A Low-Cost Position Sensing Technique for Linear Switch Reluctance Motion System

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Abstract:

This paper presents a novel position sensing system for a linear switched reluctance motor. By measuring the magnetic flux differences on the fixed tooth track using two coiled devices aligned 90 degrees out of phase, the position and direction information of the moving platform can be obtained. To increase the resolution 16 times its original tooth pitch, a novel non-sinusoidal waveform interpolation technique is employed. The proposed sensing system is designed, fabricated and implemented on a linear variable reluctance motor platform. Results show that the proposed sensing system can produce reliable position information with high accuracy and repeatability, and at high pulse output rate. The proposed position measurement method is useful for both phase commutation and servo position feedback of the Linear Switched Reluctance Motor.

1. Introduction

The purpose of this project is to develop a high-precision position sensing system for a new type of high-performance, direct-drive, linear variable reluctance motion actuator.

To eliminate the delicate and expensive linear optical encoder, position sensing for variable reluctance motors can be achieved through indirect position estimation or observer based position estimation. Indirect position estimation involves obtaining position from a second variable. Acarley et.al., first proposed to obtain position from current signal [1]. Since then, other variables have been used for indirect position estimation. These include flux [2], inductance [3], mutual inductance [4], and di/dt of PWM waveform [5]. Observer based position estimation has attracted less attention, due to its heavy computation demand. Works have been done in this area by Lumsdaine and Lang [6]. However, the above type of position sensing methods suffer from one or more of the following deficiencies:

1. Inoperative at low or zero speed.
2. Inaccurate during large speed dynamics.
3. Unreliable and give false readings when there are frequent direction reversals.
4. Cannot operate at high speed.

Therefore the above methods are unsuitable for high acceleration/deceleration trajectory control of limited stroke variable reluctance linear motor.

To overcome the above problems, this paper proposes to measure the inductance change on the tooth track of the linear variable reluctance motor to obtain the position information. The proposed method takes advantage of the fact that the variable reluctance linear motor is an "open structure" and inductance-sensing coils can easily be incorporated into the motor. Also, the tooth track is an ideal "ruler" for position measurement. To provide reliable position output under frequent direction reversals, two search coils are needed, and they should aligned 90 degrees out of phase.

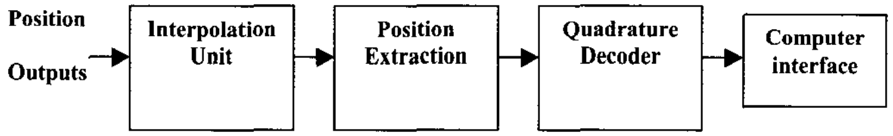

Fig. 1 The block diagram of the position sensing system

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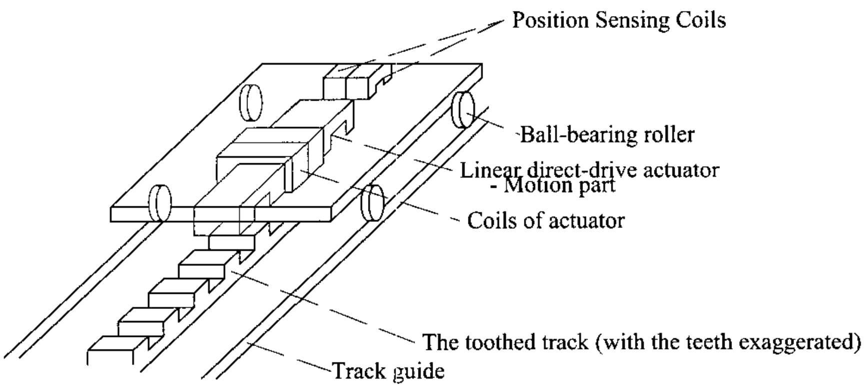

Fig. 2 Location of the position sensor in the linear VR drive system

2. Structure of the Position Sensing System

Fig. 1 and 2 show the block diagram of the position sensing system and its install location. In the actual system, the sensing coils are placed side by side instead of back to front. The sensor contains an E-shaped magnetic structure with a central drive tooth equal to the width of the pole pitch and two side sense teeth equal to the width of the pole width. The sense windings are connected in series-opposite polarity to produce a balanced ac output.

To provide reliable position output under frequent direction reversals, two sensors are needed, and they need to align 90 degrees out of phase. The sensor uses a drive coil to create an ac magnetic flux through its drive tooth, which then couples to the tooth track. Depending on the relative location of the toothed track and the sensor, varying amounts of flux will return through the two sense teeth such that its output is proportional to the difference of the flux in the two teeth. The cross-sectional view of the sensor and its actual photo is shown in Fig. 3a and Fig. 3b respectively. As a result, the sensor produces a near-sinusoidal waveform with a voltage output that is proportional to the travel of the sensor head.

