Sensorless Position Control of SPMLSM based on High-Gain Observer

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***Abstract*—This paper presents a novel sensorless position control for a surface permanent magnet linear synchronous motor (SPMLSM). The position and speed of the SPMLSM drive is obtained through a closed loop observer by only measuring phase voltages and currents. Estimation of speed is done using difference between estimates of the current derivatives in the *dq* frame, which calculated two different ways: one using a high-gain observer, another using the motor model. Estimation of the mover position is done through integrating the estimation of speed. In addition, an initial position of the SPMLSM is the key to starting smoothly, therefore, an estimation method of initial position for the SPMLSM is also developed in this work. The principle of the estimation is based on low frequency voltage injection. The amplitude and phase of the voltage is controllable. When a rotating voltage vector is injected to the motor at standstill, there is a microinching when the voltage phase is line to the direct axis of the motor. Then the current will decrease due to the back electromotive force. The initial mover position is identified by this change. Sensorless control of a SPMLSM based on the proposed strategy has been investigated by comprehensive computer simulation. The experimental testing results verify the effectiveness of the proposed approach.**

***Index Terms*—surface permanent magnet linear synchronous motor, sensorless position control, high-gain observer, initial position**

I. Introduction

Recently the permanent magnet linear synchronous motors (PMLSMs) are increasingly utilized in industrial automation, transportation, and domestic appliances because it has the characteristic of compact structure, reduced size, and low maintenance cost. The PMLSMs are gradually substituting linear drive systems which use a combination of rotary motors and lead-screws. To achieve high dynamics and stable performance, linear position sensors are required for the servo loop feedback. However, linear position sensors account for a large proportion of the total system cost. Furthermore, most linear position sensors have problems of difficult installation, low reliability, and are sensitive to alien surroundings. The reduction in mechanical robustness and cost of sensors makes elimination of these devices very desirable.

Consequently, position sensor elimination schemes have recently received wide attention. The position sensor elimination schemes have been successfully implemented for the interior permanent magnet motor drives [1]-[5]. In these schemes, the back EMF of the motor is integrated in order to estimate the rotor position. The rotor position can also be estimated using the terminal voltages and the currents through the motor phases [6, 7]. These wave form detection techniques have been investigated by others for the permanent magnet synchronous motor (PMSM) and the switched reluctance motor drives [8, 9]. All these techniques look for certain specific commutation instants and do not attempt to provide continuous position estimation.

Using the advanced observers to estimate the rotor position is a recent approach discussed in the literature [10]. Extended Kalman filter (EKF) is well-known to be used to estimate position and speed. EKF is an optimal stochastic observer in the least-square sense for estimating the states of dynamic non-linear systems, and provides optimal filtering of the noises in measurement and inside the system if the covariances of these noises are known. However, for PMLSM drive system, convergence can not be guaranteed, and this algorithm is very complex. Speed observers based on model reference adaptive system theory (MRAS) are the most popular techniques to have been implemented for the speed sensorless PMSM drive [11]-[13]. An error vector is derived using the difference between the outputs of two dynamic models of the PMSM, where only one of the models includes the estimated speed as a system parameter. The error vector is driven to zero through an adaptation law and the estimated speed then converges to its true value. However, in the low speed range, the observer is very sensitive to the variation of stator resistance and integrator drift [14]. Moreover, the accuracy of speed estimation is affected by the parameter variations of the PMSM [15].

In the past decade, the high-gain observer has been the focus of many studies into the control of the AC servo

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drive system [16]. This observer works in a closed-loop fashion mean that it has an inherent correction mechanism, which can offer many advantages, such as insensitivity to parameter variations, external disturbances rejection and fast dynamic response.

This paper investigates the characteristics of an SPMLSM drive system, estimates the magnetic pole position and mover speed by detecting the terminal voltage and current using the high-gain observer. The observer is developed from the *dq* model of the motor. Estimation of speed is done using differences between estimates of the current derivatives in the *dq* frame. High-gain observer is used to reduce the effect of the disturbance.

This paper is divided into three sections. Section I presents position and speed detection algorithm using the high-gain observer. Section Ⅱ is dedicated to an estimation method of the mover initial position based on low frequency voltage injection. Section Ⅲ gives the results of implementation to verify the viability of the proposed scheme.

