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Simulation study of wireless power transmission in rotary joints

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Abstract

For rotating joint, wired power transmission needs to connect the power supply to the rotating joint through the connection wire, which limits the motion range of the joint, and easy to occur in the rotation process of entanglement, fracture and other problems. Meanwhile, the usage of wired power transmission causes wear, bending, pulling and other problems of the connection wire, which limits the life of the joint. Therefore, the magnetic field characteristics of the wireless power transmission module are revealed through electromagnetic field simulation and theoretical analysis in this paper, and the coupling module is optimized. The results show that the installation distance of the coupling coil should be shortened as much as possible to achieve higher efficiency of wireless transmission of short-distance rotating joint. At the same time, the usage of EE core is far better than UU or II type. In addition, the adverse effects of installation offset on wireless power transmission can be reduced by widening one of the iron cores. The present work shows guiding significance for the research of rotary joint power supply, drilling joint power supply and manipulator power supply.

Keywords

Rotating joint, Wireless power transmission, Electromagnetic simulation.

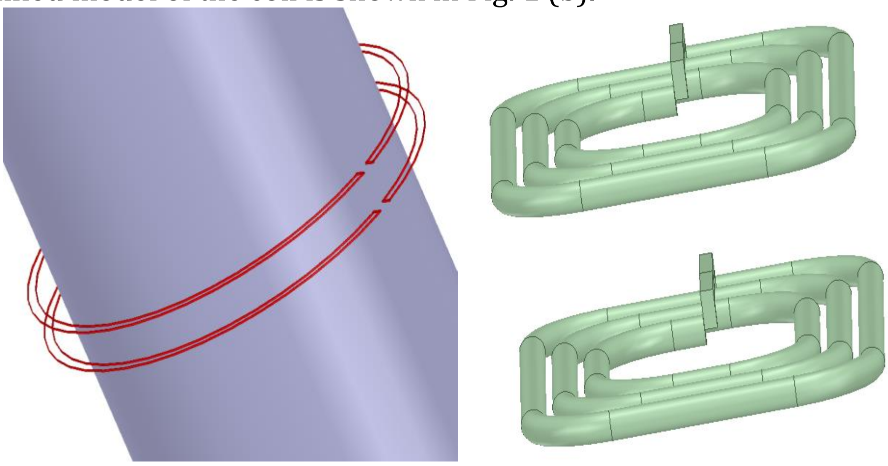
1. Introduction

Wireless power transmission is different from the previous power transmission methods with electrical contact, with more advantages than conventional wired power transmission. It avoids the safety problems caused by poor contact of electrical contact power transmission and leakage caused by aging of transmission cable [1]. Its greater advantage is to get rid of the constraints and restrictions of transmission line in non-contact power transmission. It makes the power transmission more flexible and saves the space occupied by electric wires. As early as 1891, the famous electrical expert Tesla has explored radio energy transmission methods [2]. Nikola Tesla was one of the pioneers of radio technology, and his research and invention laid the foundation for wireless energy transmission. He proposed the principle of resonance induction, and the principle of wireless energy transfer through resonance is applied to today's wireless charging technology. Tesla also built the famous Wolnafu Tower power transmission tower, demonstrating the potential for wireless energy transfer over long distances. In recent years, inductive power transfer technology has been applied in various industries, and many scholars have also carried out research in this field and achieved good results: in the 1990s, the BOYS team of the university of Auckland in New Zealand took the lead in conducting experimental research on the application of inductive power transfer technology in the power supply of manned tour buses [3-5]; In 1993, German scholars A. Esser and A. Nagel used three independent magnetic coupling structures based on the study of inductive power transmission [6]; Sogo University in Japan has conducted research on the basic principle design, magnetic field coupling mechanism, etc., in the synchronized transmission of inductive electrical energy and signals [7].

Most of the above studies focus on the case where the coupling coils are relatively fixed, but for the rotating joint, the induction coil moves relative to each other. In this paper, the magnetic field characteristics of the coupling coil are revealed by studying the shape of the iron core, the installation distance and the installation error, and the improvement scheme is proposed.

