Position Sensing and Signal Transmission of Linear Synchronous Motor for High Speed Maglev

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ABSTRACT: Maglev train is an application of linear synchronous motor (LSM) in which the mechanical motion is in synchronism with the magnetic field. To achieve high performance motion control with a LSM, a position sensor is typically required. On the investigation of Shanghai Maglev from Pudong airport to Longyang Rd, the motion control of LSM is realized by thrust and speed closed loop control with a feedback of rotor position. Because of the special characteristic of LSM, magnetic encoders replace the typical optical encoders. This paper analyses the merits and shortcomings of the magnetic sensors, and introduces a new design for improvement, one testing technology of position by inductive sensors and a topology of the sensors. The propulsion system of the maglev train is located not on the vehicles but along the track, it is a synchronous long stator linear propulsion system. The stator is integrated in the guideway. A three-phase winding is fitted in the stator-laminated core and this winding is attached to the two bottom sides of the guideway. The rotor of the synchronous machine is in the form of magnets fitted in linear fashion along the vehicle. As the maglev train moving on the track, the position signals getting from the sensors must be transmitted to the propulsion system through a long distance and a series component, errors may occur during this process. Several innovations adopted in position signals transmission are discussed, which improve the precision and robustness. The Shanghai Maglev Transportation systems are composed of four main parts, Maglev Vehicle, Maglev Guideway, Operation Control System, and Propulsion Control System. The position feedbacks needed for closed loop control are continuously transmitted to OCS and PCS while the maglev vehicle running along the guideway. In addition, an original method processing the position signals is applied, which increases the reliability and redundancy.

1 INTRODUCTION

Shanghai Maglev, from Pudong airport to Longyang Rd, is an application of linear synchronous motor (LSM) in which the mechanical motion is in synchronism with the magnetic field. Unlike the traction system of conventional wheel-on-rail systems, the propulsion system of the maglev train is located not on the vehicles but along the track. It is a synchronous long stator linear propulsion system. An idea of the linear motor can be derived from a rotating machine cut open along its axis of rotation and unrolled lengthwise. The rotor of the synchronous machine is in the form of magnets fitted in linear fashion along the vehicle. These magnets simultaneously generate the vehicle's magnetic levitation field. The stator is integrated in the guideway. A three-phase winding is fitted in the stator-laminated core and this winding is attached to the two bottom sides of the guideway, as shown in Figure 1. In accordance with the principle of electromagnetic levitation, the magnetic fields generate forces of attraction between the support magnets on the vehicle and the stator-laminated core. As a result, the vehicle is pulled towards the guideway and maintained in a hovering position.

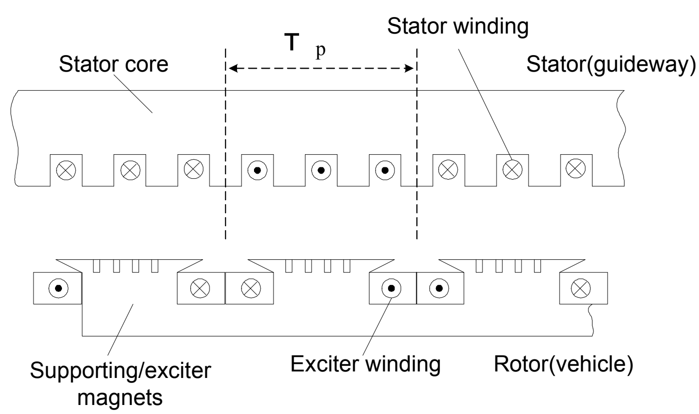

Figure 1. Structure of the long stator linear synchronous motor

In contrast to the rotating synchronous machine, the synchronous long stator linear motor has the following special features: Due to the combination of supporting system and propulsion system, excitation of the motor is mainly determined by the vehicle's weight, and the thrust can be influenced only by the magnitude and phase angle of the stator current.

To reduce the energy consumption, the long stator winding of the guideway is divided into sections. Only that section in which the vehicle is running is supplied with three-phase current of variable frequency and amplitude by converters installed in substations, which are distributed along the guideway.