II. Position and Speed Detection Algorithm

A. Mathematic Model of the SPMLSM

The SPMLSM, a linear guide and an optical scale are mounted on an anti-shock table. Fig. 1 shows the configuration of mechanical mounting. Optical scale is used to measure the position and speed of the mover for comparison with the estimation.

In this work, the following assumptions are made regarding the SPMLSM:

(1) The induced electromotive force is sinusoidal;

(2) Magnetic saturation, magnetic hysteresis and erratic current are neglected;

(3) Primary windings are star connected and symmetrical. Number of turns in each winding is equal. Resistance of each winding is equal. And three armature windings are set at 120° to each other;

(4) Surfaces of primary and secondary are both smooth.

The voltage phase-variable equation of a SPMLSM in stator-fixed reference frame (a, b, c) is as follows,

$$\begin{cases} u_a = Ri_a + Lpi_a - \dfrac{\pi}{\tau} v\psi_f \sin\theta \\ u_b = Ri_b + Lpi_b - \dfrac{\pi}{\tau} v\psi_f \sin(\theta - \dfrac{2\pi}{3}) \\ u_c = Ri_c + Lpi_c - \dfrac{\pi}{\tau} v\psi_f \sin(\theta + \dfrac{2\pi}{3}) \end{cases} \tag{1}$$

where u_a, u_b, u_c are voltage of three phase windings respectively. i_a, i_b, i_c are current of three phase windings respectively. R, L, τ are the phase resistance, the synchronous inductance, the pole pitch respectively. ψ_f is the amplitude of the flux linkage established in the phase windings, by the permanent magnet. θ and v is the position and speed of the motor respectively. p is the differential operator, $p=d/dt$.

B. Structure of Observer

The primary objective of this work is to formulate a scheme which estimates the position of the mover, with the knowledge of only three motor parameters: resistance R, inductance L, and flux linkage ψ. The input to the scheme must consist of only the terminal quantities: voltages and currents. The scheme must not rely on rotor saliency or any physical modification.

The underlying steps in the proposed scheme are:

(1) Measure the motor currents and voltages;

(2) Transform these variables to the *dq* rotor frame of reference using $\hat{\theta}$, the estimate of θ;

(3) Calculate the derivatives of each of the currents $\hat{i}_q$ and $\hat{i}_q$, two different ways;

(3) Use the error between the current derivatives to drive the observer.

Fig. 2 gives an overview of the proposed scheme. The details of the scheme as follow.

Firstly, voltage model of SPMLSM shown as (1) should be transformed to the *dq* frame. If the motor position θ is known, the following matrix will be used:

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \end{bmatrix} \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{2}$$

where, f represents either a voltage or a current.

Since we are developing a sensorless scheme, θ is unknown, we use its estimate $\hat{\theta}$. This modifies (2) to:

$$\begin{bmatrix} \hat{f}_d \\ \hat{f}_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\hat{\theta} & \cos(\hat{\theta} - 2\pi/3) & \cos(\hat{\theta} + 2\pi/3) \\ -\sin\hat{\theta} & -\sin(\hat{\theta} - 2\pi/3) & -\sin(\hat{\theta} + 2\pi/3) \end{bmatrix} \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{3}$$

Carrying out the transformation, (1) and (2) yield:

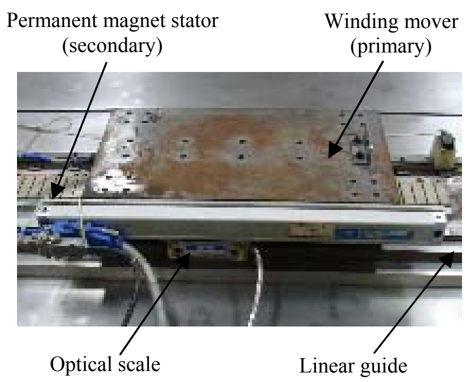


Figure 1 The configuration of mechanical mounting

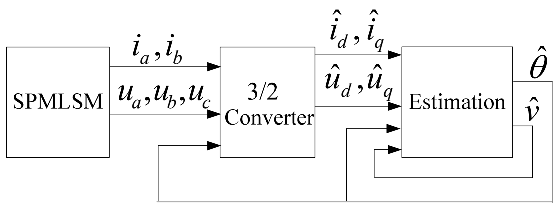


Figure 2 Overview of the estimation algorithm

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} R+Lp & -L\dfrac{\pi v}{\tau} \\ L\dfrac{\pi v}{\tau} & R+Lp \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{\pi v}{\tau}\psi_f \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{4}$$

