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Optimal Design of Detection Coil of Relative Position Detection Sensor for High Speed Maglev Train

***Abstract**. The relative position detection sensor for high speed maglev train obtains precise relative position messages for traction system by detecting the changing coil inductance along the long stator. In this paper, the finite element analysis soft Maxwell 3D is utilized to study the performance of coils with different shapes, and a planar rounded-square spiral coil with an excellent performance is proposed. And then, the influences of the geometric parameters on the performance of the coil are studied, based on which the optimal geometric parameters are determined.*

Streszczenie** W szybkiej kolei magnetycznej typu maglev informację o dokładnym względnym położeniu pociągu w stosunku do systemu trakcyjnego zapewnia czujnik względnego położenia Działa on na zasadzie detekcji zmian indukcyjności cewki wzdłuż długiego statora. W opracowaniu przeprowadzono analizę własności cewek o różnych kształtach wykorzystując uproszczone 3-wymiarowe równanie Maxwella (soft Maxwell3D). Doskonałe parametry uzyskano dla płaskiej cewki z kolisto-kwadratową spiralą. Następnie zbadano wpływ parametrów geometrycznych na własności cewki i ustalono optymalne wymiary. **Projekt optymalizacji cewki detekcyjnej względnego czujnika położenia w szybkiej kolei magnetycznej Maglev

Keywords: high speed maglev train; relative position detection sensor; planar spiral coil.
Słowa kluczowe: szybka kolej magnetyczna Maglev; czujnik względnego położenia; cewka z płaską spiralą

Introduction

High speed maglev train is driven by linear synchronous motor[1,2]. The rotor is the suspension electromagnet, and the long stator inlaid with 3-phase windings has a tooth-slot structure [1,3] and is made of laminated silicon steel with large permeability, as shown in Fig. 1.

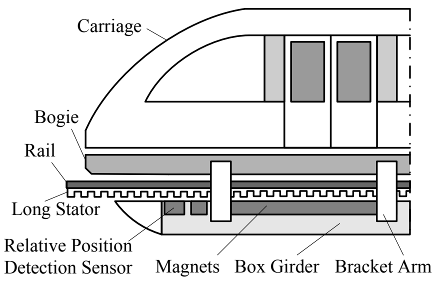


Fig.1. Diagrammatic sketch of high speed maglev train

The relative position detection sensor is a contactless position detection sensor, which is installed under the bogie and facing the long stator tooth-slot structure. When the sensor is moving above the teeth and slots, the equivalent magnetic resistance varies periodically, and accordingly the inductance of the detection coils vary periodically. By detecting the varying coil inductance, the information about position, direction and speed can be gained for the operation and control system [3], as shown in Fig.2.

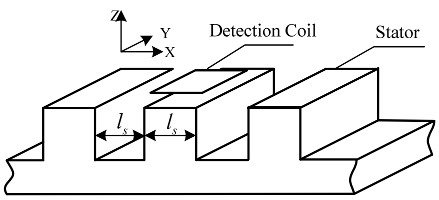


Fig.2. Diagrammatic sketch of the detection coil and the long stator

The detection coils are one of the key units of the reltive position detection sensor, and have significant influence on the performance of the sensor.

The planar spiral coils are widely applied in communication, detection and other engineering fields. The theoretical modeling of the planar spiral coils has been published in microelectronics literatures [4-6], where only the coils in free space or above defect-free substrates are treated. So the modelings are not applicable for the detection sensor where the coils are surrounded with different mediums.

The analytical modeling and the equivalent circuit modeling of the coil impedance in eddy-current NDE are respectively investigated in literatures [7-10]. For the relative position detection sensor, the stator is made of laminated silicon steel with large permeability in which the eddy current induced can be neglected, so the modelings of coil in eddy-current NDE mentioned above are not applicable.

The current relative position detection sensors for high speed maglev train mostly adopt the planar square spiral coils as the detection coils[11,12]. In this paper, finite element analysis soft Maxwell 3D is utilized to study the performance of coils with different shapes. Based on the comparison results, a new coil shape with an excellent performance is proposed. Then the influences of the geometric parameters on the performance of the coil are studied, based on which the optimal geometric parameters are determined.

Performance parameters of detection coils

In the sensor, the detection coils are driven by a harmonically varying source $I\exp(j\omega t)$, which produces a time-harmonic electromagnetic field in the air. And the electromagnetic field would cause the magnetization in the silicon steel stator, which affects the electromagnetic field in the air. So when the detection coils are moving above the stator, their equivalent inductance would vary periodically [12], as shown in Fig.3.