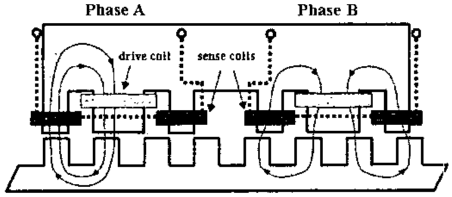

Fig. 3a Cross-section diagram of the position sensor

3. Signal Processing and Information Extraction

To measure the inductance variation of the tooth track, a low current and high frequency signal is injected into the sensing coils. This prevents errors due to hysteresis and saturation effects. A balanced output demodulator circuit shown in Fig. 4 is used to detect the change in the coupled flux. An output voltage, which is proportional to the position of the sensor head, is produced for each channel.

A total of 6 coils (four for the signal sensing, and two for the signal drive) are winded on the structure. For the sensing coils, the two coil pairs are connected in series, so that the net output signal from each of the coil pair gives the differential voltage sensing output.

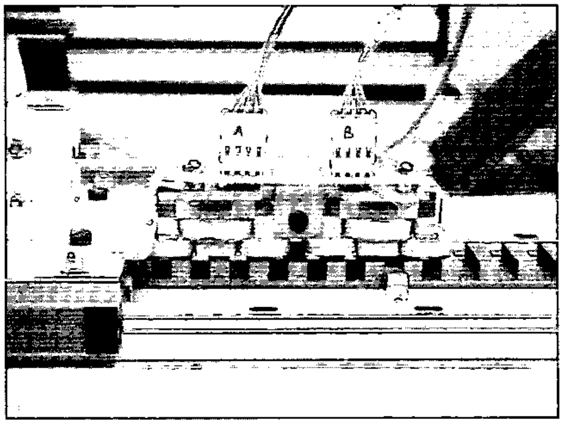

Fig. 3b Actual cross-section view of the position sensor

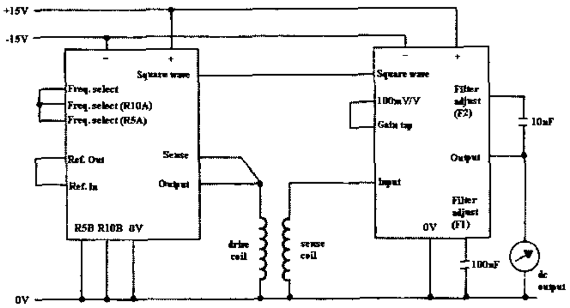

Fig. 4 Construction of the interface circuit

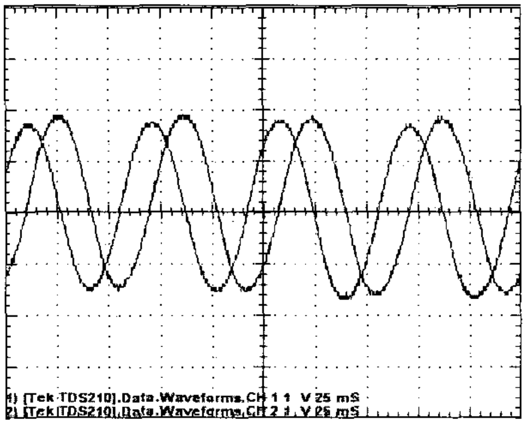

Fig.5 Two sensor output phase in 90° quadrature

Fig. 5 shows the relation between the output voltages of the two search coils and the tooth track position. Due to the nonlinearity of the magnetic circuit, the analogue waveforms are actually non-sinusoidal; therefore tradition circuits for sine-cosine interpolation cannot be applied. The two outputs from the sensing coils are then sent to the interpolation hardware to further divide the non-sinusoidal waveform to a higher resolution.

4. Resolution increase through sine-cosine interpolation

The resolution of the tooth track is inadequate for the linear motor's commutation process and the trajectory motions. To overcome this, a simple and effective method of resolution enhancement needs to be proposed and implemented.

In this paper, a simple and innovative method to obtain the vector angle of the sine cosine waveform is proposed. The proposed method uses very few components to accomplish the sine-cosine interpolation task. The method does not need to use an expensive resistor network, additional computing overheads, or data acquisition units.

The method takes advantage of the fact that both channel A and channel B waveforms decrease by the same ratio when the vector rotating speed is increased, and the shape of the semi-circular profile remains the same. Therefore, instead of comparing the waveforms to reference voltages, the two waveforms can be compared with each other to find out the angle of the rotating vector, and deduce the immediate position values. The problems of non-circular locus and signal variation at different speeds can be effectively eliminated.