while, (1) and (3) result in:

$$\begin{bmatrix} \hat{u}_d \\ \hat{u}_q \end{bmatrix} = \begin{bmatrix} R+Lp & -L\dfrac{\pi \hat{v}}{\tau} \\ L\dfrac{\pi \hat{v}}{\tau} & R+Lp \end{bmatrix} \cdot \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} + \frac{\pi v}{\tau}\psi_f \begin{bmatrix} -\sin\Delta\theta \\ \cos\Delta\theta \end{bmatrix} \tag{5}$$

where $\hat{v}$ is speed estimate, and $\Delta\theta = \theta - \hat{\theta}$

Rearranging (5), we get

$$p\hat{i}_q = \frac{1}{L}\hat{u}_q - \begin{bmatrix} L\dfrac{\pi\hat{v}}{\tau} & R \end{bmatrix} \cdot \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} - \frac{\pi v}{\tau}\psi_f \cos\Delta\theta \tag{6}$$

where $p\hat{i}_q$ can be calculated by finding the derivative of the signal known to us: $\hat{i}_q$. High-gain observers will be used to find the derivative.

Another way will be used to calculate the derivative. We define a new set of variables, replicating (6) but assuming $\Delta\theta$=0 and $\hat{v} = v$:

$$p\hat{i}_{qm} = \frac{1}{L}\hat{u}_q \begin{bmatrix} L\dfrac{\pi\hat{v}}{\tau} & R \end{bmatrix} \cdot \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} - \frac{\pi\hat{v}}{\tau}\psi_f \tag{7}$$

Further defining: $\Delta p\hat{i}_q = p\hat{i}_q - p\hat{i}_{qm}$. (6) - (7) yields the error in current derivative:

$$\Delta p\hat{i}_q = \frac{\pi\psi_f}{\tau L}(-v\cos\Delta\theta + \hat{v}) \tag{8}$$

Assuming that $\Delta\theta$ is small. Thus,

$$\Delta p\hat{i}_q = \frac{\pi\psi_f}{\tau L}\Delta v \tag{9}$$

where $\Delta v = v - \hat{v}$. Rearranging (9), we get: $\Delta v = -\dfrac{\tau L}{\pi\psi_f}\Delta p\hat{i}_q$

Substituting the definition of Δv from the above equation, it can be re-written as:

$$v = \hat{v} - \frac{\tau L}{\pi\psi_f}\Delta p\hat{i}_q \tag{10}$$

For the purpose of implementation, (10) can be expressed as:

$$\hat{v}_{new} = \hat{v} - \frac{\tau L}{\pi\psi_f}\Delta p\hat{i}_q \tag{11}$$

(11) is a high-gain observer. Divides each side of (11) by the sample time *T*. we obtain:

$$\frac{\hat{v}_{new} - \hat{v}}{T} = -\frac{\tau L}{T\pi\psi_f}\Delta p\hat{i}_q = h\Delta p\hat{i}_q \tag{12}$$

Because T is small, the left-hand side of (12) can be regarded as the derivative of $\hat{v}$. Thus,

$$\dot{\hat{v}} = h\Delta p\hat{i}_q \tag{13}$$

where h is the observer gain. The typical sampling frequency is 10kHz-20kHz. Therefore, the gain h is very high. This high-gain observer ensures that the effect of the disturbance can be neglected.

The estimation of position $\hat{\theta}_{new}$ can be calculated by integrating the speed estimation $\hat{v}_{new}$.

Fig. 3 shows the above algorithm graphically. Fig. 4 gives the speed and position estimate results by numerical simulation with velocity command 320mm/s. Fig. 5 gives their errors.

III. Estimation Method of Mover Initial Position

Unlike asynchronous machine such as an induction machine, the stator flux angle of the SPMLSM is determined by the actual mover position. Development of the initial mover position estimation method is one of some serious problems about sensorless drives, and is also very important to achieve the sensorless control of the motor at starting. If the initial mover position is inaccurately estimated, the starting force of the motor decreases, and the mover may temporarily move in the wrong direction. Therefore, unless the mover position is known exactly, it is impossible to start the motor smoothly. It is difficult to detect the initial position for a SPMLSM because it has no salience [17-18]. Several initial rotor position estimation methods have been proposed, which are based on the current peak caused by the pulsewise voltage [20, 21], the relation between current and phase voltage by voltage equation of the motor [22-24], saliency of the rotor [25, 26]. However, most of them are methods for interior-type permanent magnet synchronous motors and are based on the principle that the inductance of interior-type motors is changed according to the rotor position.