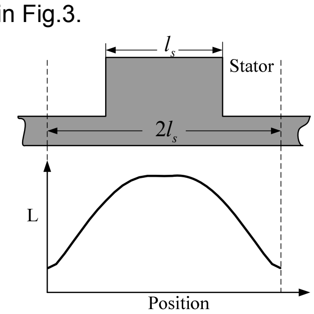


Fig.3. The coil inductance variation with position along the stator

Just for the derection coils, the inductance L and the quality factor Q are the most important performance parameters. With the same exciting current, the larger the inductance L is, the stronger the alternating magnetic field is, and the stronger the anti-interference ability of the sensor is. And the higher the quality factor Q is, the lower the energy loss is, and also the stronger the ability to inhibit the temperature drift is.

Generally, in the sensor the derection coils are are connected in the LRC resonance circuit driven by the excitation $\dot{U}_i$, as shown in Fig. 4. When the coils are moving above the stator, the inductance L varies periodically, and accordingly the amplitude of output signal $\dot{U}_o$ varies periodically, which can be detected to abtain the corresponding position.

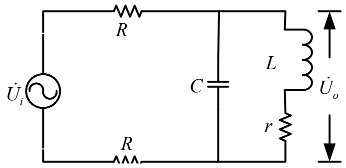


Fig. 4. LRC Resonance Circuit

In Fig.4, $\dot{U}_i$ denotes the driving source with constant voltage and constant frequency; L and r respectively denote the inductance and resistance of the detection coil; C denotes the resonance capacitance; R denotes the dividing resistor; $\dot{U}_o$ denotes the output signal, and can be expressed as follows:

(1) $$\dot{U}_o = \frac{1}{1+2R[jwC+1/(jwL+r)]}\dot{U}_i$$

In general, to make the amplitude variation of output signal $\dot{U}_o$ maximal, the LRC resonance circuit should be working in the resonance state. When the inductance reanches the maximum L_{max}, the circuit should be just at the resonance point, so the resonance capacitance C should be set as :

(2) $$C = \frac{L_{\max}}{r^2+\omega^2 L_{\max}^2}$$

For the sensor, the sensitivity is a significant performance parameter, which represents the response capacity of the sensor to the input change. And the sensitivity K can be defined as the ratio of the maximal amplitude variation $\dot{U}_o$ to the length of a tooth-slot period $2l_s$:

(3) $$K = \frac{\Delta U_o}{2l_s}$$

As Eq.(1) and (3) show, the sensitivity K is not only related with the inductance L, but also the dividing resistor R. Take the planar square spiral coil with a single-turn and an external $l_s \times l_s$ area as an example [11], and assume that the amplitude of driving source $U_i = 1\text{V}$, with different dividing resistors R, the output signal amplitude U_o variation with positions in a tooth-slot period and the sensitivity K are shown in Fig.5.

As Fig.5 shows, with the increasing of the dividing resistors R, the output signal amplitude U_o decreases, and the sensitivity K increases to a certain value then begins to decrease.

For a detection coil, there exists an optimal dividing resistor R_{opt} making the sensitivity reach the maximal $K_{\max}$. However, a larger dividing resistor would result in a lower output signal amplitude U_o, which is not beneficial to the subsequent signal processing. In addition, a larger dividing resistor would cause more energy loss, so that to achieve enough transmitted power, the power of the driving source should be increased significantly, which would increase the complexity of the circuits and even is not realistic sometimes. Therefore, for a coil the maximal sensitivity $K_{\max}$ should be as large as possible, meanwhile the optimal dividing resistor R_{opt} should be as little as possible.

a) b)

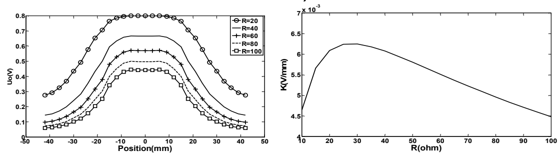


Fig.5. (a) Output signal amplitude U_o variation with positions (b) sensitivity K variation with dividing resistors R

To sum up, the inductance L, the quality factor Q, the maximal sensitivity $K_{\max}$ and the optimal dividing resistor R_{opt} can serve as the performance parameters to evaluate the detection coils.