2. Model of wireless power transmission coil.

The winding mode of the coil on the rotating joint is shown in Fig.1 (a). The red part is represented the electromagnetic induction coil, and the gray part is the simplified rotating joint arm. The wireless transmission efficiency can be optimized by arranging the magnetic core around the coil. In this winding mode, the change of coupling strength between the coils can be ignored when the two coils rotate relative to each other. In addition, for the convenience of research, the receiving and transmitting coil is shortened. Under the simplified model, the magnetic field distribution law of its central cross section is similar to that of the original coil, and the simplified model of the coil is shown in Fig. 1 (b).

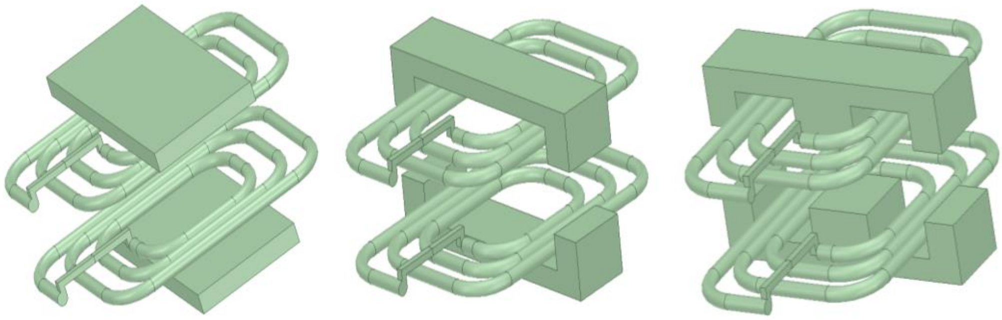


(a) the coil on the joint (b) Simplified coil model

Fig. 1. Coil winding and simplified model

3. Optimization of core distribution

In order to investigate the characteristics of magnetic field distribution under different shapes of Iron cores, several common iron cores of coupling coils were selected. The coupling models established by software are shown in Fig. 2.



(a) II iron core model (b) UU iron core model (c) EE iron core model

Fig. 2 Iron core distribution

The simulation results are shown in Figs. 3-6, where Fig. a depicts the distribution of the magnetic induction strength and Fig. b demonstrates the direction of the magnetic field. The same scale range is used for the color bars of each graph, so that the magnetic field strength can be determined by the color of each point.

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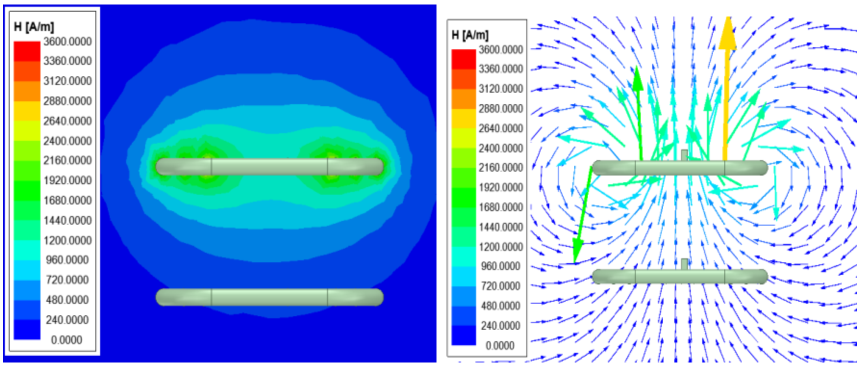
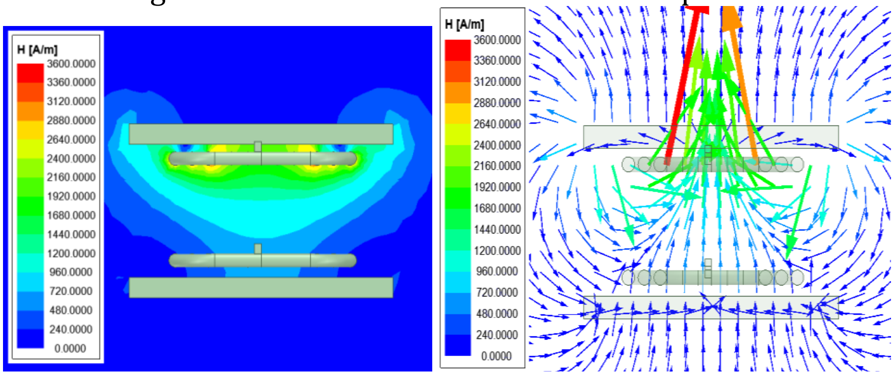