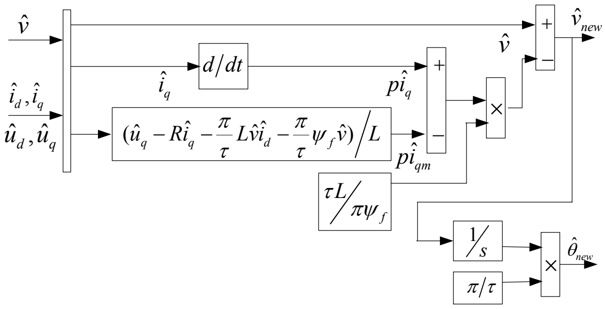


Figure 3 Details of the proposed scheme

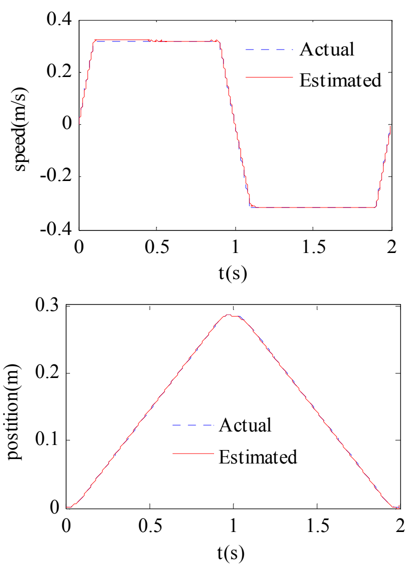
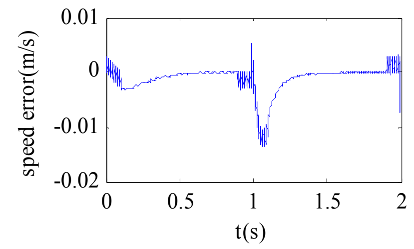
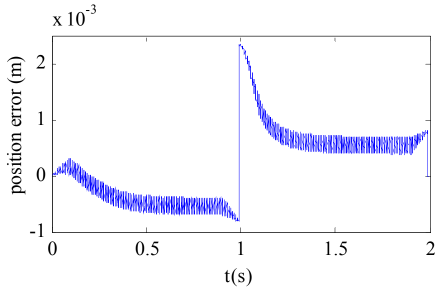


Figure 4 Speed and position estimate curves



(a) speed error



(b) position error

Figure 5 Errors of speed and position estimation

This paper proposed a method to estimate the initial position without motor parameters and the additional hardware for the SPMLSM. The initial position estimate scheme is presented as follows.

According to the Clarke transformation, voltage model of SPMLSM shown as equation (1) can be transformed to the $\alpha\beta$ frame.

$$u_\beta = Ri_\beta + L\frac{\mathrm{d}i_\beta}{\mathrm{d}t} + e_\beta \tag{14}$$

$$u_\alpha = Ri_\alpha + L\frac{\mathrm{d}i_\alpha}{\mathrm{d}t} + e_\alpha \tag{15}$$

where i_α, i_β are current of α-β axis respectively. e_α, e_β are back electromotive force (EMF) current of α-β axis respectively. Back EMF e_α, e_β are functions of speed v and position θ, which can be expressed as:

$$e_\alpha = -k_e v \sin\theta \tag{16}$$

$$e_\beta = k_e v \cos\theta \tag{17}$$

where k_e is the constant of the back EMF.

From equation (14) and (15), we can derive:

$$i_\alpha = \frac{u_\alpha - e_\alpha}{R}(1 - \mathrm{e}^{-R/Lt}) \tag{18}$$

$$i_\beta = \frac{u_\beta - e_\beta}{R}(1 - \mathrm{e}^{-R/Lt}) \tag{19}$$

where T is the electrical time constant, T=R/L. After t_0 seconds, e^{-Tt} would decay and approach to zero. Therefore, after current vector rotated an little angle ε (ε=ωt_0), the current would reached its maximum. When the motor starts to run, the back EMF e_α, e_β are not equal to zero, and the current will decrease. According to this change process, the initial mover position can be estimated through injecting a low frequency rotary voltage phasor to the motor. Its amplitude must make the motor inching only.