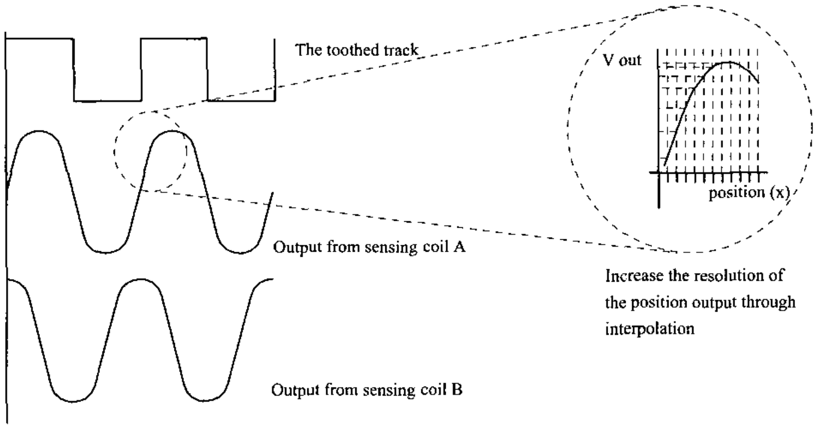

Fig. 6 Output Waveforms from the Phase Lock Loop Circuits

To provide maximum resolution enhancement while minimizing the circuit complexity, a 16-fold resolution enhancement is chosen. The interpolation unit divides the sine-cosine cycle into 16 sections, with an angular distance of 22.5° for each section.

Fig. 6 shows the concept of non-sinusoidal interpolation/sectioning. Due to the fact that both outputs are non-sinusoidal, the locus of the X-Y plot is not an ideal circle. After acquiring the two voltage levels from the phase lock loop outputs, a simple interpolation circuit is used to determine the angle of the rotating vector.

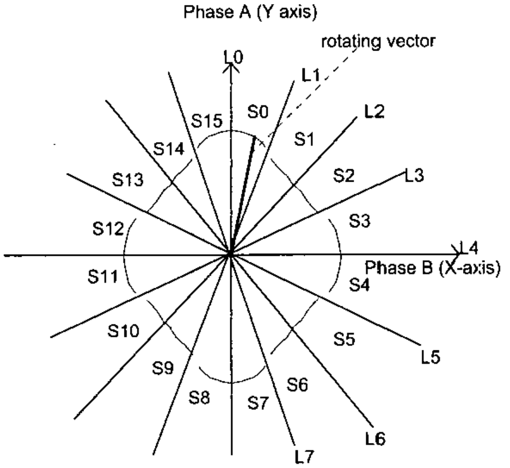

Fig. 7 16 times resolution increase, using non-sinusoidal interpolation/sectoring

The rotating vector diagram shown in Fig. 7 is sectioned into 16 equal parts. Boundary lines (L0-L7) are used to divide the 16 sectors (S0-S15). The boundary conditions of L0-L7 can be represented as:

$L0$: $Y=0$ (1)
$L1$: $X=0.414Y$ (2)
$L2$: $Y=X$ (3)
$L3$: $Y=0.414X$ (4)
$L4$: $X=0$ (5)
$L5$: $Y=-0.414X$ (6)
$L6$: $Y=-X$ (7)
$L7$: $X=-0.414Y$ (8)

The position of the search coils are represented by a rotating vector in figure 7. In this way the change of signal amplitude will merely change the magnitude of the rotating vector; the angle of the rotating vector remains the same. By testing boundary conditions of the rotating vector, one can find out which sector the rotating vector resides

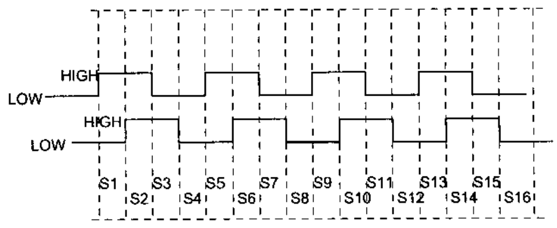

Fig. 8 The quadrature output waveform of the 16-fold interpolation unit

.By setting the conditions for each of the sector (e.g. S1 $\Rightarrow$ $Y>0$ and $X<0.414Y$) all 16 sectors can be identified. Since the interpolation unit is designed to be interfaced with conventional quadrature decoding unit, the interpolation unit should output 90° phase-shifted A-B digital pulse-trains, as shown in figure 8. The figure shows that for channel A, output is high at S1, S2, S5, S6, S9, S10, S13, and S14. For channel B, output is high at S2, S3, S6, S7, S10, S11, S14, and S15. These output criteria can be matched with the boundary conditions of figure 4, to form a table shown in figure 9.

