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Improved Performance of a Linear Pulse Motor with Repetitive Positioning Control

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Abstracts We propose a method to improve repeatability positioning precision of a linear pulse motor. By using this method the systematic error which may make the precision worse can be suppressed easily. And also we show that Power OP-Amp drive system enables the accidental error to be suppressed in comparison with PWM control drive system using IGBT inverter. As a result of the suppression of systematic and accidental error, improved performance of a linear pulse motor with repetitive positioningcontrol is shown by experimental results.

Keywords Linear pulse motor, Repetitive positioning control, Systematic error, Accidental error

1. INTRODUCTION

With a pole position sensor, one can drive a linear pulse motor as a servo motor and reduce the risk of step-out exceedingly [1]. In general positioning-control systems high feed rate and suppression of a disturbance which may make positioning accuracy worse are required. When Two-Degree-of-Freedom controller is applied to the positioning controller, one can set up the controller so that the response characteristic with a command reference should be independent of that with a disturbance [2]-[4]. Generally, a linear pulse motor is applied to repetitive positioning control. Therefore, repeatability positioning precision should be considered. As a solution, repetitive control gives improvement of the repeatability [5][6]. In this paper we apply Two-Degree-of-Freedom PID controller to the positioning-control system and describe a simple design method of the controller. It is shown that Power OP-Amp drive system is available to suppress the accidental error in comparison with PWM control drive system using IGBT inverter. And the systematic error is suppressed effectively by taking advantage of repetitive control. Experimental results of repetitive positioning control prove the usefulness of the proposed method.

2. LINEAR PULSE MOTOR

2.1 Motor Construction

Figure 1 illustrates a basic construction of the tested 3-phase 12-pole PM type linear pulse motor. The motor mover is provided with Magnetic Resistance (MR) sensor unit. A motor position and 3-phase pole position signals are detected from MR sensor unit. Therefore, it becomes possible to drive a linear pulse motor as a servo motor and to reduce the risk of step out remarkably. Main specifications of the tested linear pulse motor are given in Table 1.

2.2 Drive System

Figure 2 illustrates the drive system with Power OP-Amp for a linear pulse motor. The encoder signals and 3-phase pole position signals are detected from the MR sensor unit. A command current reference I_m^* is calculated with a digital processing unit (NEC PC9801). The 3-phase AC current references, represented by the signs i_u^*, i_v^* and i_w^*, are obtained from multiplying I_m^* by 3-phase sinusoidal pole position signals. Power OP-Amp amplifies voltage so that exciting currents can be equal to command current references. Main features of Power OP-Amp are presented in Table 2.

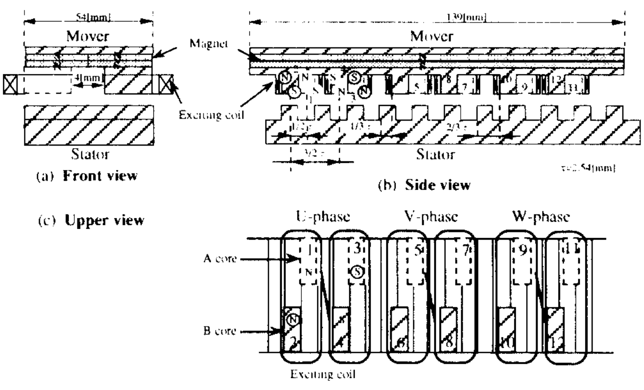

Figure 1. Basic construction of the PM type linear pulse motor.

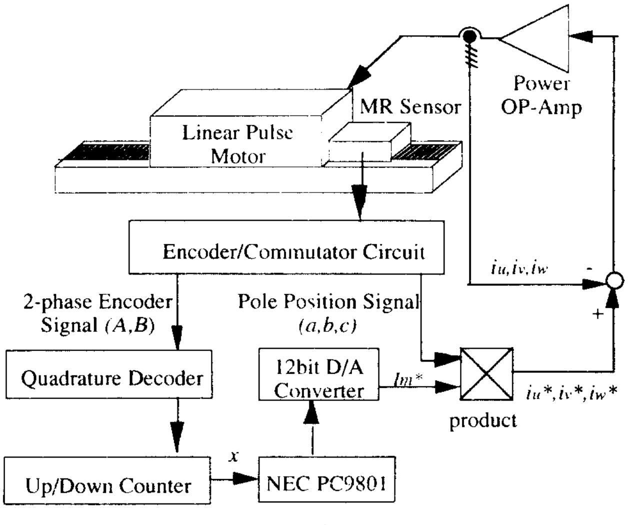

Figure 2. Drive system for a linear pulse motor.