The scheme is implemented by rotating the voltage phasor at a very low frequency and observing the magnitude of the resulting current phasor at machine standstill. The voltage magnitude and frequency can be controlled because the machine is voltage-fed. The voltage is such that the winding current is 1 p. u. after build up governed by the electrical time constant of the motor. The North pole (d axis) of the permanent magnet, referred as "the mover" is held by the load force in an unknown position.

The current phasor is slowly rotated resulting in a sinusoidal electrical thrust. When the electrical thrust exceeds the load force the mover will move. In the moment the mover starts to move and the back EMF will be subtracted from the applied voltage producing a decrease (notch) in the magnitude of the current phasor. From the phase angle of this notch, we can obtain the initial position θ_0 using equation (20).

$$\theta_0 = \omega t - \varepsilon \tag{20}$$

where ω is rotating speed of the voltage phasor. ε is lagging angle, which results from current can not jump.

The processed initial position estimate theory can be shown in Fig. 6. According this theory, numerical simulation is done. The estimated initial electrical angle is shown in Fig. 7. Fig. 7 illustrates that its estimated error is ±7°, which can ensure the motor starting smoothly.

IV. Position Experimental Results

To investigate the viability of the proposed scheme, an implementation was carried out. The experimental setup, built to test the scheme in real-time, is shown in Fig. 8, which is consisted of a control box, a SPMLSM drive, and several measuring apparatus. The control box is consisted of a transformer, a 24VDC power supply, a motor driver, several contactors, and a computer etc. The SPMLSM drive includes a SPMLSM, an encoder with resolution 1μm, a pair of limit switches, a zero switch, and a pair of linear guide rail and so on. A laser interferometer with resolution of 1nm is utilized to verify its positioning accuracy.

A fixed point digital signal processor (DSP), TM320F2812, is used to run the vector control algorithm. The control and estimation period is 60 μs. The PWM switching frequency for insulated gate bipolar transistors is 16 kHz. The DSP also runs the speed and position estimation algorithm. Sensorless control system is shown in Fig. 9, and the SPMLSM's parameters are given in table 1.

