ホールセンサを用いたリニア同期モータ長距離駆動位置速度切替制御

Zhao Qi*　　古関隆章　　（東京大学）

Alternating Position and Speed Control of Long Stroke Linear Synchronous Motor Based on Hall Sensor

Zhao Qi*, Takafumi Koseki (The University of Tokyo)

This paper proposes a method of motor-position acquisition from hall sensors installed on the mover of linear synchronous motor. The sensors are combined to Dual-rate sampling observer to estimate motor speed and position. Then this paper describes a design method of speed and position controllers for smooth transition between alternating speed and position control. And the parameters of speed controller are variable with motor speed.

キーワード：リニア同期モータ，デュアルレートサンプリングオブザーバ，位置と速度のコントロール，ホールセンサ
(Linear synchronous motor, Dual-rate sampling observer, Position and speed controller, Hall sensor)

1． Introduction

Linear motion is very commonly used in industrial applications. And linear motors offer many advantages compared to those based on traditional rotating motors: the elimination of the transmission gears and the reduction of the maintenance. Hence linear motor drives are widely used in applications such as pick and place, X-Y machines, linear compressor and elevator [1].

The linear synchronous motor (LSM) needs position information to synchronize the current vector to the permanent-magnet position. The position of the mover can be measured from linear encoder. But for linear encoder, there are two main problems [2]. The first problem is that cost of linear encoder is proportional to linear motor stroke. The second problem is that many environments of industrial applications have contamination and disturbance so that optical linear encoder is problematic for this kind of application.

Because of the disadvantages of the linear encoder, we propose a method of motor-position acquisition from hall sensors installed on the mover of linear synchronous motor. Then dual-rate sampling observer is combined to position pulses from hall sensors to estimate motor position and speed. Finally this paper describes a design method of speed and position controllers for fulfilling smooth transition between alternating speed and position control.

2. Proposed Hall Sensors with LSM Combined with Dual-rate Sampling Observer

Three analog hall sensors are determined to be used. The proposed hall sensors of LSM structure is shown in Fig. 1.

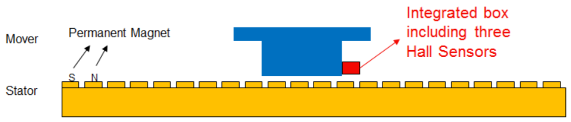


Fig. 1. Proposed structure of LSM with three hall sensors on mover.

In preliminary experiment, two analog hall sensors which is A1324 created by Allegro Microsystems are installed on mover of linear motor. They are installed by each other half pole pitch. Here pole pitch τ in this paper is 13.5mm. Fig. 2 shows the output signals of two hall sensors which differ from each other half pole pitch. We can see that the phase difference is 90 degrees.

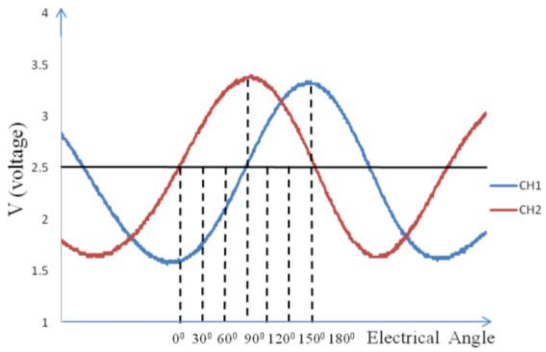


Fig. 2. Output signals of two analog A1324 hall sensors.

Later three analog hall sensors are determined to be used as shown in Fig. 3 and Fig. 4.

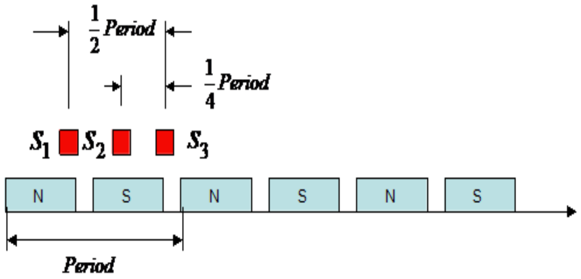


Fig. 3. Three analog A1324 hall sensors install location.