Table 1. Main specifications of the tested linear pulse motor.

Windings	3-phase star connection
Tooth pitch	2.54[mm]
No. of teeth/pole	5
No. of turns/phase	50
Rated current	2.1[A]

Table 2. Main features of Power OP-Amp.

High output	50[V] 25[A]
Over-current self-limited around	25[A]
External current shutdown control	
Voltage gain	4

3. TWO-DEGREE-OF-FREEDOM POSITIONING CONTROLLER

3.1 Basic Structure

Figure 3 shows a block diagram of positioning-control systems for a linear pulse motor. The elements of the controller C_1 and C_2 are given as

$$C_1(s) = (1-\alpha)K_P + K_I / s + (1-\beta)K_D s \tag{1}$$

and

$$C_2(s) = \alpha K_P + \beta K_D s \tag{2}$$

The differential equation of a linear pulse motor is given as

$$M_n \ddot{x} + 2M_n \gamma \dot{x} = k_n I_m \tag{3}$$

where M_n : mover mass, γ : damping coefficient,
k_n : thrust constant .

However, the second term of the left side on Eq. (3) is ignored because it can be included in a part of a disturbance.

3.2 The Controller Design

In general positioning-control systems it is important to suppress an overshoot and a transient vibration. Therefore, the closed-loop transfer function with a command reference is considered.

The closed-loop transfer function with a command reference G_{cp} and the closed-loop transfer function with a disturbance G_{cd} are written as

$$G_{cp}(s) = K\frac{(1-\beta)s^2 + (1-\alpha)q_1 s + q_1 q_2}{s^3 + Ks^2 + Kq_1 s + Kq_1 q_2} \tag{4}$$

and

$$G_{cd}(s) = \frac{1}{M_n} \cdot \frac{s}{s^3 + Ks^2 + Kq_1 s + Kq_1 q_2} \tag{5}$$

where $K = k_n K_D / M_n, q_1 = K_P / K_D, q_2 = K_I / K_P$.

It is assumed that G_{cp} has a transfer function of the form

$$G_{cp}(s) = \frac{\omega_b}{s+\omega_b} \cdot \frac{(s+\omega')^2}{(s+\omega')^2} \tag{6}$$

Thus, following conditional equations are derived from the assumption.

$$(1-\beta)K - q_2 = (1-\alpha)\left(K - \frac{1-\alpha}{1-\beta}q_1\right) \tag{7}$$

$$(1-\beta)K = K - \frac{1-\alpha}{1-\beta}q_1 = \omega_b \tag{8}$$

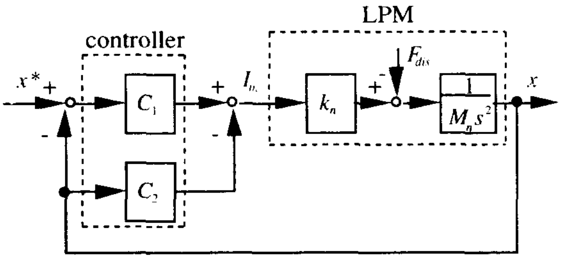

Figure 3. Block diagram of a positioning-control system using Two-Degree-of-Freedom controller.

$$(1-\alpha)^2 q_1 - 4q_2(1-\beta) = 0 \tag{9}$$

When Eqs. (7), (8) and (9) are satisfactory, closed-loop transfer functions G_{cp} and G_{cd} are rewritten as

$$G_{cp}(s) = \frac{\omega_b}{s+\omega_b} \tag{10}$$

$$G_{cd}(s) = \frac{1}{M_n} \cdot \frac{s}{(s+\omega_b)(s+\varepsilon\omega_b)^2} \tag{11}$$

where $\varepsilon = 2\alpha/(1-\alpha), \varepsilon \geq 1$.