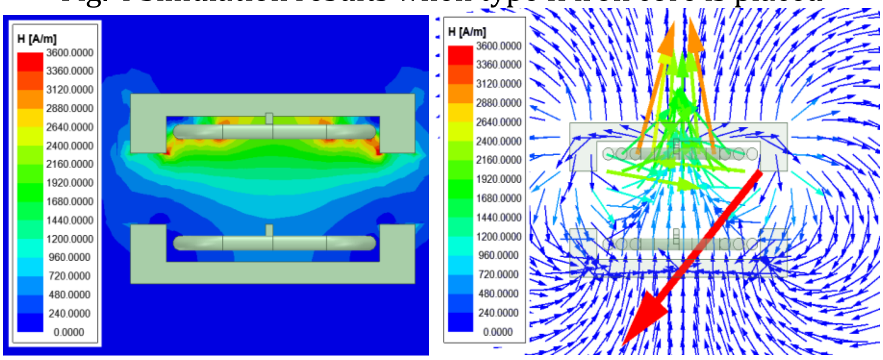
(a) Distribution of magnetic field strength (b) Direction of the magnetic field vector

Fig. 3 Simulation results when no core is placed



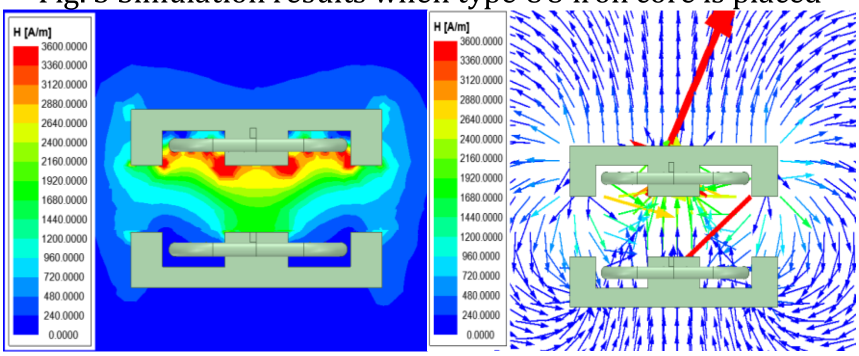
(a) Distribution of magnetic field strength (b) Direction of the magnetic field vector

Fig. 4 Simulation results when type II iron core is placed



(a) Distribution of magnetic field strength (b) Direction of the magnetic field vector

Fig. 5 Simulation results when type UU iron core is placed



(a) Distribution of magnetic field strength (b) Direction of the magnetic field vector

