Optimal Design of Gap Sensor for High-Speed Maglev Train

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Abstract. The gap sensor plays an important role in high-speed maglev train which is able to measure the variation of trains’ suspension gap. The magnetic fields distribution is different clearly when the sensor is opposite to different position in a tooth-groove period of stator railway. The fluctuation of equivalent inductance leads to the slot-effect. The slot-effect is an important factor affecting the stability of the high-speed maglev train suspension control system. The distribution of magnetic field intensity of the flat rectangular coil in different gaps and positions is analysed, and the mechanism of slot-effect is revealed. A new coil is proposed in this paper and this optimized coil can create a smaller slot error than the flat rectangle coil. The simulation results show that the slot error of optimized coil is always less than the error of original coil in any gap distance. The slot error is reduced by half at the working air gap from 8mm to 12mm. The slot error of the optimized coil reaches a maximum at 2mm and reaches its minimum at the rated suspension gap 10mm.

1. Introduction

As an idea vehicle on land, high-speed maglev trains have particular characteristics, including high speed, lower energy consumption, low noise, safety and comfort [1][2]. The high-speed maglev train has been successfully operated in Shanghai for many years. The maglev train is driven by the long stator linear synchronous induction motor. The maximum speed can reach up to 500km/h.

The high-speed maglev train cannot be stably levitated without an accurate gap signal. The gap sensor is mounted between two support magnets as shown in Figure 1.

![Figure 1. Position of gap sensor in the maglev train system](image-url)
The levitation gap sensor provides the levitation air-gap distance from 0mm to 20mm between the support electromagnet and the stator railway. The gap sensor plays an important role for electromagnetic suspension system which is a critical component of high-speed maglev train. So, it is very important to study and improve the performance of the gap sensor for the development and implement of the maglev vehicle technology.

The detection object of gap sensor is long stator with tooth-groove structure. Because eddy current could not be generated in the stator railway constituted of silicon steel sheets, the eddy current displacement sensor could not work well in this situation. An inductive gap sensor is employed because of its high sensitivity and non-contact measurement. However, it is difficult to be applied in the situation that the detection object has an uneven surface. The simulation and experimental results show that the magnetic fields are different clearly when the sensor is opposite to different position in a tooth-groove period of stator railway. The fluctuation of equivalent inductance leads to the slot-effect. The slot-effect is an important factor affecting the stability of the high-speed maglev train suspension control system. When the slot-effect is too large, the control system will be unstable or even divergent. The slot-effect will seriously threaten the safety of the train and the safety of passengers when the train is running at high speed.

Many researches have been carried out on the slot-effect of the gap sensor. The three-dimensional coil geometry has been analysed and optimized to reduce slot error\[3\]-\[4\]. A compensator was designed to eliminate the slot-effect \[5\]. The compensator of the RBF neural network and T-S fuzzy neural network has been established to compensate for the error of the sensor slot \[6\]-\[7\]. The multi-sensor information fusion technology has been used in the gap sensor. There are two redundant sensors at the same suspension point and the two gap signals are processed by iterative algorithm \[8\]. Another detection coil structure consisting of two coils with a range of 180 degrees has been proposed. When one coil is opposite to the tooth, the other one must be opposite to the groove. Thus, the slot-effect of the two coils has been reduced \[9\]. In this paper, a new coil is proposed and this optimized coil can create a smaller slot error than the flat rectangle coil

2. Slot-effect of the rectangle sensor coil

An inductive magnetic sensor is employed for gap detection when high-speed maglev trains are moving forward. Any variation of air-gap distance would affect the coil inductance. If the relative permeability $\mu_r$ of the material is assumed to be infinitely large and linear, the influence of the flux guiding structures can be neglected. The inductance characteristic can be defined as follow:

$$L(\delta) = \frac{n^2 \mu_0 S}{\delta}$$

(1)

The parameter $n$ represents the number of coil windings, $S$ is the coil area, $\mu_0$ is the magnetic permeability of free space and $\delta$ is the width of the air-gap between the coil and the detected object. Because the inductance $L$ is in inverse proportion to air gap $\delta$, the sensor has a highly nonlinear response characteristic.

Since the gap sensor is mounted between the magnets, the sensing coil has to be design as a flat rectangle, as shown in Figure 2.

Figure 2. Detecting coil and groove-tooth stator
The detection coil is simplified as a rectangular ABCD. The length of AB is just a groove-tooth stator cycle and the length of BC is less than the width of the stator. At any position, the projection of the coil on the track is always a whole tooth and a whole groove. The stator surface includes tooth and groove. If normal inductive sensor with flat rectangle coil is applied in this situation, the inductance calculated in different gaps from 0mm to 15mm and different position is shown in Figure 3.

![Figure 3. Equivalent inductance slot-effect in different gaps](image)

From Figure 3, it may be observed that the measurement accuracy of gap sensor is directly impacted by the air gap as well as the dynamic position on the groove-tooth stator. When the position is 0mm, it indicates that the coil center is facing the center of the groove. When the position is 43mm, it indicates that the coil center is facing the center of the tooth.

In order to show the relationship between the inductance and position in the different gaps clearly, the relationship curves for different gaps are plotted separately in Figure 4.