It is found that the parameter ω_b is determined from a response frequency and ε is determined in order to suppress a disturbance effectively. From solving Eqs. (7), (8) and (9) arbitrary parameters are calculated as

$$\left.\begin{array}{c} \alpha = \dfrac{\varepsilon}{\varepsilon+2}, \beta = \dfrac{2\varepsilon}{2\varepsilon+1} \\ K = (2\varepsilon+1)\omega_b , q_1 = \dfrac{\varepsilon(\varepsilon+2)}{2\varepsilon+1}\omega_b , q_2 = \dfrac{\varepsilon}{\varepsilon+2}\omega_b \end{array}\right\} \tag{12}$$

Generally, it is important to reduce an effect of noises in a high frequency region. Therefore, the complementary sensitivity function is fixed in a frequency region where an effect of noises should be reduced. The complementary sensitivity function T and the sensitivity function S are written as

$$T(s) = K \cdot \frac{s^2 + q_1 s + q_1 q_2}{s^3 + Ks^2 + Kq_1 s + Kq_1 q_2} \tag{13}$$

$$S(s) = \frac{s^3}{s^3 + Ks^2 + Kq_1 s + Kq_1 q_2} \tag{14}$$

As a method of approximate fixation, the parameter K is kept constant.

Figure 4 shows calculations of frequency characteristics of G_{cp}, T and S. It is found that T and S are approximately fixed in a frequency region even if the cutoff frequency ω_b is varied. The parameter K is determined instead of ε in order to suppress a disturbance effectively. The parameter ε is determined as the following equation by giving K and ω_b.

$$\varepsilon = \frac{1}{2}\left(\frac{K}{\omega_b} - 1\right) \tag{15}$$

From substituting ε into Eq. (12) all the parameters of Two-Degree-of-Freedom PID controller are calculated as shown in Table 3.

4. EXPERIMENTS

4.1 Experimental Setup

An one-sample-delay digital control system is composed of NEC PC9801. The sampling period is $500[\mu s]$, the encoder resolution is $2.48[\mu m]$ and the current limitation is $|5|[A]$. Parameters for setting up the controller are given in Table 4.

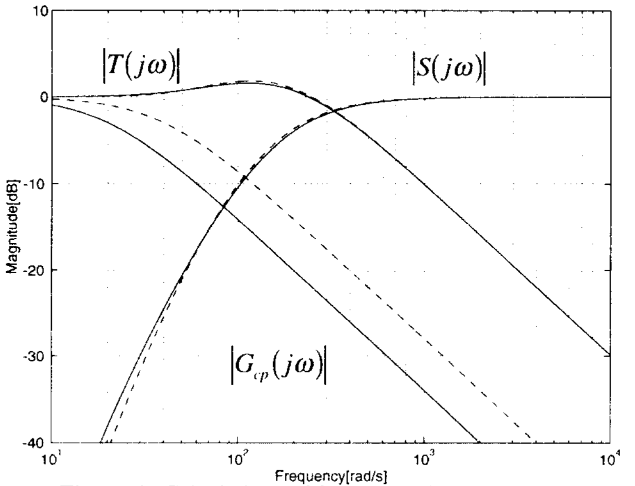

Figure 4. Calculations of frequency characteristics (Thick line: $\omega_b = 20[rad/s]$, Broken line: $\omega_b = 40[rad/s]$ when $K = 320$).

4.2 Repetitive Positioning Control

Figure 5 illustrates the experimental result of repetitive positioning-control response. A frequency of the command reference is $2[Hz]$. The motor is operated for 100 cycles and the positioning errors are detected on both $5[mm]$ point and $0[mm]$ point. These positioning errors are shown in the left side of Fig. 7. On the other hand, the right side of Fig. 7 describes the error distribution in order to recognize both accidental and systematic errors evidently.

4.2.1 Performance Comparison with PWM Control and Power OP-Amp Drive System

PWM control drive system is composed of a voltage-source IGBT inverter in place of Power OP-Amp inverter.