Fig. 6 Simulation results when type EE iron core is placed

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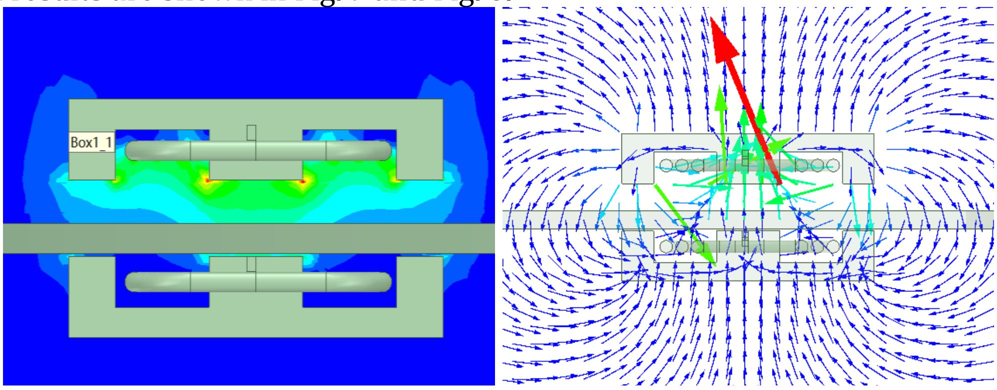
According to the simulation results, the magnetic field generated by the transmitting coil diverges in all directions without the installation of the iron core, and does not converge to the direction of the receiving coil. Although the installation of type II cores can effectively prevent the magnetic field strength from diverging in the opposite direction to the receiving coil, as without the installation of no core, the center of the receiving coil cannot vertically pass through more magnetic fields. The difference is, the magnetic field generated by the transmitting coil can be convergent to the receiving coil through the use of UU and EE cores, so that the distributed magnetic field can greatly improve the induction intensity of the coupling coil. Among them, the most ideal magnetic field distribution can be achieved by using the coupling coil of EE core combination.

4. Installation distance analysis

In order to obtain the relationship between core distance and magnetic field distribution, simplified transceiver devices with different installation distances were simulated. Two sets of simulation results are shown in Fig. 7 and Fig. 8.

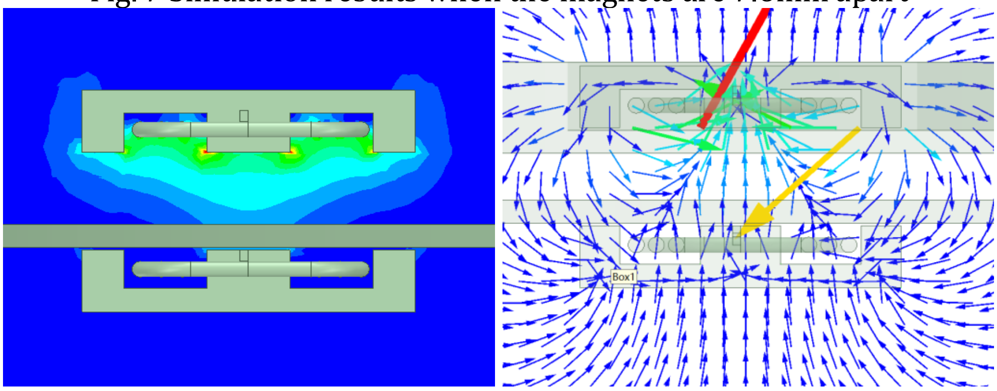


(a) Distribution of magnetic field strength (b) Direction of the magnetic field vector

X [mm]	Matrix1.Lnom(Current1,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current1,Current2) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current2) [nH] Setup1 : LastAdaptive
0.000000	597.459924	200.338556	200.338556	587.132590

(c) Induction strength of the coil

Fig. 7 Simulation results when the magnets are 7.6mm apart



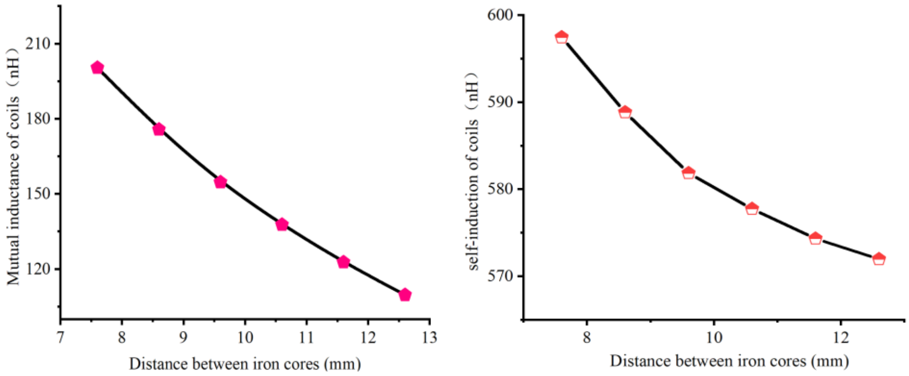
(a) Distribution of magnetic field strength (b) Direction of the magnetic field vector

