A Simplified Position Control of a Transverse Flux Type Linear Synchronous Motor Using Hall Sensors

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Abstract—**For position feedback control in long linear synchronous drives, high-resolution sensors such as linear encoders are often expensive for industrial applications. Furthermore, their fine precision comes along a higher sensitivity to contamination and disturbance. We propose an economic position sensing method which uses two Hall sensors for position control of long linear synchronous motor drives where field flux distribution can be approximated to sinusoidal. We obtain position signal from the Hall sensors. Two methods to derive speed signal from the position signal given by the Hall sensors have been compared. The first is an approximate differential operation of position with low-pass filter. The second is application of state observer including external load force in its state variables. In addition, the performance of the cascade position control feedback is verified to satisfy technical requirements in numerical studies.**

Keywords—Transverse Flux; Linear Synchronous Motor; Hall Sensors; Cascade Position Control; State Observer; Position Sensing

I. INTRODUCTION

The Linear Synchronous Motor is attracting attention in recent years and it is widely used in industrial applications [1]. High-resolution position sensors such as optical linear encoders for precise position control of linear motors are costly and delicate, especially for long linear drives [2]. Hence, economic position sensors are needed for long linear motor position control system in industrial applications. We propose to use a couple of Hall sensors on a mover to achieve economic position sensing in long linear drives. A Transverse Flux linear Synchronous Motor, which produces high thrust due to its small pole pitch and multipolar configuration [3] has been introduced to our research on economic position control for long linear drives.

Contrary to position sensing for rotary motor, which requires only a 360-degree-angle sensing, the first problem of position sensing for long linear drive is that the sensor cost is proportional to the linear motor stroke. The longer the stroke, the higher the cost for a linear encoder. The second problem is that many environments of industrial applications have contamination and disturbance to an optical linear encoder. Hence, we propose to use an economic and robust position sensing scheme for long linear position control system. There have been many studies on the driving methods of rotary synchronous motor with Hall sensors [4]-[6].

Since DC brushless drives are fed with 120 electrical degrees square-wave currents, they require a 60-degree resolution for motor position sensing. Inexpensive Hall sensors can provide this resolution. Digital Hall sensors and additional hardware for low-cost AC linear synchronous drives have been proposed by S. Morimoto [4]. This method obtained high-resolution position information by processing the low-resolution position measurements. Constant speed was assumed throughout a 60-degree block. However, this assumption is not valid in accelerating operation from zero speed. Hall sensors can also be used for position control in combination with a sensorless algorithm [5]. The combination of sensorless algorithm and Hall sensors have also been used with a combination of dual observer and position sensor offset compensation strategy [6], which overcome some hardware problems. But those methods are dependent on the electrical model of motors.

We have studied on driving methods of linear synchronous motor with Hall sensors and proposed alternating position and speed control of long linear synchronous motor based on Hall sensors [7]. Sensors were combined to a dual-rate sampling observer to estimate motor speed and position. In this work, the observer time constant was varying in relation to motor speed. This method could estimate the motor position and speed, and could suppress oscillation when speed becomes low in numerical studies. Parameters for the speed controller were also varying in relation to motor speed. Thus, if we can obtain approximate continuous position signal directly from a simple sensor, the control algorithm would become much simpler.

This paper proposes an economic position sensing method from low-cost Hall sensors installed on the mover of a transverse flux linear synchronous motor. It also compares two methods to obtain speed from position signal from Hall sensors. The first is an approximate differential operation of position with low-pass filter and the second is a single sample rate state observer which includes external load force estimation. Furthermore, position error in a cascade control is also analyzed. The system consists of two Hall sensors and generates two quadrature analog waveforms. This paper is organized in five sections. Principle, structure and advantages of Transverse Flux Linear Synchronous Motor will be presented in the second section following this introduction. Fundamental idea to use Hall sensors to detect position will then be shown in the third section. Methods to obtain signals requested to cascade control will be analyzed in the fourth section. The last section concludes the paper.

II. PRINCIPLE, STRUCTURE AND ADVANTAGES OF TRANSVERSE FLUX TYPE LINEAR SYNCHRONOUS MOTOR

Transverse flux rotary machines were proposed by H. Weh in 1986 [8]. Fig. 1 shows the rectilinear model of a single sided TFM [9]. As this figure shows, the fundamental principle can be directly applicable to linear synchronous motors. Its stator consists of individual 'C' cores of laminated steel positioned around the machine and windings .The rotor consists of two rows of alternately polarized surface mounted permanent magnets and a series of laminated steel elements. This kind of structure guides the main flux through a path transverse to the direction of motor movement. When the windings are excited with a sinusoidal alternating current, continuous torque will be produced and motor moves.

