obtained from an incremental optical encoder. Among them, a, v, x express the acceleration, speed, position of the motor respectively. F_{rel}, F_V and $F_{cogging}$ express the thrust, frictional force and ripple forces separately. The carriage is comprised of the motor translator and an additional dummy mass to realize a total mass m. The frictional force affecting the movement of the translator may be modelled as a combination of Coulomb friction, viscous friction and sliding friction. In the simulation model, only viscous friction is considered with a friction coefficient K_v of 10[Nm^{-2}], in other words, F_v=$K_v v$. Apart from friction, one of the known disturbance forces generated in the PMLM is the force ripple due to cogging and reluctance forces presented in the PMLM structure [7]. In

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reality, the ripple force is more complex in shape, e.g., due to variation in the magnet dimension. In the simulation model, cogging can be modelled as a sinusoidal function of the load position [8-9], with a spatial period of L (mm) and the amplitude of A (N), in formula as

$$F_{cogging} = A \cdot \sin\left(\frac{2\pi}{L}x\right) \tag{1}$$

In this paper, the spatial period L is 16mm and the amplitude A is 10N, so the ripple force can be described as

$$F_{cogging} = 10 \cdot \sin\left(\frac{2\pi}{0.016}x\right) \tag{2}$$

Disregarding the non-linearity and the friction, a simplification of the model depicted in Fig.1 can be performed, resulting in a stable linear second-order plant as

$$P_0 = \frac{1}{ms^2} \tag{3}$$

Where P_0 is called the nominal plant transfer function.

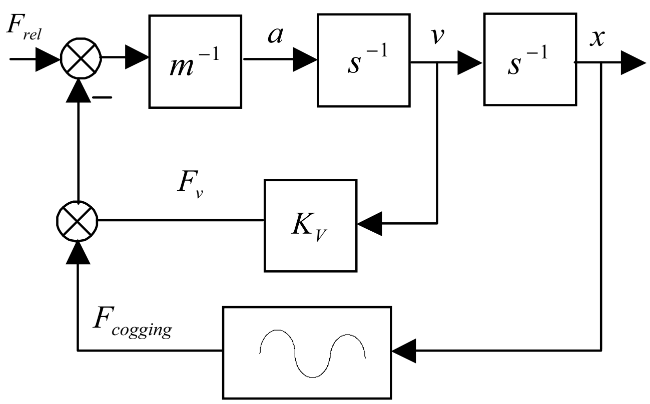

Fig. 1 A model of the linear motor system

In a scanning machine, movements take place with low velocity and low acceleration. In this case, cogging and friction disturbance are the dominant cause for the position errors of the translator. In a pick-and-place machine, translator movements take place with high velocity and large acceleration. In this case, cogging disturbance is relatively small and the influence of dynamic characteristic is more dominant.

For high precision PMLM motion control, friction and ripple force disturbances are major challenges to the controller design. The accurate modelling of the whole system is extremely time consuming and cost-inefficient, if not impossible. Therefore, the practical problem is to control the linear motor efficiently with a limited amount of modelling work.

III. ILC USING FEEDBACK CONTROL

A. Iterative Learning Control

Iterative Learning Control, or ILC, was originally proposed in the robotics community as intelligent teaching mechanism for robot manipulators. It is a technique that is designed to improve the performance of tracking control systems that have a repeated reference trajectory. Such systems include food processing plants, assembly lines, chemical batch reactors and robotic arm manipulators. Each time the trajectory is implemented, known as a trial or iteration, ILC uses data from past iterations to modify the control signal in an attempt to reduce the tracking error obtained during the next iteration. Between every time of iteration and its following iteration, there is an undefined stoppage time, during which the plant is reset to known initial states. ILC is theoretically capable of reducing the tracking error to zero as the number of iterations increases towards infinity. This is a significant advantage over conventional algorithms where the same level of tracking error can be expected at each trial [10].

Iterative learning control has been used in control systems that perform repeated tasks. ILC requires less model information. However, ILC is an open-loop control scheme, when an inappropriate initial control law is chosen, this control scheme may generate harmful effects, such as instability and low robustness. To overcome the instability of the system or the effects of the disturbances on the system, ILC is applied to PMLM systems along with PID feedback control for enhancing robustness against unrepeatable disturbances and reducing the tracking error in the early stage of learning.

