Study on Signal Processing Technology of Relative Position Detection Sensor for High Speed Maglev Train

Cuicui Huang [a], Chunhui Dai [a], Guibin Luo [a]

[a] College of Intelligence Science
National University of Defense Technology,
Changsha, China. huangcui@163.com

***Abstract*—Relative position detection sensor is critical component for High Speed Maglev Train (HSMT) as they provide direction, speed, tooth-slot count and phase angle for traction system which drives maglev train. The traction system has higher requirements on the accuracy and stability of the phase angle signal. The demodulated wave signal directly affects the precision of the phase. In order to obtain higher accuracy of the demodulation signal, a demodulation approach based on an analog switch is proposed. The difference between early and present signal generating circuit is compared. Then the proposed demodulation method is analyzed mathematically. Moreover， the comparison between demodulation of the early sensor based on the analog multiplier and that based on the analog switch is implemented. A series of tests have been adopted to validate the performance of the proposed demodulation method and show that a more stable and accurate demodulation signal can be obtained.**

***Key words*: relative position detection sensor, signal processing, analog switch**

I. INSTRODUCTION

Relative position detection sensor is an important part of location and speed detection system for HSMT. And the precision and reliability of location and speed detection system depend on the relative position sensor [1~3]. Signal processing plays an important role in the performance of the sensor.

In the early relative position detection sensor, the modulation signal is demodulated by analog multiplier filtering circuitry. Its signal generating circuit includes a function waveform generator and a phase-locked loop frequency synthesizer and the circuit is complex. Moreover the detection coefficient of analog multiplier is low and this method has poor noise rejection [4].

The modulation signal of the present relative position detection sensor is demodulated by the analog switch. the signal generating circuit is constant frequency signal produced by crystal oscillator frequency division. Unlike prior work, its circuit is simple. The method present here seeks to improve the detection coefficient.

II. RELATIVE POSITION DETECTION SENSOR

As shown in Fig. 1, relative position detection sensor is mounted beside the suspension electromagnet of maglev train bracket arm, facing the surface of long stator and moving with the train.

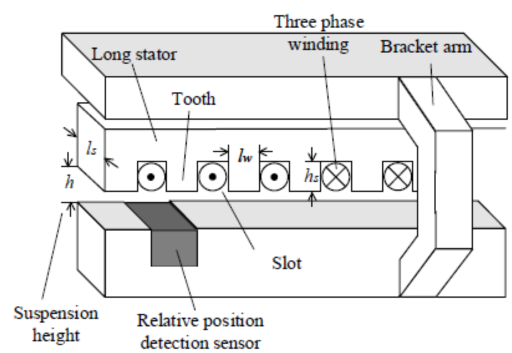

Figure 1. Relative position detection sensor and long stator

In the Fig. 1, l is the length of a tooth-slot structure of the long stator, which is 86mm. lw is the length of the long stator teeth, 43mm, which is half of the tooth-slot structure. A three-phase winding of a traction linear motor is embedded in the slot of the long stator.

The distance between the upper surface of the detection coil of the sensor and the long stator surface is equal to the suspension gap of the maglev train, usually 10mm [5], The long stator tooth-slots are made of silicon steel laminations with magnetoconductivity, while the traction three-phase windings are multi-core aluminum cables [6]. The magnetic permeability of aluminum is approximately 1. It does not have magnetic properties.

Relative position sensor is a kind of inductance type sensor, which is composed of two groups of '8' formed coils used to detect the tooth-slot structure on long stator. It is described in paper [7].

When the detection coil of the relative position sensor is close to the long stator, the magnetic field excited by the detection coil is bound to be affected by the lamination of the long stator silicon steel sheet, resulting in changes in the magnetic flux of the coil. According to the definition of the coil inductance, the detection coil flux chain is affected by the long stator tooth-slot structure, leading to the changes in the coil equivalent inductance. Therefore, this relationship can be used to detect the tooth-slot structure of the long stator to measure the position, which is the basic principle of relative position of the sensor measurement position.