Figure 7 (a) and (b) show the error distribution by PWM control drive system and Power OP-Amp drive system respectively. It should be noted that the axis range is different between them. Thus, it is found that Power OP-Amp drive system enables the accidental error to be suppressed in comparison with PWM control drive system. However, the systematic error, especially on $0[mm]$ point, can not be suppressed even when Power OP-Amp drive system is applied. Therefore, a repetitive controller is appended to the conventional positioning-control system in order to suppress the systematic error.

4.2.2 Repetitive Controller

Figure 6 illustrates the block diagram of a repetitive positioning-control system with a repetitive controller. The sampling interval T_L is a period of the command reference. The controller H can be easily composed by a digital computer as a following operation.

$$e_H[n+1] = \sum_{k}^{n} e_L[k] \tag{16}$$

where $e_H[n+1]$: a manipulated value on (n+1) th cycle,

$e_L[n]$: a positioning error on (n) th cycle.

It can be seen that the operation of the repetitive controller is equivalent to an addition of the systematic error to a command reference. Thus, the repetitive controller is available to the conventional positioning-control system easily.

Figure 7 (c) shows the error distribution by Power OP-Amp drive system with a repetitive controller. It is found that the systematic error, especially on $0[mm]$ point, is suppressed in comparison with Fig. 7 (b). However, the positioning error exists on the first cycle because the repetitive controller can not operate on the first cycle. Except on the first cycle, repeatability positioning precision on both $5[mm]$ point and $0[mm]$ point is between $\pm 5[\mu m]$.

Table 3. Parameters of Two-Degree-of-Freedom PID controller.

$$K_P = \varepsilon(\varepsilon+2)\omega_b^2 M_n / k_n$$

$$K_I = \varepsilon^2 \omega_b^3 M_n / k_n$$

$$K_D = (2\varepsilon+1)\omega_b M_n / k_n$$

$$\alpha = \varepsilon/(\varepsilon+2)$$

$$\beta = 2\varepsilon/(2\varepsilon+1)$$

Table 4. Parameters for setting up the controller.

Mover mass	M_n	$6.7[kg]$
Thrust constant	k_n	$28[N/A]$
Cutoff frequency	ω_b	$30[rad/s]$
The constant	K	210

5. CONCLUSION

With consciousness of a repetitive positioning operation of a linear pulse motor, we proposed a method to improve repeatability positioning precision of a linear pulse motor.

Two-Degree-of-Freedom controller which is applied to the positioning controller can be set up the controller so that the response characteristic with a command reference should be independent of that with a disturbance. And a simple design method of the controller was described.

The proposed repetitive controller is appended to the conventional positioning-control system in order to suppress the systematic error. And Power OP-Amp drive system is available to suppress the accidental error in comparison with PWM control drive system using IGBT inverter.

Experimental results of repetitive positioning control proved the usefulness of the proposed method.

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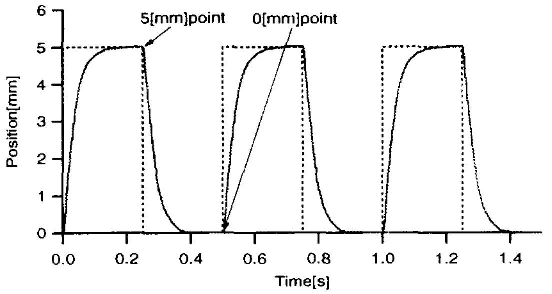


Figure 5. Experimental result of repetitive positioning-control response.