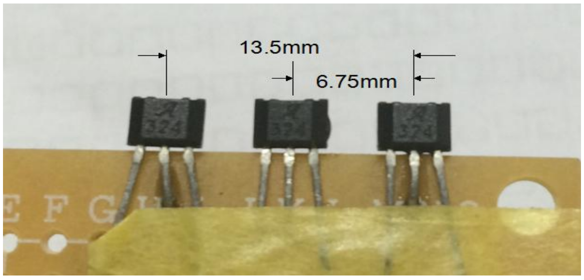


Fig. 4. Installed three analog A1324 hall sensors

Quadrature position are derived from three hall sensors in equation (1) and (2). Here x is motor position, τ is pole pitch 13.5 mm.

$$s_{1c} = s_1 - s_2 = \sqrt{2}\cos\left(\frac{\pi}{\tau}x + \frac{1}{4}\pi\right) \quad (1)$$

$$s_{2c} = s_3 - s_2 = \sqrt{2}\cos\left(\frac{\pi}{\tau}x + \frac{3}{4}\pi\right) \quad (2)$$

Transfer this quadrature signals by logic circuits, position pulses are obtained which has resolution of half pole pitches 6.75mm as shown in Fig. 5.

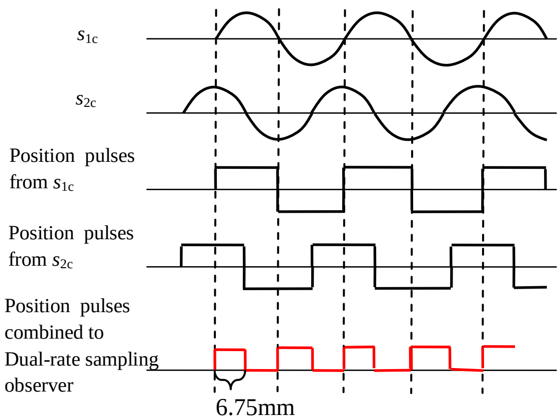


Fig. 5. Position pulses from hall sensors.

3. Principle and Design of Dual-rate Sampling Observer

Before talk about dual-rate sampling observer, Fig. 6 shows three control modes of linear motion. Assume point A and B in Fig. 6 are the switch points among three modes.

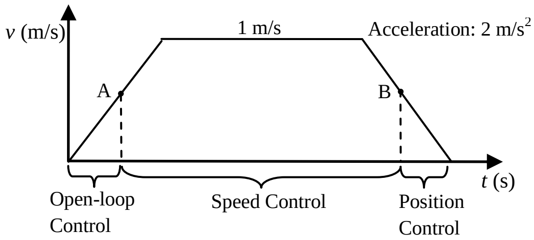


Fig. 6. Three control modes of linear motion.

There are three control modes: open-loop current control, speed control and position control. In speed control section, position pulses are combined to dual-rate sampling observer to estimate motor speed and position. In position control section, without dual-rate sampling observer, analog positions from hall sensor are used to make motor stop. And for smooth transition from speed control to position control, position integral parameter is determined in a linear way both consider the estimated motor position from dual-rate sampling observer and analog position from hall sensor, which will be described in part four.

<3.1> Principle of Dual-rate Sampling Observer

Dual-rate sampling observer deals with condition in Fig. 7 (b) that position pulse period T_1, which is variable according to motor speed and renewed 6.75 mm, is larger than constant DSP control period T_2. It combines prediction and correction [(3)-(4)] to estimate motor speed and position when speed is low or sensor is poor as shown in Fig. 8.

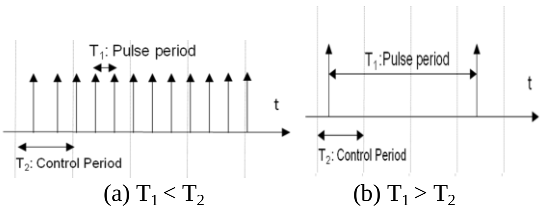


Fig. 7. Dual-rate sampling

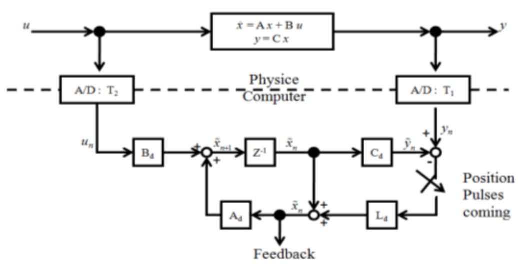


Fig. 8. Current Dual-rate Sampling Observer

<3.2> Keypoint of Pole Placement in Design of Dual-rate Sampling Observer

We use three steps to design observer.

Step 1: Select state variables: position, speed and disturbance. Select current and position as input and output respectively.