The relative position sensor mainly consists of three parts: the detection coil, the analog signal processing board and the digital signal processing board. The analog signal processing board includes the signal generation circuit, demodulation circuit and ADC circuit.

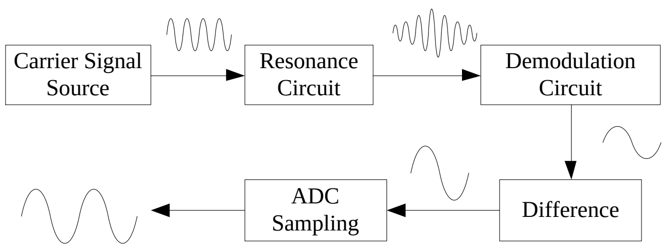

Figure 2. Signal processing flow of relative position sensor

Signal processing flow of relative position sensor is shown in Fig. 2. After the high-frequency carrier signal source from the analog board passes through the resonant circuit constituted by the detection coil, the carrier signal is modulated into a modulation signal. Then the modulation signal is demodulated by the demodulation circuit on the analog board, it becomes a low-frequency signal related to the position. And after the difference and amplification, the output signal is converted into a digital signal by the ADC sampling. The digital signal processing board further processes the obtained signal and sends the sensor data to the on-board signal processing unit through the communication interface. Multiple sensor information will be transmitted through the on-board signal processing unit.

The resonant circuit is formed by the detection coil and the shunt capacitor. Fig. 3 shows the equivalent circuit diagram of detecting coil. The circuit model can be approximated by the following circuit [8][9].

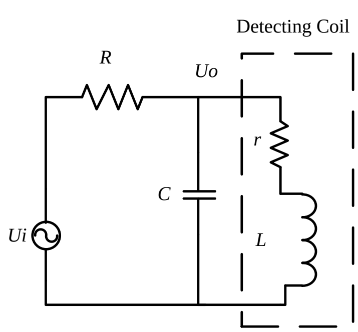

Figure 3. Equivalent circuit diagram of detecting coil

Applying a high-frequency excitation signal to the resonant circuit, resonant output signals can be obtained at both ends of the circuit and can be expressed as:

$$U_o = U_i \frac{1}{1 + R[j\omega C + 1/(j\omega L + r)]} \tag{1}$$

Inductance of the detection coils in the relative position detection sensor can vary with the changing position. The sensor acquires position by taking the relationship between coil inductance and position. Low-frequency signal related to the position can be obtained by the demodulation circuit.

Demodulation method based on analog multiplier is used in the early relative position detection sensor. In this paper a demodulation method based on analog switch is proposed. These two methods will be analyzed.

III. SYNCHRONOUS DEMODULATION BASED ON ANALOG MUTIPLIER

The modulation signal of the early relative position sensor is demodulated by the synchronous demodulation based on the analog multiplier. Synchronous demodulation based on the analog multiplier is analyzed mathematically.

A. *Acquisition of high-frequency carrier signals*

The main difference between the early relative position sensor and the optimized relative position sensor is the signal generation circuit and the detection circuit. For signal generation circuit, early relative position sensors used a signal generation chip with a phase-locked loop to generate a 1 MHz to 10 MHz constant-frequency signal. The optimized relative position sensor uses a crystal oscillator to obtain a constant frequency signal. The acquisition method of the carrier signal has no effect on the working principle of the sensor.

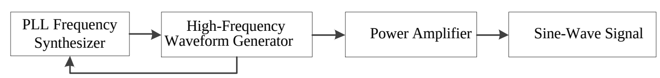

Figure 4. Signal generation circuit of the early relative position sensor

As shown in Fig. 4, the signal generation circuit of the early relative position sensor uses a phase-locked loop frequency synthesis chip combined with a high-frequency waveform generator to form a closed-loop system, which can generate a stable frequency sine-wave signal.