To achieve high performance motion control with a LSM, a position sensor is typically required. The motion control of LSM is realized by thrust and speed closed loop control with a feedback of rotor position. Because of the special characteristic of LSM, magnetic encoders replace the typical optical encoders. Merits and shortcomings of the magnetic sensors are discussed, and a new design is introduced, one testing technology of position by inductive sensors and a topology of the sensors. The position sensing system is composed of four inductive encoders installed on the vehicles, a series of position flag board installed on the guideway, and code reader on the vehicles.

As the maglev train moving on the track, the position signals getting from the sensors must be transmitted to the propulsion system in substations through a long distance by the train radio communication system. The radio control units along the guideway get these signals, and then send them to the propulsion system by RS485.

Errors may occur during this process. Several innovations adopted in position signals transmission are discussed, which improve the precision and robustness. In addition, an original method processing the position signals is applied, which increases the reliability and redundancy.

2 POSITION SENSING AND SIGNALS TRANSMISSION

2.1 Inductive Sensor Topology

Magnetic encoders utilize magneto-resistive (MR) sensing elements and magnetically salient targets. The magnetically salient target is a long, alternatively magnetized ruler. The MR sensor resistance changes as the magnetic field excited by the passing salient target changes its polarity. The sensor output voltage reflects changes of sensor resistances. Processing it can produce the position signal.

As compared with optical sensors, magnetic sensors are characterized by simplicity, reduced sensitivity to contamination, robustness and low cost.

One disadvantage of magnetic encoders is their sensitivity to external magnetic fields and temperature changes. Sometimes, the magnetic noise can exceed the sensor-generated signal up to one order of magnitude.

As shown in Figure 1, the long stator is made up of laminated silicon core with three-phase winding fitted in. the stator core is made of a tooth-slot structure. So a new design of inductive sensor based on the long stator is introduced as follows, show in Figure 2:

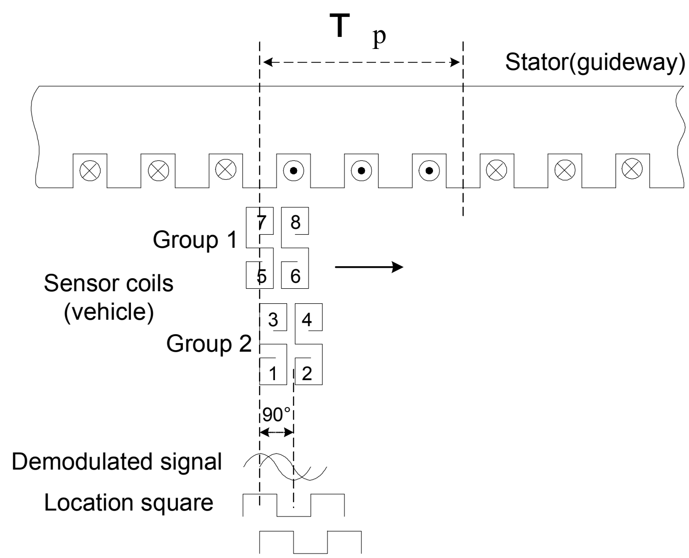

Figure 2. Topology of the sensor coil

Firstly, assume that the suspension gap is constant.

When the inductive sensor is above a tooth or a slot respectively, the gaps between the sensor coil and the laminated silicon core are different which makes the equivalent inductance of the sensor change. The sensor transmits signals of a certain frequency as it moving above the long stator flatly, the amplitude of the sensor signals will vary regularly because of the change in equivalent inductance of the sensor. The demodulated signal of amplitude change is similar to sine wave. By comparing the sine wave with a certain threshold, Location Square can be gotten. Counting the edge of the square wave, the location signal can be gotten. Phase angle of the stator current in one tooth-slot can be figured out though processing of the sine wave signal. The synchronous speed of the motor is determined by the pole spacing τ_p = 0.258 m and the frequency f of the stator current, as the following formula.

$v=2 \cdot f \cdot \tau_p$

The inductive sensors are composed of 8 coils, the width of each coil equals half-length of a tooth-slot to increase signal intensity. So does the space between Coil 1 and coil 2, which assures that when one coil is right above a tooth with the highest equivalent inductance value, the other coil is right above a slot with the lowest equivalent inductance value. This is easy for processing and eliminating disturbances. The space between group 1 and group 2 equals quarter length of a tooth-slot, which produces sine wave signals with 90° phase difference.