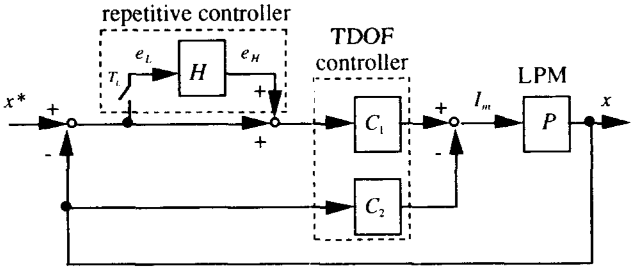
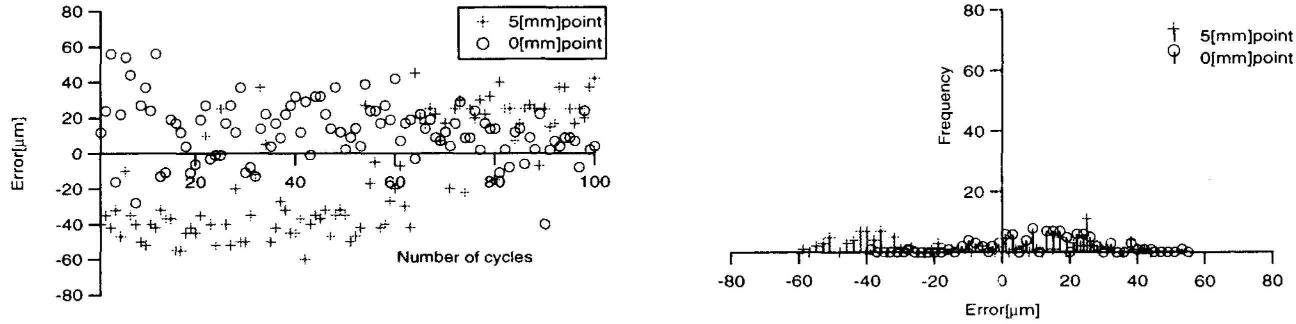
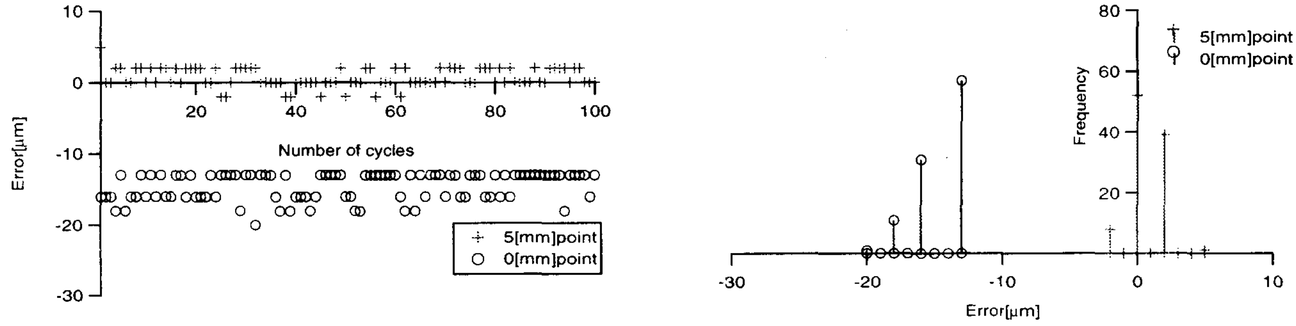


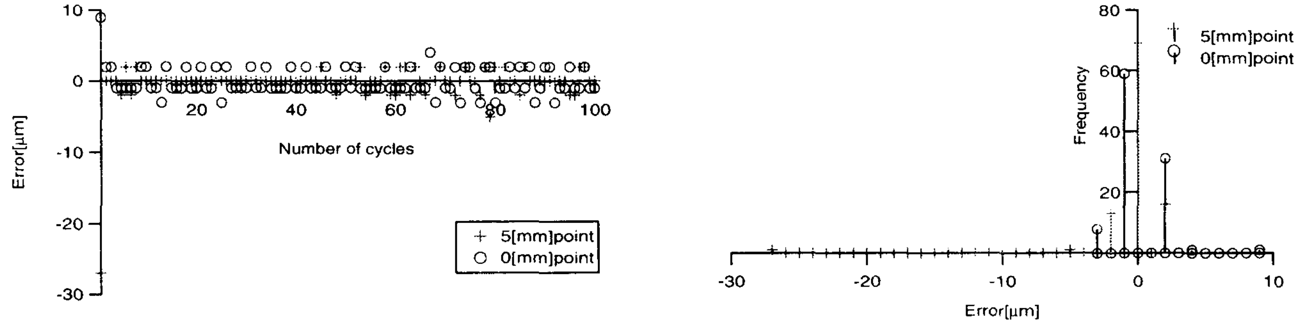
Figure 6. Block diagram of a repetitive positioning-control system with a repetitive controller.



(a) by PWM control drive system.



(b) by Power OP-Amp drive system.



(c) by Power OP-Amp drive system with a repetitive controller.

Figure 7. Experimental results of error distribution

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