B. *Working principle of the detction based on analog mutiplier*

The early relative position sensor demodulated the modulation signal based on the synchronous detection method based on analog multiplier. The principle of synchronous demodulation is to input signal and amplitude modulated signal into analog multiplier simultaneously. It is assumed that the signal source is expressed as $U_0 = A_0 \cos(\omega_0 t)$, the amplitude modulated signal is $U_e(t) = A_e \cos(\omega_0 t + \varphi)$, in which the ω_0 is the carrier angle frequency, and the phase difference between the two signals is φ, and the A_0 and A_e are the amplitude of the signal source and the amplitude modulated wave signal respectively, and the two signal multiplies can be obtained.

$$\begin{aligned} U_A(t) &= U_o(t)U_e(t) = A_0 \cos(\omega_0 t) A_e \cos(\omega_0 t + \varphi) \\ &= \frac{A_0 A_e}{2}\cos(\varphi) + \frac{A_0 A_e}{2}\cos(2\omega_0 + \varphi) \end{aligned} \tag{2}$$

Where, φ is the phase difference of two signals, which is a constant, so the product signal consists of a direct current (DC) signal and a high frequency alternating current signal. After the low-pass filter, only $\frac{A_0 A_e}{2}\cos(\varphi)$ the DC component is left. The amplitude A_e of the modulation signal is a function of position, so the position can be measured according to this DC component.

IV. ENVELOPE DETECTION BASED ON ANALOG SWITCH

A demodulation method based on analog switch is proposed in the signal processing of the relative position detection sensor and mathematical analysis is conducted. Then the comparison between demodulation of the early sensor based on the analog multiplier and that based on the analog switch are implemented.

A. Acquisition of high-frequency carrier signals

The new relative position sensor directly uses the square wave signal as the excitation signal of the resonant circuit. Signal generation circuit of the new relative position sensor is showed in Fig. 5.

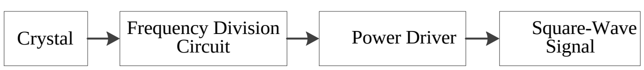

Figure 5. Signal generation circuit of the new relative position sensor

A constant frequency signal of optimized relative position sensor is obtained by using a crystal oscillator. The acquisition method of the carrier signal has no effect on the working principle of the sensor. Both methods can obtain a signal with stable frequency.

B. Working principle of the detction based on analog switch

The essential difference between the old and new sensors is the detection circuit, which means that the output position signal is obtained in different ways.

An LC resonance circuit is formed by the coil and parallel capacitance. By applying constant frequency and constant amplitude high frequency excitation, a constant frequency and amplitude modulated signal will be obtained at the output of the resonant circuit.

The synchronous detection method based on analog switch is equivalent to the multiplication of modulation signal and square wave, and the equation of square wave can be expressed as

$$U_s = \begin{cases} 1 \quad ,(0 < t \le \frac{\pi}{\omega_0}) \\ -1 ,(\frac{\pi}{\omega_0} < t \le \frac{2\pi}{\omega_0}) \end{cases} \tag{3}$$

Where ω_0 is the angular frequency of the modulated signal. The square wave signal and the modulated signal are in the same frequency and the same phase.

The optimized relative position sensor uses a synchronous detection method based on analog switch. The modulation signal first passes through an analog switch and becomes a half-wave signal. The switch control signal of the analog switch is obtained by dividing the excitation signal source and has the same frequency as the modulation signal.

The optimized relative position sensor adopts synchronous detection mode based on analog switch. The modulation signal is transformed into a half wave signal after passing through analog switch. The switch control signal of the analog switch is obtained by dividing the excitation signal source with the same frequency as the modulation signal.

Assuming that the modulation signal is expressed $U_e(t) = A_e\cos(\omega_0 t)$, the modulation signal is pressed after analog switching multiplier:

$$U_e(t) = \begin{cases} A_e\cos(\omega_0 t) \quad ,(\frac{n\pi}{\omega_0} < t \le \frac{(n+1)\pi}{\omega_0}) \\ -A_e\cos(\omega_0 t) \ ,(\frac{(n+1)\pi}{\omega_0} < t \le \frac{(n+2)\pi}{\omega_0}) \end{cases} \tag{4}$$

After passing through the low-pass filter, only the DC component is left, and the position information can be obtained according to this DC component. The synchronous detection circuit based on the analog switch is shown in Fig. 6, and the waveform is shown in Fig. 7.