Optimization of the coil shape

Due to the restriction of installation space, the relative position detection sensor mostly adopts the planar spiral coils, and the common coil shapes are planar square spiral coil, planar circular spiral coil and planar rectangular spiral, as shown in Fig.6.

a) b) c)

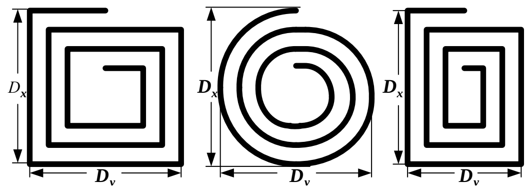
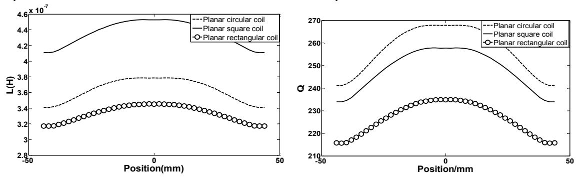


Fig.6. (a) Planar square spiral coil (b) Planar circular spiral coil (c) Planar rectangular spiral coil

Researches show that [13], when the dimension of the detection coil along the stator D_x (in direction X shown in Fig.2) is odd times of the length of a slot (or tooth) l_s, the tooth-slot effect is most intensive, so the dimension D_y is determined as l_s. In addition, the width of stator (in direction Y shown in Fig.2) is about equal to the length of a tooth-slot period ($2l_s$). According to the principle of the sensor [11], two coils are set on a same plane in direction Y, so the dimension D_y should not be larger than l_s.

a) b)



c)

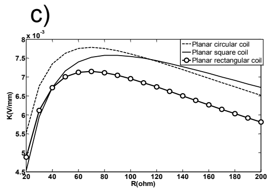


Fig.7. (a) Inductance variation of three shapes of coils (b) Quality factor variation of three shapes of coils (c) sensitivity K of three shapes of coils

For the three shapes of coils, the dimensions D_x are all set as l_s, and the dimension D_y of the lanar rectangular spiral coil is set as $l_s/2$. With the excitation frequency f=1MHz and the same turns, the performance parameters of them are shown in Fig.7.

As Fig.7 shows, for the planar rectangular spiral coil, its inductance L, quality factor Q and maximal sensitivity K_{max} are all smaller than those of the other two coils. The inductance of the planar square spiral coil is larger that of the planar circular spiral coil, but its quality factor and maximal sensitivity are all lower than those of the planar circular spiral coil. And the three coil have an approximate optimal dividing resistor R_{opt}. On the whole, the performance of the planar rectangular spiral coil is the worst, and the other two coils all have their own advantages and disadvantages.

To achieve the advantages of both the planar circular spiral coil and the planar square spiral coil, the planar rounded-square spiral coil shape is proposed, which is shown in Fig.8.

As Fig.8 shows, the planar rounded-square spiral coil is the combination of the planar circular spiral coil and the planar square spiral coi, and the geometric parameters include the external dimension D_{out}, the internal dimension D_{in}, the number of coil turns N, the width of wires w, the space of wires s and the radius of rounded corner $r_i (i = 1...N)$.

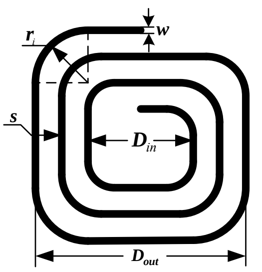


Fig.8. Planar rounded-square spiral coil

With the same geometric parameters except the radius of rounded corner r_i, the performance parameters of the planar circular spiral coil, the planar square spiral coil and the planar rounded-square spiral coil are shown in Fig. 9.

a) b)

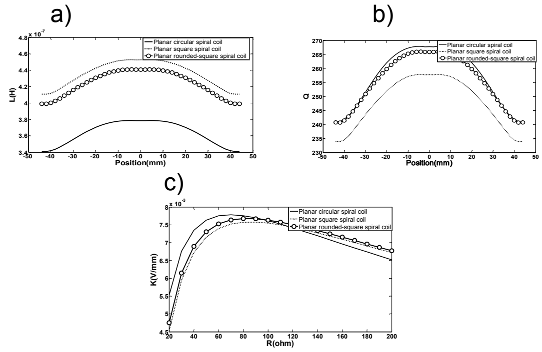


Fig.9. (a) Inductance variation (b) Quality factor variation (c) Sensitivity K variation

As Fig.9 shows, the inductance of the planar rounded-square spiral coil is larger than that of the planar circular spiral coil and close to that of the planar square spiral coil, and meanwhile the quality factor of the planar rounded-square spiral coil is larger than that of the planar square spiral coil and close to that of the planar circular spiral coil. And for the maximal sensitivity K_{max} and the optimal dividing resistor R_{opt}, the three coils have little difference. On the whole, the planar rounded-square spiral coil has the outstanding comprehensive performance, and it is determined as the detection coil of the relative position detection sensor.