Inductive sensors can withstand more severe vibrations, and are perceived to be more reliable. In addition, these devices have lower power requirements, good performance characteristics and are well suited for high-speed maglev train.

2.2 Absolute Position Sensing

The inductive sensors can detect the rotor position (vehicle) and phase angle of stator current. It's a relative position on the guideway. The topology of absolute position sensing system is introduced as follows, shown in Figure 3.

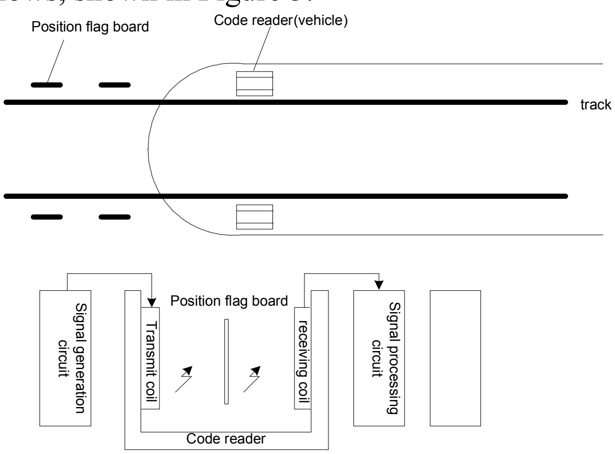

Figure 3. Topology of absolute position sensing system

The Position Flag Boards are placed along the track, which are plastic boards with copper middle layer. Each board has its unique narrow gap, each gap corresponds a binary code, containing the absolute position information.

The coder reader is placed on the vehicle with a U type structure. Induction coils are placed symmetrically on both sides of the reader. When the vehicle moves along the track, the code reader sans the PFBs. Signal generation circuit sends e electromagnetic waves through the transmit coils, part of the wave pass through the narrow gap on the PFB and reach the receiving coils. Signal processing circuit get these signals through the receiving coils and make absolute position out of them. Each time the vehicle passing a PFB, the relative position must be cleared to eliminate the accumulative error.

2.3 Transmission of Speed and Position Signals

The propulsion system of the maglev train is located not on the vehicles but along the track. The stator is integrated in the guideway. The rotor of the synchronous machine is in the form of magnets fitted in linear fashion along the vehicle. As the maglev train moving on the track, the position signals getting from the sensors must be transmitted to the propulsion system through a long distance. A radio communication system is adopted, as shown in Figure 4.

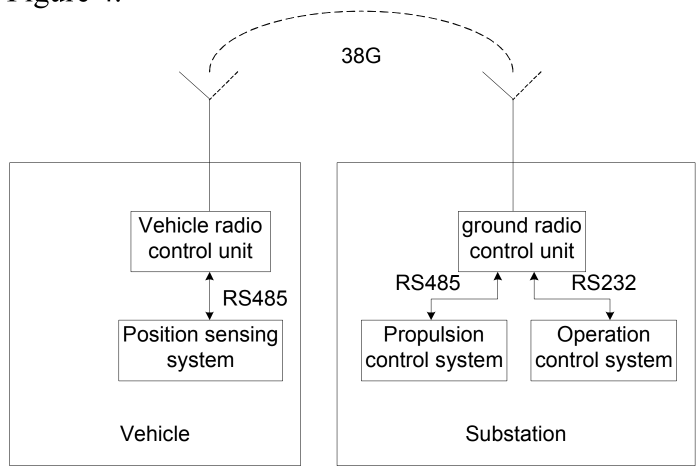

Figure 4. Structure of the radio communication

The system adopts 38Ghz radio, which realizes the communication between the vehicle and substation. The position sensing system is composed of inductive sensor and absolute position sensing system, which is depicted in detail before. The relative and absolute position signals are coded one packet by the vehicle radio control unit and sent to the ground radio control unit through the 38G communicating channel. The GRCU transmit these signals to PCS and OCS by RS485 and RS232 respectively.

As this process takes a long distance and involves a series of components, errors may occur during the transmission. To avoid interference and disturbance of the signal, several innovations are adopted. A redundant design of hardware is shown in Figure 5.