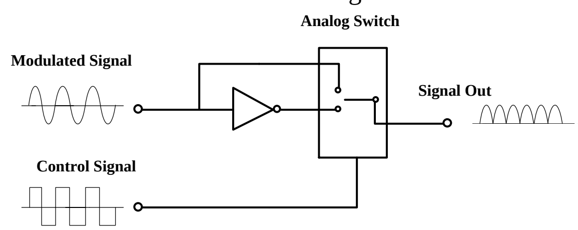

Figure 6. A demodulation method based on analog switch Signal processing flow of relative position sensor

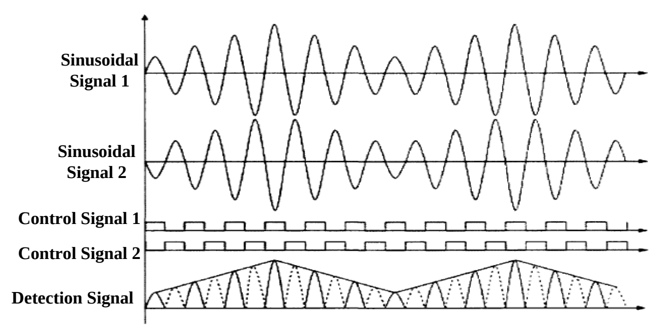

Figure 7. Detection signal waveform

However, because the resonant circuit is a LC circuit, when the change of the tooth-slot position leads to the inductance change of the coil, the resonant circuit will deviate from its no-load resonance. According to equation (1), the phase of the modulation signal will shift relative to the carrier signal, and the offset will change with the inductance changing. When the resonant circuit is completely in resonance, the phase offset is zero. The phase relationship between the modulation signal and the carrier signal is shown in Fig. 8.

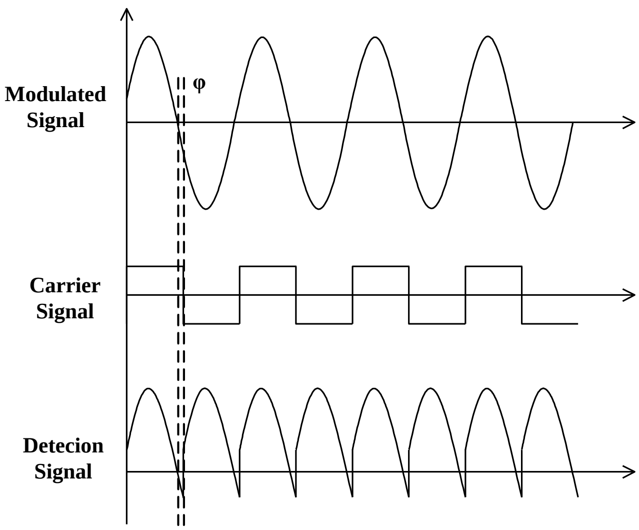

Figure 8. The phase relationship between the modulated signal and the carrier signal

Due to the phase difference between the modulation signal and the carrier signal, the expression of the detection signal becomes:

$$U_e(t) = A_e \cos(\omega_0 t), \quad (-\frac{\pi+\varphi}{2\omega_0} < t \le \frac{\pi+\varphi}{2\omega_0}) \qquad (5)$$

where, A_e is the peak value of the detection signal, and the Fourier series of the above equation is obtained again.

$$U_e(t) = \frac{2A_e}{\pi}\cos\varphi + \sum_{n=1}^{\infty}(b_{2n}\cos\varphi\cos(2n\omega_0 t) + a_{2n}\sin\varphi\sin(2n\omega_0 t)) \qquad (6)$$

The influence of the phase difference on the demodulated signal can be found by comparing Equation (5) and Equation (6). The phase difference causes the amplitude of the demodulated signal to become the original cosφ times. When $\varphi \neq 0$, cosφ<1, that is, the phase difference reduces the detection coefficient of the detector. This is the same as the synchronous demodulation based on the analog multiplier.