Optimization of the coil geometric parameters

The planar rounded-square spiral coil is made from the printed circuit board (PCB) with a tiny (about 100um) copper layer, and the external dimension D_{out} is determined and set as l_s.

The influence of the coil turns number N on the coil performance is much larger than that of other geometric parameters. With the same turns, different geometric parameters make the inductance and the quality factor just vary in a same order of magnitude, and cause little difference of the maximal sensitivity K_{max} and the optimal dividing resistor R_{opt}, which can be verified in Fig.8(c) and Fig.9 (c). Therefore , when the influence on the coil performance due to the geometric parameters except N are discussed in the following parts, only the inductance L and the quality factor Q are considered to evaluate the coil performance.

a. Optimization of Wire width and Wire space

Literature[14] points out that with the same D_{out} and N, the smaller the wires space s is, the higher the inductance L and the quality factor Q are, yet a too small wire space would cause a strong proximity effect, which is not in favour of the coil. Therefore, consider the proximity effect and the actual coil processing technology synthetically, the space of wires s is determined and set as 0.5 mm.

When the wires width w varies, both the resistance r and the inductance L of the coil would change, so maybe there exists an optimal wires width corresponding to a maximal quality factor Q. With different wires width, the inductance L and the quality factor Q are shown in Fig.10.

As Fig.10 shows, with the incresing of the wire width w, the inductance L decreases continually, and the quality factor Q tends to increase to a certain value and then begin to decrease. When the wire width reaches 1mm, the quality factor Q is maximal, so the optimal wires width is 1mm.

a) b)

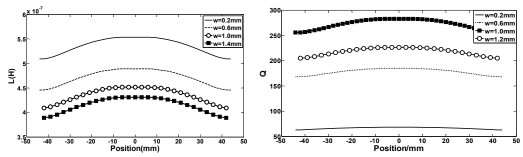


Fig.10. (a) Inductance variation with different wires width (b) Quality factor variation with different wires width

b. Optimization of Rounded Corner Radius

For the planar rounded-square spiral coil, the ratio of the rounded corner radius r_i in the ith turn to the external dimension D_{out} is denoted by K_r:

$$K_r = \frac{r_i}{D_i} = \frac{r_i}{D_{out} - (i-1)(s+w)} \tag{4}$$

In order to be convenient for the design and manufacture of the coils, K_r is designed to be constant for a coil. Particularly, when K_r=0, the planar rounded-square spiral coil is just the planar square spiral coil, and when K_r=0.5 it is just the planar circular spiral coil.

With different rounded corner radiuses, the inductance L and the quality factor Q are shown in Fig.11.

As Fig.11 shows, with the increasing of the rounded corner radiuses, the inductance L decreases continually, and the quality factor Q increases, but when K_r=0.3~0.4, it tends to be stable, and after that it decreases slightly. Therefore, K_r is set as 0.3, with which the inductance L is much higher and the quality factor Q is the maximal.

a) b)

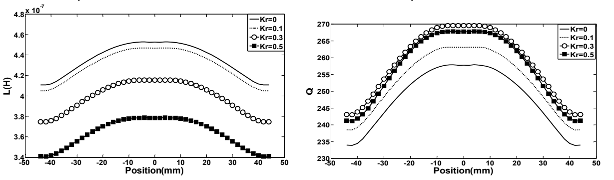


Fig.11. (a) Inductance variation with different rounded corner radiuses (b) Quality factor variation with different rounded corner radiuses

3. Optimization of Turns Number

The coil turns number N has a very significant influence on the performance, and with different turns numbers, the performance parameters of the coil are shown in Fig. 12.

As Fig.12 shows, with the increasing of the coil turns numbers, the inductance L, the quality factor Q and the maximal sensitivity $K_{\max}$ all increase, so just in the view of the coil, the turns number N should be as large as possible to achieve an excellent performance. However , as Fig.12(c) shows, a larger turns number brings in a larger optimal dividing resistor R_{opt}, which would result in a lower output signal amplitude and cause more energy loss. Considering thoroughly, when the turns number N is set as 6, the inductance L, the quality factor Q and the maximal sensitivity Kmax are large enough, and the optimal dividing resistor R_{opt} is small relatively, so the coil could achieve an excellent performance. a) b)