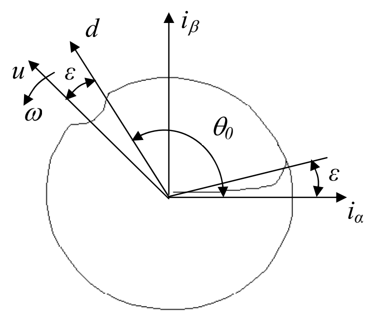


Figure 6 Theory of initial position estimation

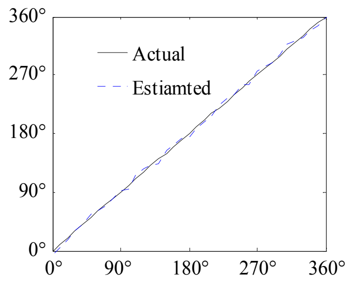


Figure 7 Initial mover position

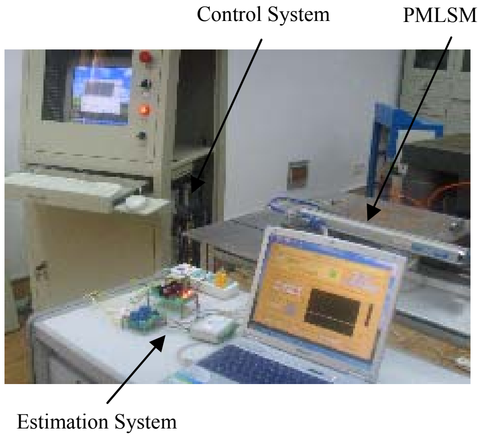


Figure 8 Implementation of SPMLSM sensorless control

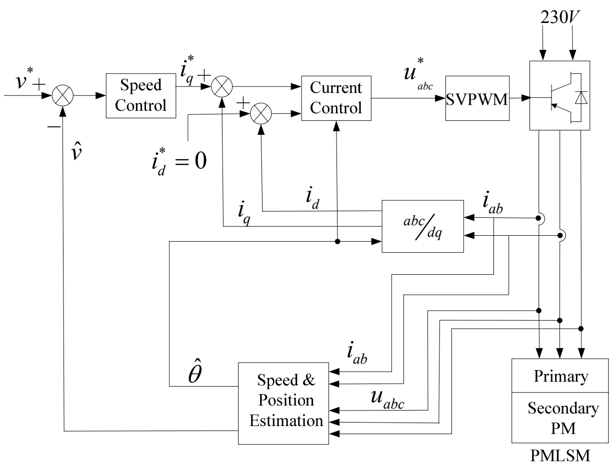
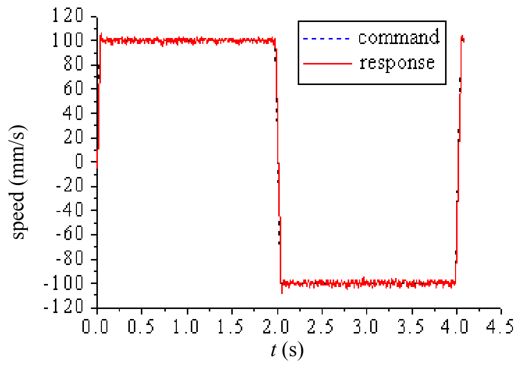


Figure 9 The details of the sensorless control block

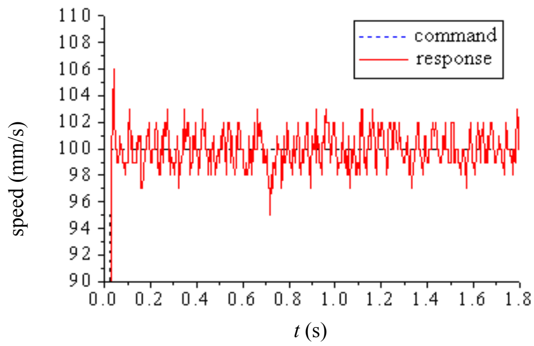
Table 1
Technical data of SPMLSM

Rated power	1413W
Operating Voltage	230 VAC
Continuous current	4.4A
Phase resistance	2.65Ω
Synchronous inductance	0.0267H
PM flux	0.1Wb

In order to test the functions of the proposed sensorless control method from lower speed to high speed, the velocity and accelerated velocity command is set up (v =100mm/s, a =3200mm/s^2; v =300mm/s, a =5000mm/s^2; v=300mm/s, a=5000mm/s^2; v =500mm/s, a =10000mm/s^2) The experimental results are shown in Fig. 10 to Fig. 13.

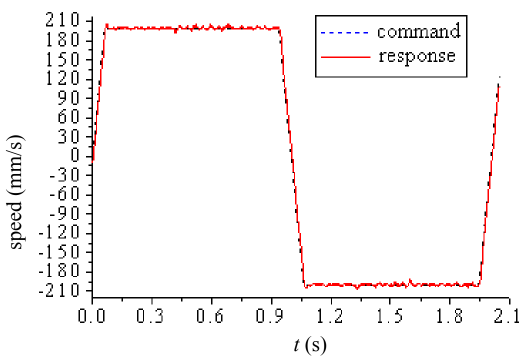


(a) Speed response

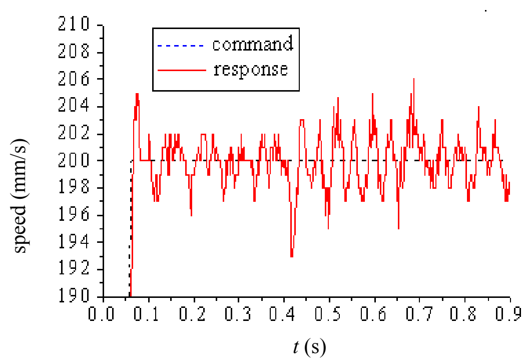


(b) Partial enlarged drawing

Figure 10 Speed response of SPMLSM sensorless control system (v =100mm/s, a =3200mm/s^2)