TFM designs had complex structural problems in the early stage. Many researchers did lots of work on transverse flux machines. Recently, H.J. Kim [3] proposed a tunnel actuator, which is a transverse flux linear motor with 'C' stator core and coreless mover. This kind of structure contributes to reduce mover mass and bearing load. On account of low power factor of transverse flux machine, Y. Yamamoto [10], considered on structure and material of rotary transverse flux linear motor stator, which enhanced the motor power factor over 0.80.

A. Advantages of Transverse Flux Machine

TFM can achieve high thrust because short pole-pitch can be realized without substantial increase of leakage flux. The short pole pitch allows for a low speed mechanical drive with high armature electric frequency without any mechanical speed reduction. Therefore, the motor is beneficial for direct drives.

B. Requirements for long and fast drive combined with position feedback control

Firstly low-cost Hall sensors are needed to obtain economic position sensing for long linear synchronous motor position drive system. Secondly, position controller should respond fast, in our research 160 msec level is satisfied. Thirdly, the position error between position command and real one should be smaller than 1mm. That is to say, the error between position feedback signal from Hall sensors and real position should be also smaller than 1mm. Fourthly, effects of unmodeled disturbance force such as friction force of linear bearing, shall be sufficiently suppressed. Feedforward disturbance compensation is useful for the disturbance suppression.

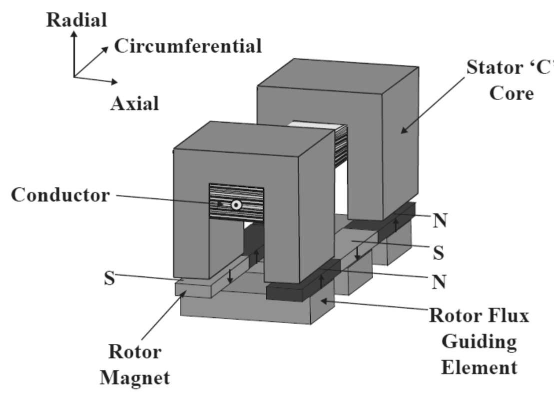
III. FUNDAMENTAL IDEA TO USE HALL SENSORS TO DETECT POSITION

As stated above, the cost of linear encoder is proportional to motor stroke and high-resolution position sensors is also delicate to environment, especially optical linear encoders. Hence, we propose to use low-cost Hall sensors to obtain the position information for long linear synchronous motor position drive system. However, Hall sensors cannot directly give out linear position signals, so we have to process the analog signal from Hall sensors to linear position information needed for position feedback control.

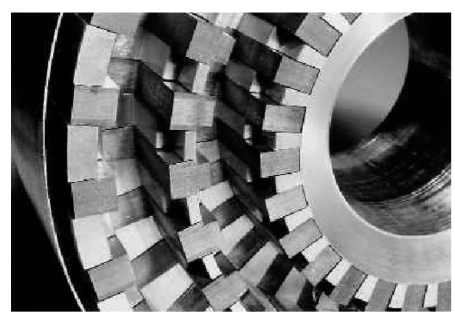
A. Cascade feedback controller design for position control

Cascade position control drive system consists in a current loop, a speed loop and a position loop, as shown in Fig. 2. The *dq*-control signals use the position information from Hall sensors for the coordinate transformation, which guarantees three phase control signals sent to the motor.

The three control loops are designed based on Kessler's canonical form. Then the current loop and speed loop can be considered as a first order system in sequence, which is convenient for the next loop design.



(a)



(b)

Fig. 1. The Structure of TFM proposed by H. Weh [9]. (a) Schematic configuration; (b) implementation to a rotary machine.

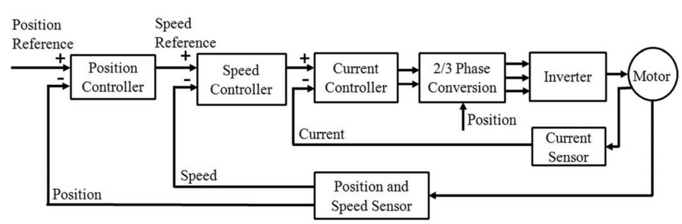


Fig. 2. Cascade position controller.