It is assumed that the analog multiplier-based synchronous detector carrier signal is the same as the analog switch-based synchronous detector carrier signal. Comparing the two detection coefficients to further compare the pros and cons of the two detectors, the results are shown in Table I.

TABLE I. DETECTION COEFFICIENT OF THE TWO DETECTORS

Detection Type	Detection Coefficient
analog multiplier	$\frac{1}{2}\cos\varphi$
analog switch	$\frac{2}{\pi}\cos\varphi$

Compared with the synchronous demodulation method based on the analog multiplier, the detection coefficient of the synchronous demodulation method based on the analog switch is 1.27 times that of the analog multiplier detection circuit.

Moreover, the analog multiplier requires a phase-locked loop circuit in order to obtain a stable sinusoidal carrier signal, and the circuit is relatively complicated. There is Low requirements for detection signals in the analog switch circuit and the circuit requires only square wave signals with the same frequency and phase. The analog switch can directly use the excitation source signal as a switching control signal. The circuit is simple and the cost is lower. Compared with sinusoidal signals, the square wave signal has stronger anti-interference ability, so the circuit is more stable. It is found that the demodulation based on analog switch has the advantages of high detection coefficient and simple circuit structure.

V. SIGNAL PROCESSING OF RELATIVE POSITION DETECTION SENSOR

Signal of relative position detection sensor is processed by the demodulation method based on analog switch. When the detection coil moves in a straight line over the long stator, the equivalent inductance of the detection coil changes periodically due to the special tooth-slot structure of the long stator. Fig. 9 shows the change of equivalent inductance measured by the coil in a tooth-slot cycle when it is 10mm away from the surface of the long stator.

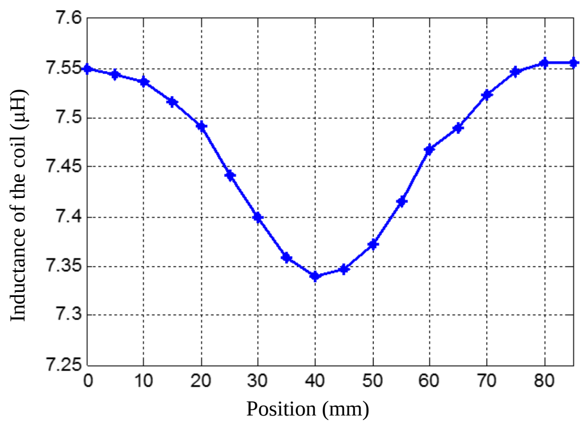

Figure 9. The change of equivalent inductance measured by the coil in a tooth-slot cycle

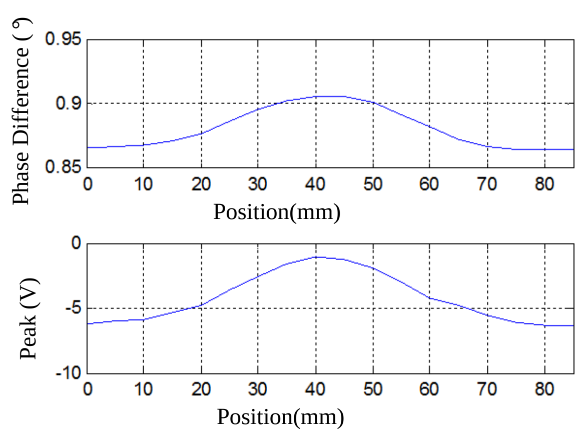

Figure 10. The change of the peak value and phase difference of the resonant signal in a tooth-slot period

According to equation (1), the modulated signal output by the resonant circuit can be calculated. Both the amplitude and the phase of the modulated signal will be affected by the change of the coil inductance. The phase difference between the peak of the output modulation signal of the resonant circuit and the modulation signal and the carrier signal varies within one tooth-slot period, as shown in Fig. 10. This article stipulates that the central axis of the tooth in the long stator tooth-slot structure is used as the starting point of the position in one tooth-slot cycle, that is the origin of the horizontal axis in the figure.