![Figure 4. Separate relationship curves in different gaps](image)

From Figure 4, it may be observed that the relationship between inductance and position is different in gaps from 0mm to 15mm. The relationship of 0mm and above 10mm is approximate to the cosine or sine function. The relationship between the inductance and position of the gap 0mm is opposite to that of gap 10mm. The relationship curves of 2mm and 5mm contain a third harmonic component and the frequency of the relationship curve is doubled at 8mm. So, when the maglev train maintains a constant
air gap and moves forward and backward along the track, the output of the gap sensor fluctuates with the position of the track.

3. Optimal design of the new coil scheme

Via numerical tests, the magnetic induction distribution is demonstrated in order to understand the slot-effect better. In the simulation calculation, the coil adopts the normal flat rectangular coil which the coil center is opposite justly a tooth center or a groove center. The magnetic induction distribution is shown separately in Figure 5-Figure 8 in the case of large gap distance and small gap distance. Figure 5 and Figure 6 represent the situation in the lager air gap, while Figure 7 and Figure 8 show the situation in the smaller gap.

Figure 5. Magnetic flux density distribution of the coil opposite to the centre of tooth stator in the larger gap

Figure 6. Magnetic flux density distribution of the coil opposite to the centre of groove stator in the larger gap

As shown in Figure 5, the magnetic flux density is much larger in central area when the coil centre locates exactly opposite to the tooth. The BC and AD of the coil are directly above the center of the groove. The magnetic field near BC and AD is very small. The magnetic induction intensity near the middle part of AB and CD is stronger, and the weak near both ends are close to zero. Figure 6 shows the magnetic flux density is almost zero in central area when the coil centre locates exactly opposite to the groove. The BC and AD of the coil are directly above the center of the tooth. The magnetic field...
near BC and AD is very strong. The magnetic induction intensity near the middle part of AB and CD is weak, but it is strong near both ends. The sum magnetic flux in Figure 5 is much more than the sum in Figure 6, so the inductance of the coil on the tooth is larger than it is on the groove at the larger air gap. So even the actual gap distance value is the same, when the gap sensor is working on the tooth, the output will be greater than it is on the groove.

Figure 7. Magnetic flux density distribution of the coil opposite to the centre of tooth stator in the smaller gap

Figure 8. Magnetic flux density distribution of the coil opposite to the centre of groove stator in the smaller gap

There are similar distribution characteristics when the air gap is small. Figure 7 shows that the magnetic flux density is much larger in central area when the coil centre locates exactly opposite to the tooth. The BC and AD of the coil are directly above the center of the groove. The magnetic field near BC and AD is very small. The magnetic induction intensity near the middle part of AB and CD is stronger, and the weak near both ends are close to zero. Figure 8 shows that the magnetic flux density is almost zero in central area when the coil centre locates exactly opposite to the groove. The BC and AD of the coil are directly above the center of the tooth. The magnetic field near BC and AD is very strong. The magnetic induction intensity near the middle part of AB and CD is weak, but it is strong near both ends.

However, there are some different distribution characteristics when the air gap is small. The sum magnetic flux in Figure 7 is less than the sum in Figure 8, so the inductance of the coil on the tooth is smaller than it is on the groove at the smaller air gap. So even the actual gap distance value is the same,
when the gap sensor is working on the tooth, the output will be smaller than it is on the groove. Since the coil is far from the stator, the magnetic field distributions in Figure 5 and Figure 6 are not significantly affected by the stator. The surfaces in Figure 5 and Figure 6 are very smooth. The variations of the magnetic induction intensity in the curved surfaces in Figure 7 and Figure 8 are relatively steep, forming the high and low steps. The stator clearly affects the distribution of the magnetic field when the coil is close to the stator. The magnetic induction distribution is different at different position and different gap distance.

According to the above analysis, changing the distribution of the magnetic field can change the characteristics of the slot-effect. A new coil scheme is designed to change the magnetic field distribution as shown in Figure 9.

The new coil is modified based on the original flat rectangle one by adding two same semi-circles on top and bottom side respectively. The radius $R$ has direct bearing of the measurement accuracy of the sensor. The central area of the coil is reduced with $\pi R^2$ whenever it is opposite to tooth or groove. The sum magnetic flux of the coil on the tooth is reduced more than it is on the groove. So the radius $R$ can be optimized to achieve a equal inductance when coil is opposite to tooth or groove.

4. Results and discussion

The slot-effect error of the optimized coil is plotted in Figure 10 with contrast to the original flat rectangle coil. It should be noted that the maximum slot error is reduced by half in the working air gap from 8mm to 12mm.

From Figure 10, it may be observed that the slot error of optimized coil is always less than the error of original coil in any gap distance. The slot error of the original coil reaches its maximum at 20mm and reaches its minimum at 5mm. However, the slot error of the optimized coil reaches a maximum at 2mm and reaches its minimum at 10mm. The rated suspension gap of the maglev train when suspended is 10mm. The normal fluctuation range of suspension air gap is 8mm to 10mm. The minimum value at 5mm is no practical significance for the original gap sensor. The maximum error of optimized coil at a small air gap does not affect the train work, because the train can hardly work under such a small air gap.
5. Conclusions
In this paper, the distribution of magnetic field intensity of the flat rectangular coil in different gaps and positions is analyzed, and the mechanism of slot-effect is revealed. And a new structural configuration of coil scheme of the gap sensor is launched. The magnetic field distribution is changed by the optimized coil and the inductance is equivalent when coil is opposite to tooth and groove. The simulation results show that the slot error is reduced by half under different working conditions with different air gap. The slot error of the optimized coil reaches a maximum at 2mm and reaches its minimum at the rated suspension gap 10mm.

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