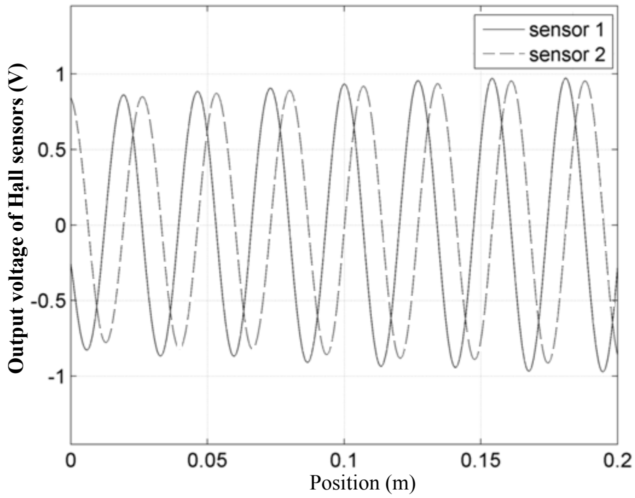


Fig. 3. The output voltage signals of two Hall sensors.

The time constants of current, speed and position loops are approximately set into 10 msec, 40 msec and 160 msec respectively. Furthermore, the three controllers possess a filter to reduce overshoot.

B. Measurements of field magnetic flux with a couple of Hall sensors

The longitudinal magnetic field of the motor is considered as a sinusoidal field; The output of Hall sensor is proportional to the magnetic field. In our method, two A1324 Hall sensors are installed on the mover and the interval between them is 6.75mm, which is the half pole pitch. Taking the saturation of Hall sensors output into consideration, the Hall sensors plate was set up about 10mm away from the permanent magnet plate. The output signals of the two Hall sensors are shown in Fig. 3.

Theoretically, the signal from Hall sensors should be a sinusoidal wave with the same amplitude in every period; however, in reality the amplitude of the output signal is not a standard sine wave as Fig. 3 shows.

C. Method to detect position

In order to get the position of the motor from the output signal of Hall sensors, we must know the mapping between them. When a Hall sensor moves with the mover, the output signal of this Hall sensor s is a sinusoidal wave theoretically, which can be expressed as follows:

$$s = A\sin\left(\frac{\pi}{\tau_{pole\_pitch}}x + \varphi_0\right) \tag{1}$$

where τ_{pole_pitch} = 13.5mm, A is the maximum amplitude, φ_0 is the phase at x = 0m. As Fig. 3 shows, when the motor moves from the start position (x = 0m) to the end position (x = 0.2m), the output signals of Hall sensors are recorded.

Here we pick up the peak, trough and zero points in each period of the signal; then the signal is divided into several sections according to these points, each section is a quarter of one period (Fig. 4). We assume that the signal in each quarter matches (1) strictly. In each quarter, we can pick up the maximum value $s_{\max}$ (peak) or the minimum value $s_{\min}$ (trough), which is the value of A in (1), this value changes in each quarter. We also can pick up the value s_0 of the signal when x = 0m; then φ_0 can be calculated as follows:

$$\varphi_0 = \arcsin\left(\frac{s_0}{A}\right) \tag{2}$$

here φ_0 remains constant in every quarter. Finally, in each quarter the output value of Hall sensor at every position can be calculated by (1) and we get a mapping table which shows the relationship between the output value of Hall sensor and the motor position.

When the motor moves, Hall sensors outputs are read in and we can get the position of motor by look up table at each time. However, the output of one Hall sensor changes periodically. Its value maybe corresponds to several position along the motor stroke in the table. Here when look up table, we find the position in a small subsection around motor position at the previous time. There are two subsections in Fig. 5. In subsection 1, the signal of Hall sensor 1 in the table is monotonically increasing so that one value of the signal corresponds to one position. The range of this subsection is determined by the max speed of the motor. However, when motor moves closely to the position where the output signal of Hall sensor 1 is around the peak of the waveform, the signal of Hall sensor 1 in the table is not monotonous as shown in subsection 2 in Fig. 5. But at this time output of Hall sensor 2 which has a 90-degree phase difference must be monotonous. In a word, no matter what the outputs of sensor 1 or 2 are, the signal which is monotonous having one to one correspondence to motor position in the look up range is used to look up table, then the motor position is obtained.