Step 2: Establish state space expression according to motor dynamic.

$$\frac{d}{dt}\begin{bmatrix} x \\ v \\ F_d \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \frac{1}{M} \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x \\ v \\ F_d \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_t}{M} \\ 0 \end{bmatrix} i_q \quad (3)$$

$$y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} x \\ v \\ F_d \end{bmatrix} \quad (4)$$

Here x, v, F_d is position, speed, disturbance. M and K_t is motor mass and torque coefficient.

Step 3: Pole placement for designing observer gain L_d, which satisfy observer stability condition shown in equation (5). Here subscript 1 means discrete system matrix sampled by T_1

$$\det[zI - (A_1 - L_1 C_1 A_1)] = 0 \quad (5)$$

L_2 is observer gain sampled by T_2, It has proven that L_1 is equal to L_2 [(3)-(4)]. Then just consider about pole placement on z_1 - plane so that L_1 and L_2 will be obtained at the same time.

When make pole placement, we think that dual rate sampling observer time constant τ_{obs} should change with the position pulse interval T_1. When speed is low, T_1 becomes longer compared to high speed motion. So in order to well estimate the motor state and reduce oscillation, observer time constant τ_{obs} should also become longer than high speed. On the other side, when speed is high, T_1 is short. Correspondingly, τ_{obs} is short.

So we give out the relationship like that:

$$\tau_{obs} = NT_1 \quad (6)$$

N is selected as 16 considering sampling requirements. Current loop responses very fast so that system is regarded as a second-order system. In order to realize the relationship of (6), we decide to fix poles on z_1-plane in the following:

According to Kessler's canonical form which is proposed by Kessler in the year 1960.

$$\frac{1}{8}\tau^3 s^3 + \frac{1}{2}\tau^2 s^2 + \tau s + 1 = 0 \quad (7)$$

If time constant of observer is τ_{obs}, three poles for observer are obtained as s_1, s_2 and S_3. Then three fixed poles on z_1-plane are like:

$$z_1 = e^{s_1 T_1} = e^{-\frac{2}{N}} \quad (8)$$

$$z_2 = e^{s_2 T_1} = e^{\left(-\frac{1}{N} + j\frac{\sqrt{3}}{N}\right)} \quad (9)$$

$$z_3 = e^{s_3 T_1} = e^{\left(-\frac{1}{N} - j\frac{\sqrt{3}}{N}\right)} \quad (10)$$

After fix poles on z_1-plane, observer time constant will change with motor speed. Then substitute poles on z_1-plane to equation (5), observer gain L_1 and L_2 can be obtained.

<3.3> Case study

For a speed control system, system time constant is 50ms and overshoot is set to 4%. Speed command is given as shown in Fig. 9. From 0 second to 0.5 second is constant speed. After 0.5 second, deceleration is $-2m/s^2$.

If this system has very high resolution position sensor, which is regarded as ideal sensor here. After given speed command, the system response is shown in Fig. 10.

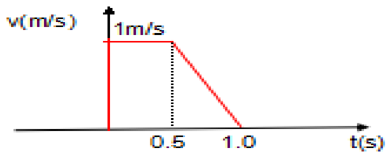
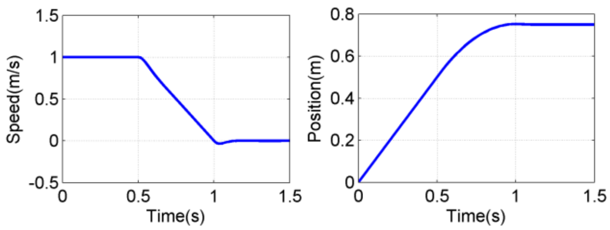


Fig. 9. Given speed command



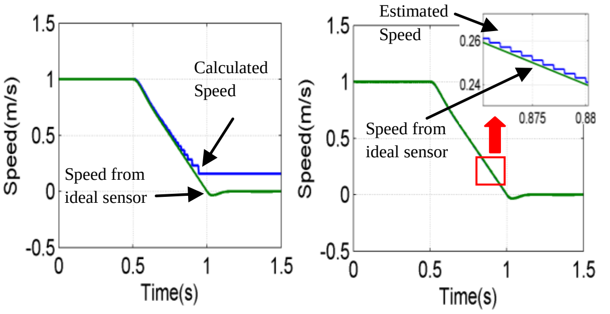
(a) Speed (b) Position

Fig. 10. Speed and position response with ideal sensor.