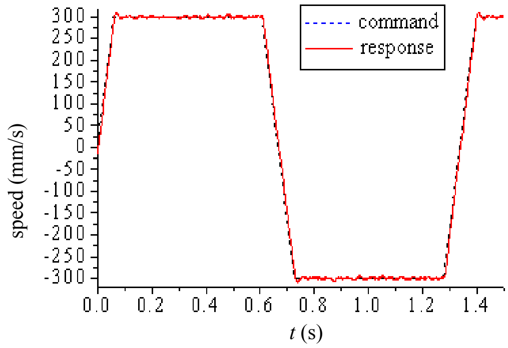


(a) Speed response

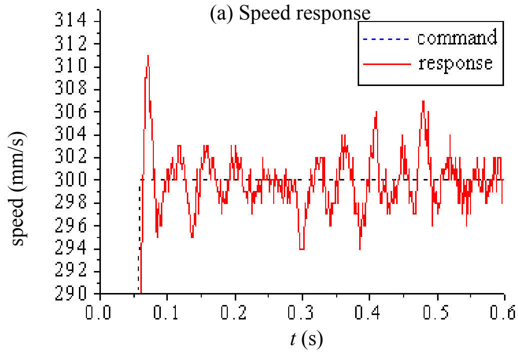


(b) Partial enlarged drawing

Figure 11 Speed response of SPMLSM sensorless control system (v =200mm/s, a =5000mm/s^2)

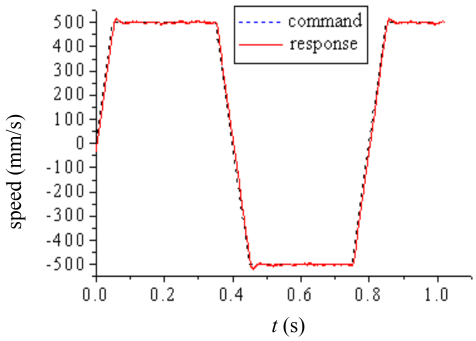


(a) Speed response

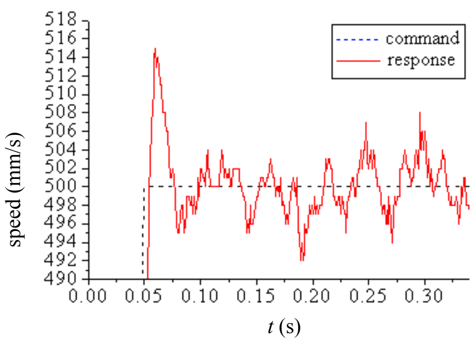


(b) Partial enlarged drawing

Figure 12 Speed response of SPMLSM sensorless control system (v =300mm/s, a =5000mm/s^2)



(a) Speed response



(b) Partial enlarged drawing

Figure 13 Speed response of SPMLSM sensorless control system (v =500mm/s, a =10000mm/s^2)

From figure 10 to figure 13, it can be seen that the steady-state errors are 3mm/s, 6mm/s and 8mm/s at different velocity command respectively. Their relative errors are 3%, 2% and 1.6% respectively. The accuracy at higher speed is higher than at lower speed.

The final experiment results demonstrate that our sensorless position control method is effective, and the SPMLSM driver has nearly the same accuracy as the resolution of the method with a position sensor. With its rapidness and high precision, the PMLSM feeding platform quite fits the requirements for micro-fabrication systems just replacing a position sensor with corresponding resolution.

V. Conclusion

In this paper a simple algorithm for detecting speed and position based on high-gain observer is proposed. It can estimate the magnetic pole position and mover speed by detecting the voltage and current of permanent magnet linear synchronous motor. The scheme does not rely on the motor having salient poles, and not rely on integration of the speed estimate to get the position estimate. It works in a closed loop model, and includes inherent correction mechanism. Also, it is computationally less intensive than many other schemes proposed.

In addition, an initial position estimation method for the SPMLSM is also developed in this work. The principle of the estimation is based on low frequency voltage injection without depending on the motor parameters, motor salience and the additional hardware.

It is demonstrated that the high-gain observer with the initial position estimation can provide reliable position information for a controlled force, closed loop start up and sound performance of low speed running at 100 mm/s.

The presented work demonstrates that the measured terminal currents and voltages, together with the machine parameters, can be used to obtain speed and position in real-time. The method can be employed in drive systems with SPMLSM, or any type of linear synchronous motor, that requires a controlled force start up under high load using the rated current, which gets better performances at low running speed.

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