We used our method to estimate the motor position from the output signals of Hall sensors. Here we obtained the following result. Fig. 6 is the position from the Hall sensors and linear encoder. Fig. 7 is the position difference between the Hall sensors and linear encoder. We calculated that the position error is less than 0.3mm. It satisfies the requirement from the second section which is that the error between position

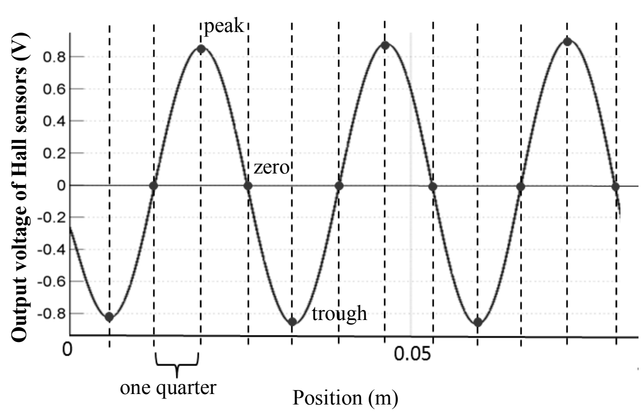


Fig. 4. The division of the signal of One Hall sensor.

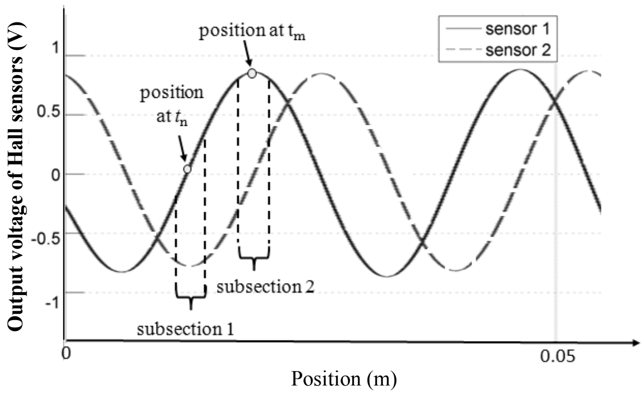


Fig. 5. The subsection of the signal of Hall sensors.

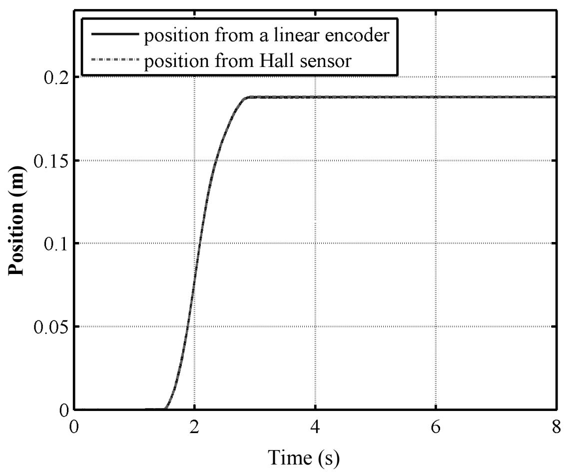


Fig. 6. Position from Hall sensors and a linear encoder.

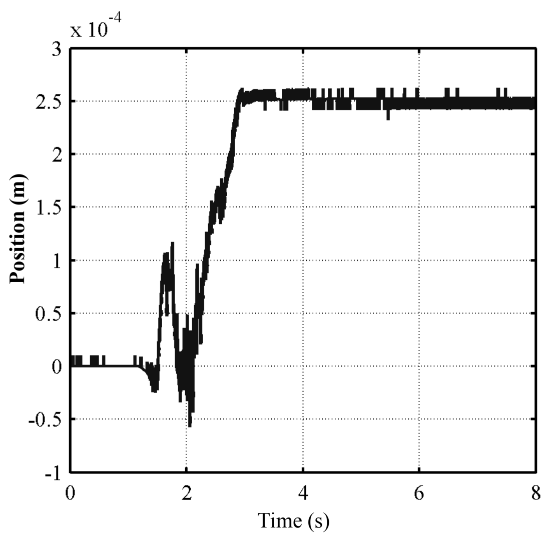


Fig. 7. Difference between position signals from a linear encoder and Hall sensors.

feedback signal from the Hall sensors and real position must be smaller than 1mm.