Now we just have position pulses shown in Fig. 5 from hall sensors. There are two methods to obtain speed and position from position pulses. Case 1 is to calculate speed from position pulses. Speed calculation equation is the following:

$$v = \frac{resolution}{T_1} \quad (11)$$

Here resolution is half pole pitch 6.75mm. T_1 is position pulse interval. Case 2 is to combine the position pulses with dual-rate sampling observer. We use speed response under ideal sensor as the basic to compare the two methods. The speed simulation is in Fig. 11.



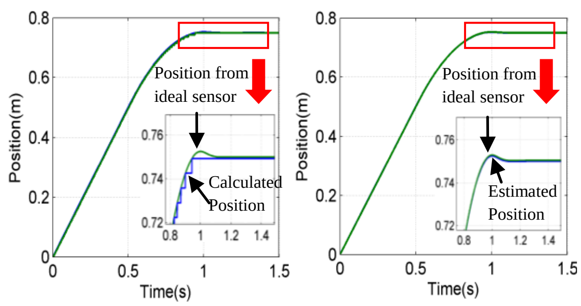
(a)Case 1 (b)Case 2

Fig. 11. Speed response

Fig. 11 (a) shows calculated speed without use of dual-rate sampling observer. Calculated speed always has delay compared to speed from ideal sensor. Fig. 11 (b) shows estimated speed with application of dual-rate sampling observer. Estimated speed is almost the same with speed response of motor system which has ideal sensor.

For position signal, Fig. 12 shows position with and without dual-rate sampling observer. We can see that with application of dual-rate sampling observer, estimated position is almost the same with position response of motor system which has ideal sensor.

So after case study, it is concluded that position pulses from hall sensor should combined with dual-rate sampling observer to estimate motor speed and position. Then the estimated speed and position can be used as feedback signal for speed control.



(a) Case 1 (b) Case 2

Fig. 12. Position response

4. Speed and Position Controller Design

<4.1> Speed Controller Design

Current loop responses very fast so that transfer function of current loop is regarded as 1 without time delay. And dual-rate sampling observer is regarded as a first-order system whose time constant is τ_{obs}.

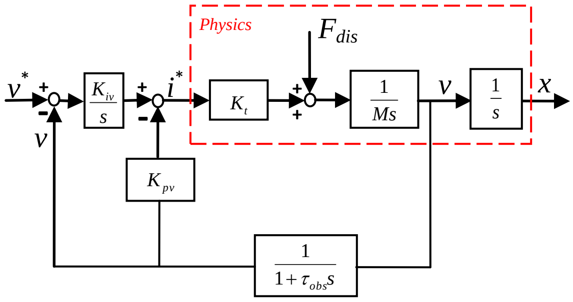


Fig. 13. Block Diagram of I-P Speed Controller.

$$\frac{v}{v^*}=\frac{1+\tau_{obs}}{\frac{M\tau_{obs}}{K_tK_{iv}}s^3+\frac{M}{K_tK_{iv}}s^2+\frac{K_{pv}}{K_{iv}}s+1}$$

$$=\frac{1+\tau_{obs}}{a_3s^3+a_2s^2+a_1s+a_0} \quad (12)$$

By compare system transfer function to Kessler's canonical form

$$\frac{a_1^2}{a_0a_2}=2\,,\ \frac{a_2^2}{a_1a_3}=2 \quad (13)$$

We can obtain

$$K_{pv}=\frac{M}{2K_t\tau_{obs}} \quad (14)$$

$$K_{iv}=\frac{M}{8K_t\tau_{obs}^2} \quad (15)$$

Equivalent time constant of speed loop is four times of observer time constant.

$$T_{veq}=4\tau_{obs} \quad (16)$$

Current control signal is like:

$$i^*=K_{iv}\int(v^*-v)dt-K_{pv}v=K_{iv}x_e-K_{pv}v \quad (17)$$

x_e is position error.

Then simulation is made. Speed command is same as Fig. 9. Integral and Proportion parameters are calculated by equation (14) and (15). Estimated speed and position from dual-rate sampling observer are used as feedback signals for speed control.

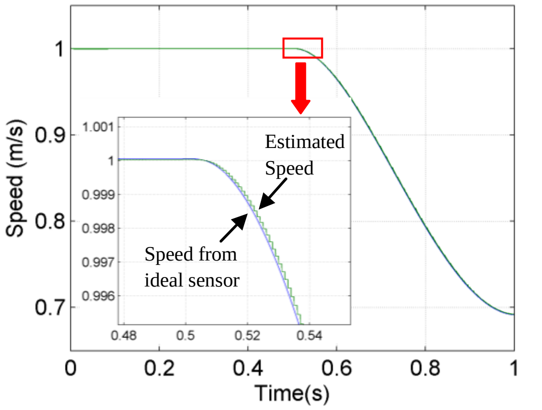


Fig. 14. Speed response.