Output	Input	Output Sector
Channel A	(x>0) & (y>x)	S1,S2 high
	(y<0) & (-y<x)	S5,S6 high
	(y<0) & (y<x)	S9,S10 high
	(y>0) & (-y>x)	S13,S14 high
Channel B	(0.414y<x) & (y>0.414x)	S2,S3 high
	(-y>0.414x) & (-0.414y<x)	S6,S7 high
	(0.414y>x) & (y<0.414x)	S10,S11 high
	(-y<0.414x) & (-0.414y>x)	S14,S15 high

Fig.9 Matching the output to the boundary conditions

Once this is obtained, the 16 sectors can be translated into A-B pulse-trains (with ×4 resolution increase), which in turn can be translated into up/down count pulses (with ×16 resolution increase) using standard logic hardware or ASIC implementation. Figure 10 shows the hardware block diagram of the interpolation unit. For the prototype, standard logic gates and operational amplifiers were used to construct the circuit. The present system uses 16 times interpolation enhancement. However, under the proposed method, sine-cosine interpolation units with much higher resolution increases can be designed in a similar manner.

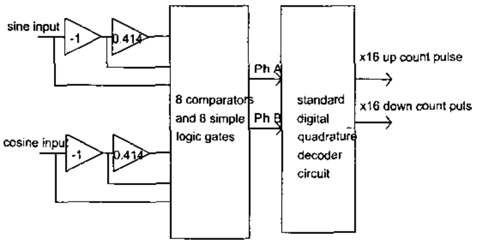

Fig. 10 Hardware block diagram of the 16 times interpolation unit.

5. Implementation and Results

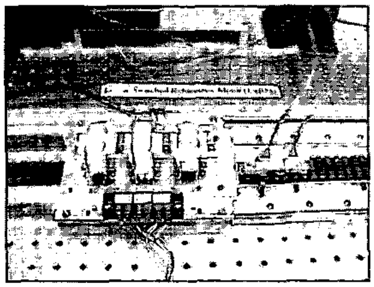

Fig. 11 The Linear Variable Reluctance Motor with integrated position sensor

The position sensing system has been designed, constructed and implemented on a linear variable reluctance motion platform, as shown in figure 11. Preliminary results show that the proposed sensing system can produce reliable position information with high accuracy and repeatability, and at high pulse output rate. The following results were achieved during preliminary testing:

Resolution output	250 micron
Tooth track pitch	4 mm
Repeatability error	> 50 micron

This kind of accuracy is already very useful phase commutation and motion control of the linear variable reluctance motor. Figure 12 shows the X-Y circular output function and the digital pulse train output from the position sensing system. This type of standard pulse train can be readily interfaced to the optical encoder input of a standard motion controller.

6. Conclusion

In this paper, a new method of sensing position from the tooth track of a linear variable reluctance motor is proposed. The method exploits the advantage of the open tooth track of the linear variable reluctance motor, and proposes to use sensing coils to measure the position through inductance variation.

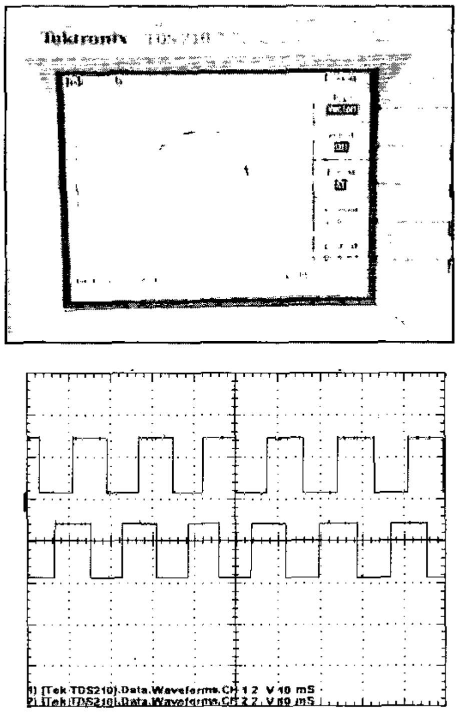

Fig. 12 The analogue output and the digital output from the interpolation decoder

A phase lock loop circuit is employed to extract the position information, and a novel yet simple interpolation method is used to increase the resolution of the tooth track 16 times. The proposed method has been implemented on a linear variable reluctance motor with a tooth pitch of 4mm. Preliminary results show that the position sensing system can output accurate and reliable position readings; and this information is useful for both commutation and motion control of the linear motor.

7. References

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8. Circuit diagram of the interpolation unit