IV. Methods to Obtain Signals Requested to the Cascade Control

A. Method 1: Approximate diffrential operation for LP-filterd speed signal

By considering speed as the differential of position, we can express it in the S-domain as:

$$v = \frac{s}{1+\tau s} x \tag{3}$$

Where τ is the time constant of the low-pass filter. Considering the stability of speed control loop, we choose the low-pass filter time constant τ as 4 millisecond. The sampling time T is 0.1ms so that the speed expression in Z- domain is shown as:

$$v[n] = \left(\frac{2}{T}x[n] - \frac{2}{T}x[n-1] - \left(1-\frac{2\tau}{T}\right)v[n-1]\right) \Big/ \left(1+\frac{2\tau}{T}\right) \tag{4}$$

Fig. 6 and 7 are the position information obtained from Hall sensors. They are used to do numerical calculation. And in order to compare the two methods of calculating speed, ideal speed from perfect position in our simulation is used as the comparison object. Based on (4), speed is shown in Fig. 8. It shows that speed from method 1 has small vibration. It also has certain delay.

B. Method 2: Single sample rate state observer (including external load force estimation)

Single sample rate state observer uses current and position information to estimate motor position, speed and mechanical load force treated as an external disturbance [11]. The dynamic characteristics of motor in continuous domain are expressed in the following:

$$\frac{d}{dt}\begin{bmatrix} x \\ v \\ F_d \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \frac{1}{M} \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x \\ v \\ F_d \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_t}{M} \\ 0 \end{bmatrix} i_q, \quad y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} x \\ v \\ F_d \end{bmatrix} \tag{5}$$

In discrete domain, the sampling time T is 0.1ms in our research. Observer time constant is also 4 millisecond. Therefore, according to Kessler's canonical from, three poles in S- domain can be obtained. Then three poles in Z- domain are also fixed. Finally, according to observer stable principle , observer gain is designed by applying the pole placement method to the following observer characteristic equation:

$$\det[zI - (A_d - L_d C_d A_d)] = 0 \tag{6}$$

where subscript d means the discretized matrix.

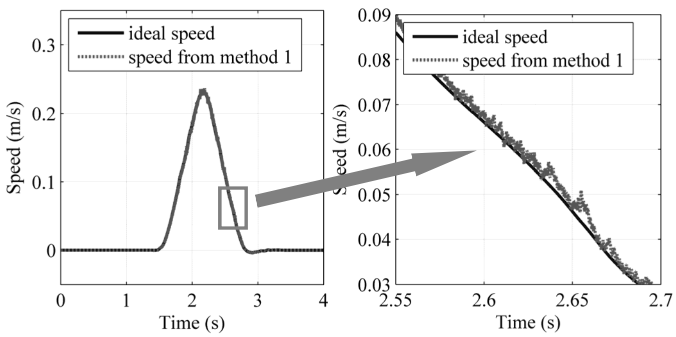


Fig. 8. Speed obtained from approximate differential of position with low-pass filter.

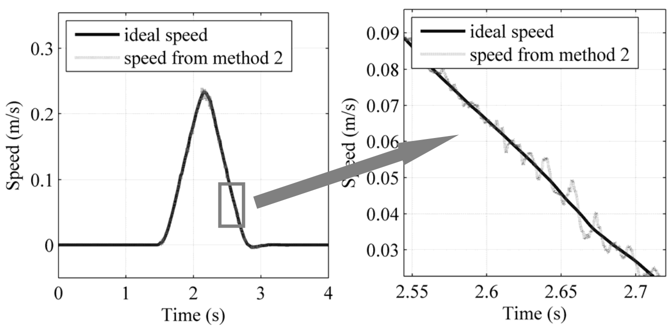


Fig. 9. Speed obtained from single rate observer.

Estimated speed from the observer is shown in Fig. 9. It has very small oscillation.

C. Comparison among the two methods and their performance

The two methods are compared by considering the speed response and position performance. Considering the speed, about method 1, as shown in Fig. 8, its advantage is that speed can be calculated directly from position from Hall sensors independent on system model. But it has one disadvantage that speed waveform has small vibration compared to estimated speed waveform from method 2. About method 2, as shown in Fig. 9, the advantage is that speed waveform has very small vibration. But method 2 is dependent on the accuracy of system model. If the system model is not very accurate, the observer performance will become bad.

Considering the position performance, Fig. 10 and Fig. 11 are position feedback performance in cascade control based on method 1 and method 2. Both of position feedback signals have delay of position command about 160ms. It satisfies the requirement from the second section that position controller must respond fast in a level of 160 msec. Finally, because that position difference from Hall sensors described in the fourth section is less than 0.3mm, so the position error between position command and position feedback signal is also less than 0.3mm. It satisfies the requirement in the second section that position error between position command and real one must smaller than 1mm in numerical studies.