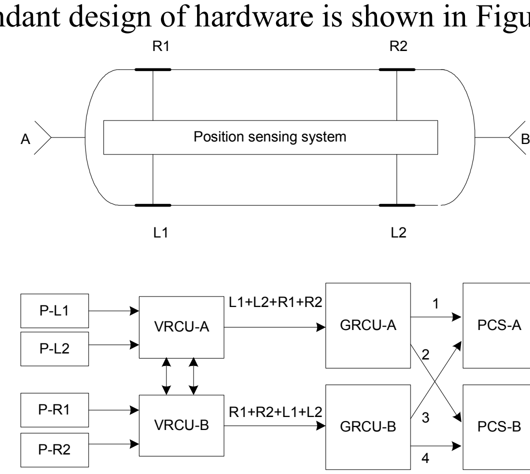

Figure 5. Topology of the transmission channel

Four inductive sensors, L1, L2, R1, R2, are placed on the vehicle. The position sensing system get these signals from left side and right side sensors of the vehicle, and send them to VRCU. Two VRCU are placed on the vehicle, which realize two communication channels, channel A and channel B, to GRCU in substation. The RS485 between GRCU and PCS are increased to four channels, which improve the robustness of the system. Once there is an error in one communication channel, the system will switch to another channel.

The software of the system is also optimized, the data frame transferred between VRCU and GRCU are expanded to 36 bytes to accommodate the position information provided by redundant sensors, as shown in Figure 6.

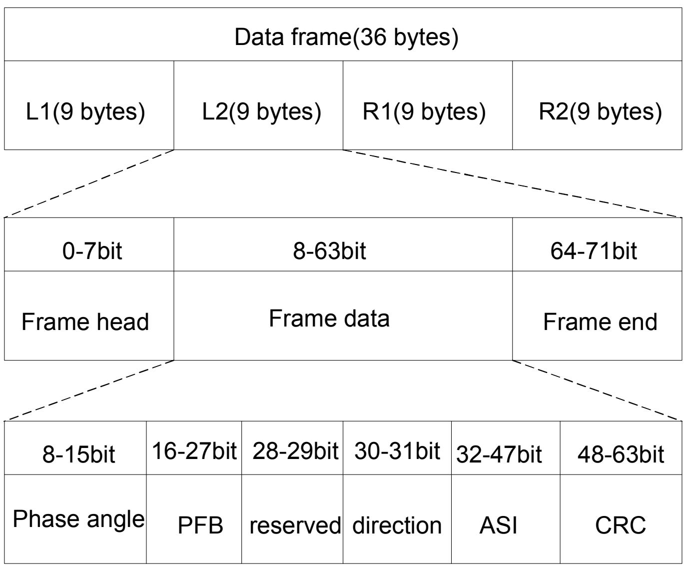

Figure 6. The coded data frame of position signal

The length of data frame is 36 bytes. Each sensor takes 9 bytes with the same data structure. The frame data is composed of phase angle, binary code of position flag board, direction, ASI and CRC.

If there is an error, the bit 8 will be set as 0. Only when it is set as 1, the phase angle is valid. The resolution of the value is 360° /2^7, each time the vehicle passing a PFB, the phase angle must be cleared and restart accumulation. If bit 16 is 0, it means the PFB is on the left side of the track, if bit 16 is 1, the PFB is on the right side. Bits 17-27 are the BCD code of the PFB corresponding to the absolute position of the maglev train. Bits 30-31 demonstrate the vehicle running direction. ASI is the relative position of the vehicle. If bits 30-31 are set as 11, the vehicle runs at positive direction, ASI will increase 1 every time the phase angle accumulate to 2^7. If bits 30-31 are set as 00, the vehicle runs at negative direction, ASI will decrease 1 every time the phase angle reduce to 0. ASI must be cleared once the vehicle passing a PFB. The CRC code is added at the end of the frame data to guarantee the precision and accuracy of the transmission data.