B. ILC with PID feedback compensator

A ILC control system incorporated with PID controller is shown in Fig.2, where, P is the control object, C is a PID compensator, L is the ILC controller, Q is a filter used to diminish the influence caused by disturbances, u_k is the control signal, and e_k is the tracking error. The memory unit is used to store the last time iterative information to form the present control input.

Generally, the first order ILC has such a formulation as the following equation

$$U_{k+1} = Q(U_k + LE_k) \tag{4}$$

The control law of the above system can be wrriten as:

$$U_{k+1} = Q\left(1 - \frac{LP}{1+CP}\right)U_k + \frac{Q(L-C)+C}{1+CP}R \tag{5}$$

According to Fig. 2, the following equations can be derived:

$$E_k = R - Y_k \tag{6}$$

$$Y_k = PU_k \tag{7}$$

$$U_k^c = CE_k \tag{8}$$

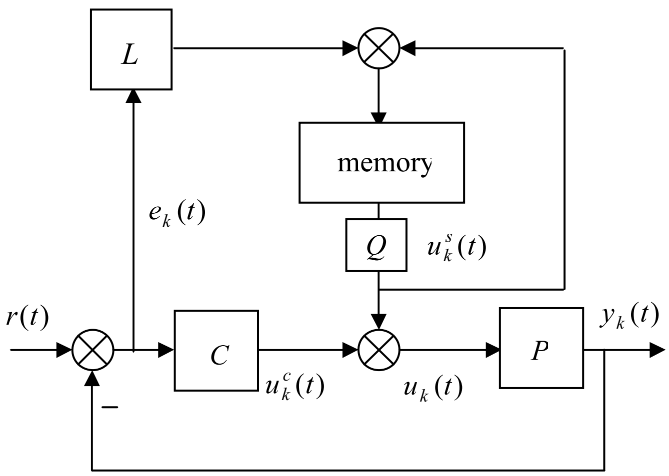

Fig. 2 ILC using feedback control

From equation (4), we can derive the following equations:

$$U_{k+1}^s = Q(U_k^s + LE_k) \quad (9)$$

$$\begin{aligned} E_{k+1} &= \frac{1-Q}{1+PC}R + \frac{Q+QPC-PQL}{1+PC}E_k \\ &= \frac{1-Q}{1+PC}R + \left(Q - \frac{PQL}{1+PC}\right)E_k \end{aligned} \quad (10)$$

If E_{k+1} can meet the infinite norm formulation as follows

$$\forall k: \left\|E_{k+2} - E_{k+1}\right\|_\infty \le \left\|E_{k+1} - E_k\right\|_\infty \quad (11)$$

Then, E_{k+1} converge to an equilibrium point.

The expanded form of the above formulation is

$$\begin{aligned} \left\|E_{k+2} - E_{k+1}\right\|_\infty &= \left\|\left(Q - \frac{PQL}{1+PC}\right)E_{k+1} - \left(Q - \frac{PQL}{1+PC}\right)E_k\right\|_\infty \\ &\le \left\|Q - \frac{PQL}{1+PC}\right\|_\infty \left\|E_{k+1} - E_k\right\|_\infty \end{aligned} \quad (12)$$

If the inequality (11) is tenable, then the following condition must be satisfied:

$$\gamma = \left\|Q - \frac{PQL}{1+PC}\right\|_\infty < 1 \Rightarrow \left\|Q(1 - GL)\right\|_\infty < 1 \quad (13)$$

where $G = \dfrac{P}{1+PC}$ denotes process sensibility.

In formulation (13), if L is equal to the converse of the closed-loop transfer function of the system, that is

$$L(s) = G^{-1} = \left(\frac{P}{1+PC}\right)^{-1}$$

Then, the convergence condition can be satisfied.