According to Equation (6), the demodulated signal after the detection signal passes through the low-pass filter can be obtained. The variation of the demodulated signal in one tooth-slot period is shown in Fig. 11. So far, according to equation (5) and equation (6), the analytical solution between the coil inductance and the demodulated signal can be expressed as:

$$U_d = \frac{2}{\pi}\left|\frac{A_0}{1+R[j\omega C+1/(j\omega L+r)]}\right|\cos(\varphi) \qquad (7)$$

$$\varphi = \angle\frac{A_0}{1+R\left[j\omega C+1/\left(j\omega L+r\right)\right]} \qquad (8)$$

According to the above analysis, the equivalent inductance of the detection coil changes periodically with the position, and the demodulated signal is only related to the inductance. It can be concluded that the demodulated signal is a position-dependent periodic signal. The relationship between the demodulated signal and the tooth-slot location is shown in Fig. 11.

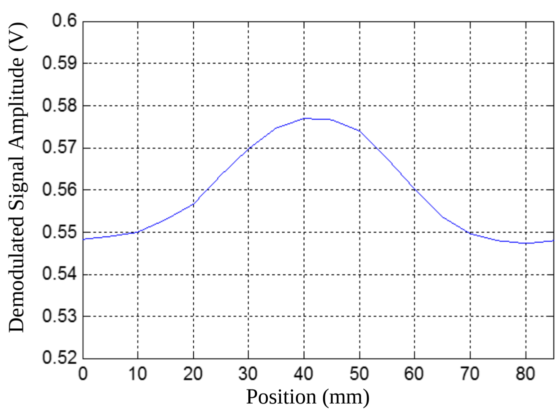

Figure 11. Relationship between demodulated signal amplitude and position

Finally, after proper amplification and processing, the output signal of the sensor can be obtained, as shown in Fig. 12. The output signal is sampled by ADC and processed by digital board.

The relative position sensor has two sets of detection coils having a difference of 1⁄4 tooth-slot, so the output signals differ in phase by 90 degrees. The corresponding relationship between the two-way signal and the long stator tooth-slot. By processing the sine waves that differ by 90 degrees, the direction, tooth-slot count, speed, and phase angle information can be derived.

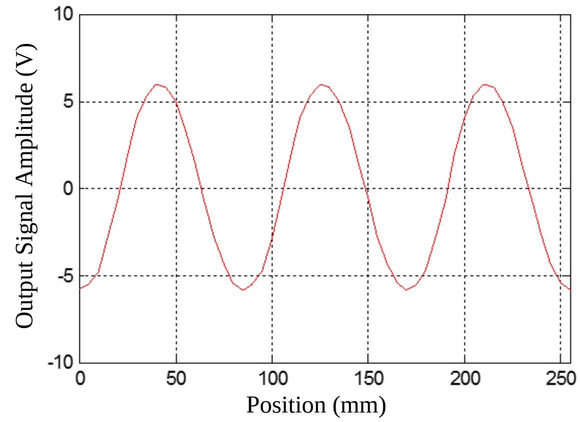

Figure 12. Relationship between output signal amplitude and position

VI. CONCLUSION

This chapter first introduced the basic principle of the relative position sensor and the signal processing flow. Then the demodulation process of the relative position sensor based on analog multiplier is analyzed. A synchronous demodulation method based on analog switch is designed and compared with the original one. The mathematical analysis shows that the detection coefficient of the synchronous demodulation method based on the analog switch is 1.27 times that of the multiplier detection circuit. The tests of signal processing of relative position detection sensor proved that the signal processing algorithms and scheme based on analog switch is feasible and effective.

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