The previous research used position pulses of Hall sensors combined to a dual-rate sampling observer to obtain motor position. The observer time constant should change with speed to guarantee the estimation of motor position and speed. Then we used alternating position and speed controller for position control. Previous research uses position pulses from Hall sensors, which enhance accuracy of position. But it needs to switch between different controllers resulting in transient process. And system response time is slow. In this paper, we directly use analog output signal of Hall sensors to obtain motor position. Speed is derived from two methods. Then we use cascade position control for motor drive. It is no need to switch between different controllers so that transient process can be eliminated. And system response time is fast than previous research.

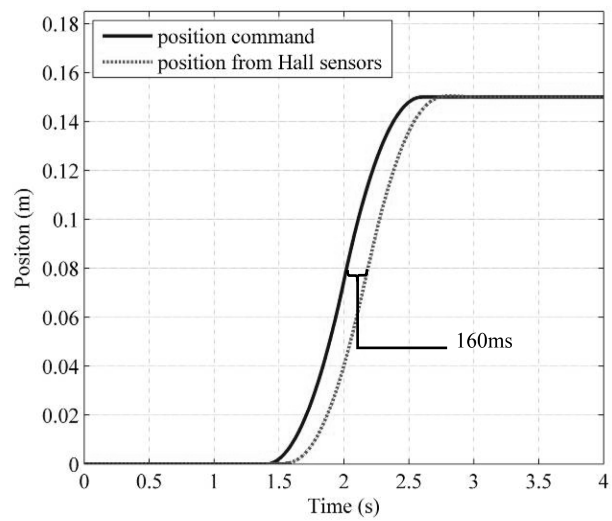


Fig. 10. Position command and position obtained from Hall sensors without use of observer (method 1).

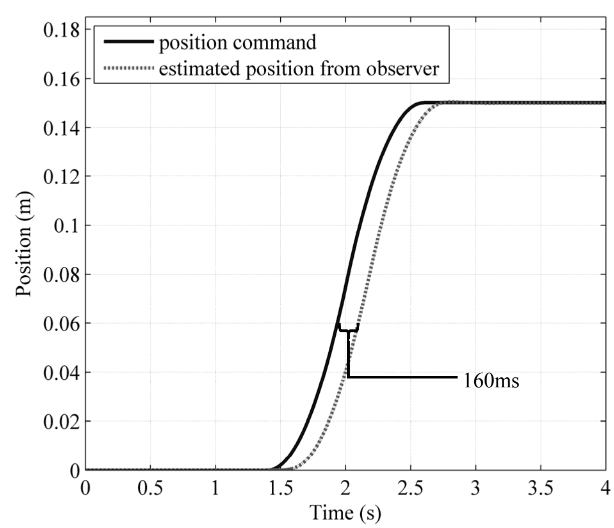


Fig. 11. Position command and estimated position from observer (method 2).

V. CONCLUSIONS

In this paper, we proposed an economic position sensing for position feedback control in long transverse flux linear synchronous motor drive. By assuming sinusoidal waveform of longitudinal flux distribution, two economy Hall sensors give an indicate of the motor position with a position error less than 0.3mm, which is smaller than 1mm as we required.

Two methods to derive speed signal from the position signal from Hall sensors have been presented and compared. One is approximate differential operation of position with low-pass filter. The other is to use state observer including external load force in its state variables. Although the first method needs no system modeling, the derived speed has a delay and the suppression of the measurement noise is insufficient. The second method can produce a fast and smooth speed signal from position signal of Hall sensors, which is based on a sufficiently good system model.

The transient responses of cascade position control feedback performances based on position signals from a conventional linear encoder and from the proposed Hall sensors are calculated and compared. The numerical study shows that the position feedback control based on the economic Hall sensors has good performance with a setting time shorter than 160msec and an accuracy of 0.3mm when it is combined with a simple single rate digital state observer.

Future work includes experimental verification of the technical feasibility of the proposed position feedback control using Hall sensors as position sensors.

ACKNOWLEDGMENT

The authors are cordially grateful to Mr. J. Shin, Mr. Y. Takada, and Mr. H. Narita for their technical support and advices in our measurements of the linear synchronous motor.

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