In the real system, because of the effects of the un-modelled dynamic states, nonlinearity and disturbances, the precise model of the controlled system cannot be obtained. Generally, in the low frequency domain, the system feature can be described very well, but in the high frequency domain, there exists some uncertainties. So, the selection for filter Q and L has great effect on the iterative learning control effectiveness. In this paper, Q and L are designed according to the following approach:

- Choose $L(s) = G^{-1}$ ($\varpi \in [0, \varpi_C]$), in which ϖ_C is the cut-off frequency, that is within the interval [0，ϖ_c], L(s) approaches to the converse of G as far as possible.
- Choose Q(s) is a low pass filter, and its cut-off frequency closes to ϖ_c. Q(s) is designed as

$$Q(s) = \begin{cases} 1, & \varpi \in [0, \varpi_C] \\ 0, & \varpi > \varpi_C \end{cases} \quad (14)$$

IV. ILC FOR PMLM

According to the ILC strategy presented above, a ILC controller incorporated with PID controller was designed. Q(s) is designed to a low pass filter, and the choice of its cut-off frequency is trade off between the improvement of the system robust performance and the reduction of the tracking error. The optimal cut-off frequency can be acquired by using the stepwise approximating approach.

Matlab/Simulink is used to simulate the linear motor system described above. Because the controlled system is marginal steady, the feedback controller is designed as a PD controller to construct a stable closed-loop system:

$$C(s) = K_p \frac{s\tau_Z + 1}{s\tau_P + 1} \quad (15)$$

The low pass filter Q is adopted as a Butterworth filter. The cut-off frequency is 1000 rad/s.

The ILC controller is

$$\begin{aligned} L = G^{-1} &= \left(\frac{P}{1+CP}\right)^{-1} \\ &= \frac{2.352 \cdot 10^8 z^2 - 4.492 \cdot 10^8 z + 2.145 \cdot 10^8}{z^2 + 0.8571z + 0.1837} \end{aligned}$$

The Bode graphics of the convergence condition is shown in Fig.3. In this condition, the infinite norm in the convergence condition is 0.31, it meets the convergence condition, and the convergence speed is very fast.

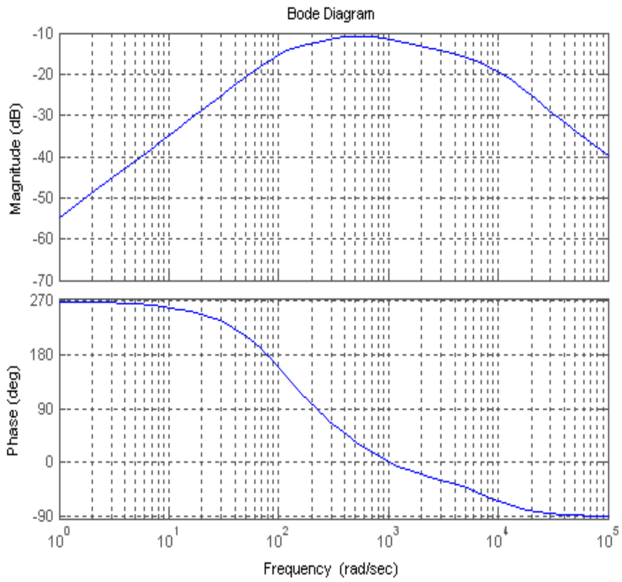

Fig. 3 Bode graphics of the convergence condition

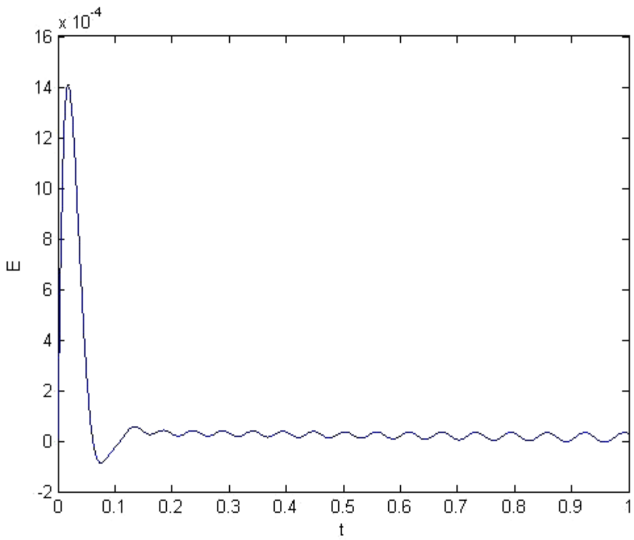

Fig. 4 Tracking error of PID control system

The chart in Fig. 4 shows the tracking error of the linear motor system in which only PID feedback control is adopted. The reference trajectory of this system is

$$y_r = 0.2\sin(0.25t)$$

The upper norm of this tracking error is 0.0014m. It can be seen from this result that using feedback controller solely cannot compensate the cogging of the linear motor.