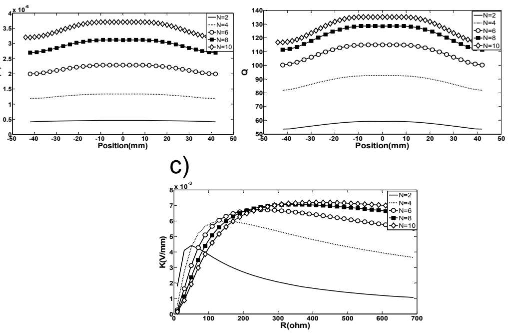


Fig. 12. (a) Inductance variation with different turns numbers (b) Quality factor variation with different turns numbers (c) sensitivity K with different turns numbers

Conclusions

In this paper, the finite element analysis soft Maxwell 3D is utilized to accomplish the optimal design of the detection coil of the relative position detection sensor for high speed maglev train. The inductance L, the quality factor Q, the maximal sensitivity $K_{\max}$ and the optimal dividing resistor R_{opt} are introduced to serve as the performance parameters to evaluate the detection coils. And the performance of the common coils for sensors are discussed and compared, based on which a new shape of coil that planar rounded-square spiral coil is proposed. And then the influence of the geometric parameters on the coil are investigated, the results are acquired as follows:

a) With the decreasing of the wires space s, both the inductance L and the quality factor Q increase continually;

b) With the incresing of the wire width w, the inductance L decreases continually, and the quality factor Q tends to increase to a certain value and then begin to decrease;

c) With the increasing of the rounded corner radiuses r_{i}, the inductance L decreases continually, and the quality factor Q increases to be stable and then decreases slightly;

d) With the increasing of the coil turns numbers, the inductance L, the quality factor Q and the maximal sensitivity $K_{\max}$ all increase, yet the optimal dividing resistor R_{opt} also increases which is not in favour of the sensor.

Based on the results above, the optimal geometric parameters are determined.

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REFERENCES

[1] Liu H. Q. Transrapid. University of Electronic Since and Technology of China Press, Chengdu, China, 1995.
[2] Zhiqiang Long, Guang He, Song Xue. Study of EDS & EMS Hybrid Suspension System With Permanent-Magnet Halbach Array. *IEEE Trans. Magn.*, 47 (2011), No.12, 4717-4724.
[3] Tang Li, Study and Realization of High-speed Maglev Vehicle Relative Location Sensor, *Southwest Jiaotong University Master Degree Thesis*, 2006.
[4] Xie Jianyong, The Design, Modeling and Parameter Extraction of Silion-Based Sprial Inductors in RIFCs, *Shanghai Jiaotong University Master Degree Thesis,* 2007.
[5] Wang Xining, Zhao Xiaolin, Zhou Yong, Cai Bingchu, The Physical Model of RF planar spiral Inductors, *Microfabrication Technology*, (2003), No.1, 57-60.
[6] C. Patrick Yue. Physical Modeling of Spiral Inductors on Silicon. *IEEE Trans. Electron Deviecs*, 47(2000) , No.3, 560-568.
[7] Yu Yating, Research on the Theoretical Basis and Realization Methods of Eddy Sensors, *University of Electronic Science and Technology of China Ph.D Degree Thesis*, 2007.
[8] Wang Peng, Ding Tianhuai, Fu Zhibin, Design of Geometric Parameters of Planar Eddy Coils, *Journal of Tsinghua University (Siceance & Technology)*, 47 (2007), No.11, 1951-1961..
[9] R.J. Ditchburn, S.K.Burk. Planar rectangular spiral coils in eddy-current non-destructive inspection, *NDT&E International*, Vol. 38(2005), 690-700.
[10] R. J. Ditchburn,S. K. Burke, M. Posada. Eddy-Current Nondestructive Inspection with Thin Spiral Coils: Long Cracks in Steel, *Journa of Nondestructive Evaluation*, 22(2003), No.2, 64-77.
[11] He Ning, Xue Song, Long Zhiqiang, Analysis and Optimal Design of Relative Position Detection Sensor for High Speed Maglev Train, *The Fifth International Conference on Intelligent Computation Technology and Automation* (2012), 89-93.
[12] Xue Song, Dai Chunhui and Long Zhiqiang. Research on Location and Speed Detection for High Speed Maglev Train Based on Long Stator. *Proceedings of the 8th World Congress on Intelligent Control and Automation, IEEE Press*, (2007), 6953-6958.
[13] Wu Jun, Li Lu, Fan Shujiang, Chang Wensen, Designs of Coils for a Gap Sensor, *Chinese Journal of Sensors and Actuators*, 3(2004), 512-515.
[14] Qi Lirong, Calculation and Simulation of Planar Spiral Inductance, *Dalian Maritime University Master Degree Thesis*, 2007.

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