Fig. 14 shows that during deceleration section, speed decreases slower and slower.

Because time constant of speed controller T_{veq} is proportional to observer time constant τ_{obs}. As equation (6) shows, when speed decreases, position pulses interval T_1 becomes longer so that τ_{obs} becomes larger. Correspondingly, T_{veq} also becomes larger which means speed controller responses slower and slower.

In addition, because simulation is not very complex compared to the real motor. Fig. 14 shows oscillation are almost zero because of the pole placement that dual-rate observer time constant τ_{obs} changes with motor speed in part three.

<4.2> Position Controller Design

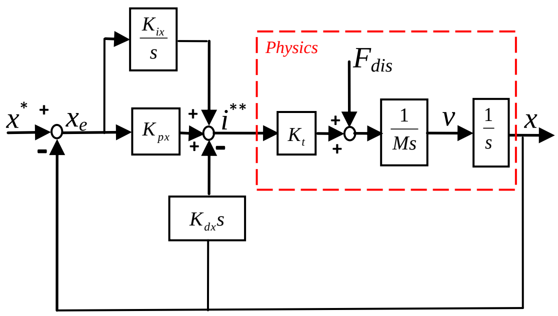


Fig 15. Block diagram of position controller.

Current control signal in position controller is like:

$$i^{**} = K_{px}x_e - K_{dx}v + K_{ix}\int x_e dt \quad (18)$$

At switch moment if we order

$$K_{px} = K_{iv} \quad (19)$$

$$K_{dx} = K_{pv} \quad (20)$$

Then

$$i^{**} = i^* + K_{ix}\int x_e dt \quad (21)$$

Compare (17) and (18), if position controller integral K_{ix} is 0 at switch moment, current control signal both in speed control and position control is same. So order $K_{ix} = 0$ at switch moment. After switch moment, we propose to change K_{ix} considering both estimated position from dual-rate sampling observer and analog position from hall sensors. That's to say, we deal with two kinds of position signals by putting weights. And K_{ix} are determined in a linear way which tries to make the difference between two kinds of position signals becomes zero. Until difference becomes zero, dual-rate sampling observer is stopped and system comes into position control which just use analog position signal from hall sensors. Alternate in this way is hoped to be smooth. Detailed calculation and simulation will be studied soon as the next research.

5. Conclusion and Future Work

This paper uses hall sensors to obtain motor position in replace of linear encoder, which reduce system cost and broaden industrial application. Then position pulses from hall sensors are combined to dual-rate sampling observer. For observer design, poles on z_1-plane are fixed in order to guarantee that observer time constant changes with motor speed, which can well estimate motor position and speed and reduce oscillation when speed becomes low. Finally it describes speed and position controller design. Speed controller parameters are designed by Kessler's canonical form. For position controller design, in order to fulfill smooth transition between alternating speed and position control, Proportion and Differential parameters of position controller are the same as Integral and Proportion parameters of speed controller respectively. And Integral of position controller changes from 0 to a value in a linear way both considering estimated position and analog position.

In the future, experiment will be done to see two main things: oscillation during speed control section to check whether the relation N between observer time constant τ_{obs} and position pulse interval T_1 is proper; Whether transition is smooth by seeing motor's current, speed and position response during transition. And obtain how to change integral of position controller during transition properly.

Reference

(1) Giangrande P, Cupertino F and Pellegrino G: "Modelling of linear motor end-effects for saliency based sensorless control," Energy Conversion Congress and Exposition (ECCE), 2010 IEEE, pp.3261-3268,Atlanta, GA(2010-9)

(2) Huikuri M, Nevaranta N, Niemela M and Pyrhonen J:"Sensorless Positioning of a Non-Salient Permanent Magnet Linear Motor by Combining Open-loop Current Angle Rotation Method and Back-EMF Estimator," Annual IEEE

Conf. on Industrial Electronics Society, No 10, pp.3142-3148,Vienna Austria(2013-10)

(3) L Kovudhikulrungsri, Koseki T: “Precise Speed Estimation From a Low-Resolution Encoder by Dual-Sampling-rate Observer,” IEEE/ASME Trans. on Mechatronics, Vol.11, No.6, pp.661-670(2006-11)

(4) Hiroshi Fujimoto, Yoichi Hori: “High Performance Servo Systems Based on Multirate Sampling Control,” IFAC Journal on Control Engineering Practice,Vol.10, No.7, pp773--781(2002-7)