Use the iterative learning control algorithm (4) to the linear motor motion system. The control effectiveness of the closed-loop system is shown in Fig.5. In this figure, the curve 1 denotes the tracking error of the system without iterative learning control, and the curve 2, curve 3 and curve 4 denote the tracking errors corresponding to the first, the third and the fifth iteration separately. The maximal tracking errors of each iterative control are shown in Fig. 6. We can see from these curves that the closed-loop system is asymptotically convergent. Compared to the system without ILC control, the tracking error diminished about 50 times.

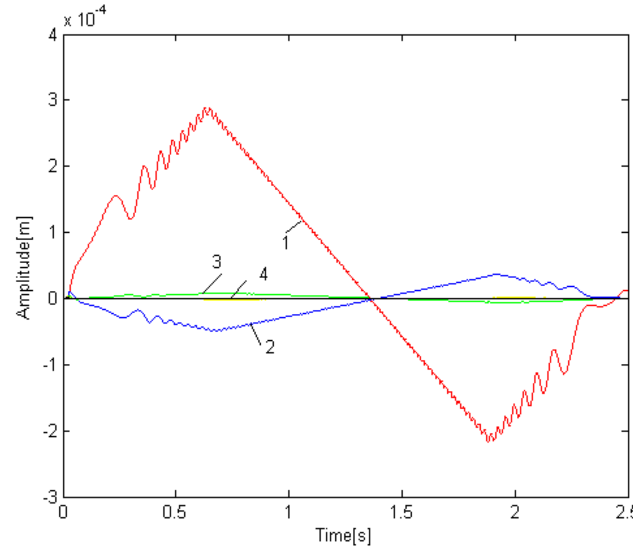

Fig. 5 Tracking errors of ILC control system

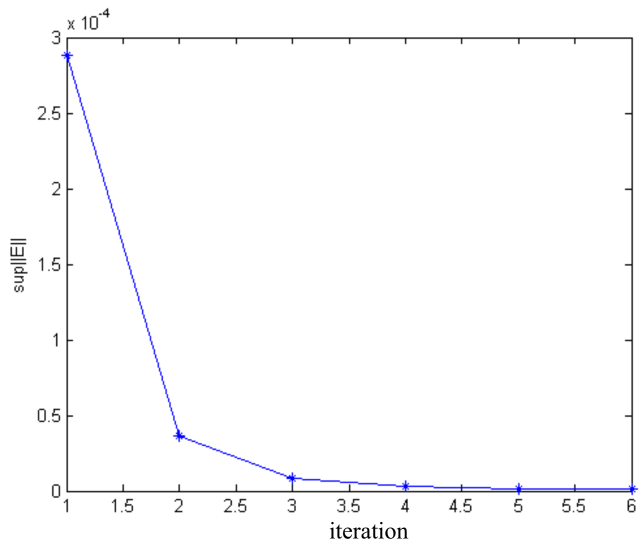

Fig. 6 The upper norm values of tracking errors of ILC

V. CONCLUSION

Ripple force is one of the predominant nonlinear factors that affect the achievable performance of linear motor motion systems. The ILC controller incorporated with PID feedback controller can overcome the nonlinearity effect on the linear motion system and improve the control precision on the basis of guaranteeing system stability. The PID controller is used as a feedback controller and it can stabilize the system. The ILC controller is used as a feedforward controller to guarantee the improvement of convergence and raise the tracking speed. The ILC has great superiority in situations when the system scale develops increasingly and the model is incompletely known. With respect to those controlled object which have repeated processes, such as linear motor motion system, we can make the most of ILC's advantage to improve control accuracy. Further research work on using ILC to improve the operation quality of linear motor system are proceeding, and then it will be extended to other nonlinear systems.

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