Take the PCS-A as an example, it receives data frame L1+L2+R1+R2 and R1+R2+L1+L2 from GRCU-A and GRCU-B through channel 1 and channel 3. At first, PCS-A chooses data frame from channel 1. It gets position and speed information from L1 only after CRC checking is right. If CRC of L1 is wrong, it will check that of L2, R1 and R2 respectively, and choose a right one instead. When all these values of CRC are wrong, PCS-A will accumulate the error number. If the CRC checking is right in next period, the error number will be cleared. But if the CRC values are still wrong in next period, the error number increases. After three periods lost of transmission data or the error number is bigger than two, PCS-A chooses data frame from channel 3 instead of channel 1. Similarly, if the same thing happens, PCS-A switches back to channel 1.

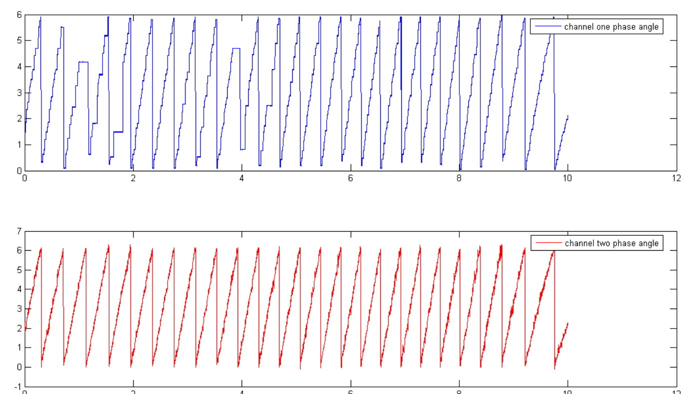

Figure 7. The phase angle wave of channel 1 and 3

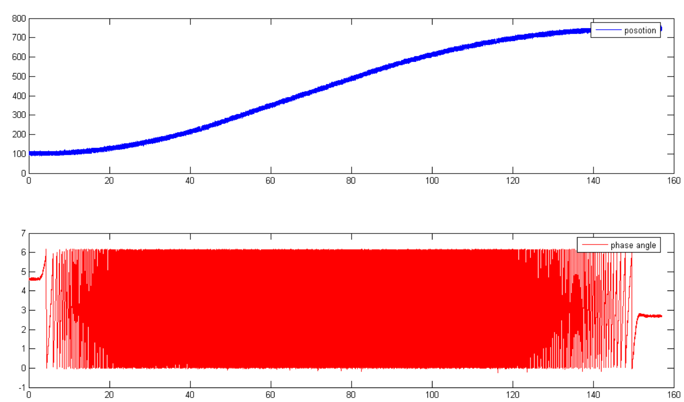

Figure 8. The wave of phase angle and position

3 EXPERIMENTAL RESULTS

In order to prove the effectiveness of the sensing system and the redundancy of the communication system, experiments are carried out, in which the

PCS-A tracts the vehicle running along the guideway. The position signals from channel one and channel three are output by PCS-A. A wave recorder records both signals. The waveforms are shown in Figure 7 and Figure 8.

Figure 7 shows the waveforms of the phase angle, which comes from channel 1 and 3. The wave above is channel 1's signal; the one bellow is channel 3's signal. PCS-A chooses channel 1 first. The wave is a series of triangle saw tooth. As the vehicle moves, the wave increases from zero to its maximum value 2π, and then restarts accumulation from zero again. The frequency of the wave reflects the moving speed. As the channel 1 signal shows, there are several platforms during the process, while the signal wave of channel 3 is still increased, which is caused by an error in channel one. It must be continuous CRC wrong or lose of communication in a short time. The PCS-A chooses channel three instead.

Figure 8 shows the waveform of phase angle and position. The position can be figured out by following formula.

$S = (PA/128+ASI)\ 2 \cdot \tau_p + PFB$

S-the position of the vehicle

PA-the value of phase angle

The resolution of S is millimeter, which suits the high-speed maglev well.

As the vehicle running, the position wave increases until the vehicle stops, which demonstrates the vehicle moves from 100 to 750 meters in about 150 seconds at the positive direction. The results prove the effectiveness of the sensing and transmission system.

4 CONCLUSIONS

Maglev train is an application of linear synchronous motor (LSM). This paper introduces a new design of position sensing system composed of inductive sensors, position flag board and code reader. The experimental results demonstrate the effectiveness of the position sensing system. Several innovations of hardware and software are adopted in position signals transmission and processing, which improve the precision of the data, and increase the reliability and redundancy of the system.

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