X [mm]	Matrix1.Lnom(Current1,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current1,Current2) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current2) [nH] Setup1 : LastAdaptive
0.000000	571.962588	109.639197	109.639197	561.081733

(c) Induction strength of the coil

Fig. 8 Simulation results when the magnets are 1cm apart

Through the two simulation results, it is easy to see that the magnetic field distribution in the case of smaller core mounting distance is more favorable for the coupling coil to transmit electricity wirelessly, and at the same time, the changing magnetic field generated by the transmitting coil is more capable of being sensed by the receiving coil. In order to reveal the relationship between the core mounting distance and the inductive strength, five sets of simulations were carried out and distance-inductance curves were made as shown in Fig. 9. From the line graph, it can be found that both the self-inductance and mutual inductance of the two coils become weaker and weaker as the distance continues to lengthen, and the closer the distance is, the more drastic is the tendency for them to change. Therefore, when designing the equipment, if the distance can be within 10mm, the minimum distance principle should be followed. If the distance is set above 10mm, one can first consider other conditions and then consider the distance.



(a) Mutual inductance versus displacement (b)Self-inductance versus displacement

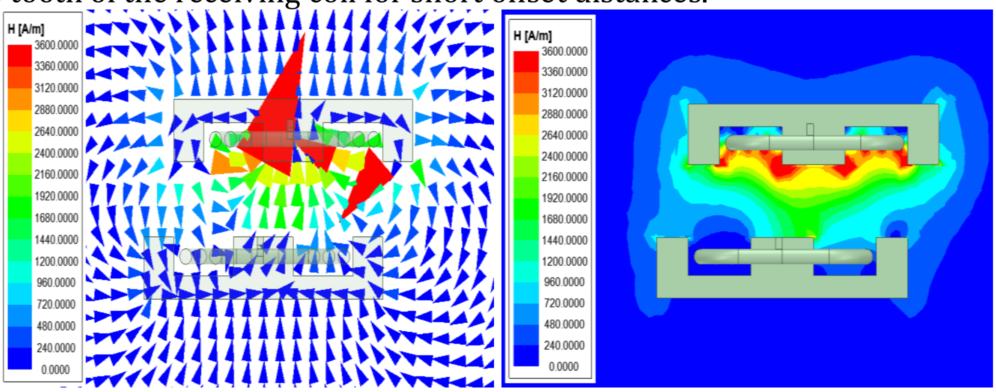
Fig. 9 The relationship between core distance and induction strength

5. Analysis of installation offset error

In this section, firstly, the magnetic field simulation of the coupling coil installation error is carried out by using the simulation software, thereby the reason why the induction intensity is affected by the installation error is analyzed, then an improvement scheme is proposed, and finally the superiority of this scheme is verified by simulation.

5.1. Installation error analysis

With the increasing offset distance, the simulation results are shown in Figs. 9 and 10, and the green part in Fig. b is gradually shifted from the middle tooth of the iron core corresponding to the receiving coil to the side tooth. The way the coil is winding around the middle tooth results in a constant reduction of the inductive strength. In order for this defect to be optimized, it is possible to start by limiting the transfer of the green part, and an intuitive way to do this is to widen the middle tooth portion of the iron core corresponding to the receiving coil, which allows to ensure that the green portion of the magnetic field strength remains concentrated in the middle tooth of the receiving coil for short offset distances.



(a) Direction of the magnetic field vector (b) Distribution of magnetic field strength

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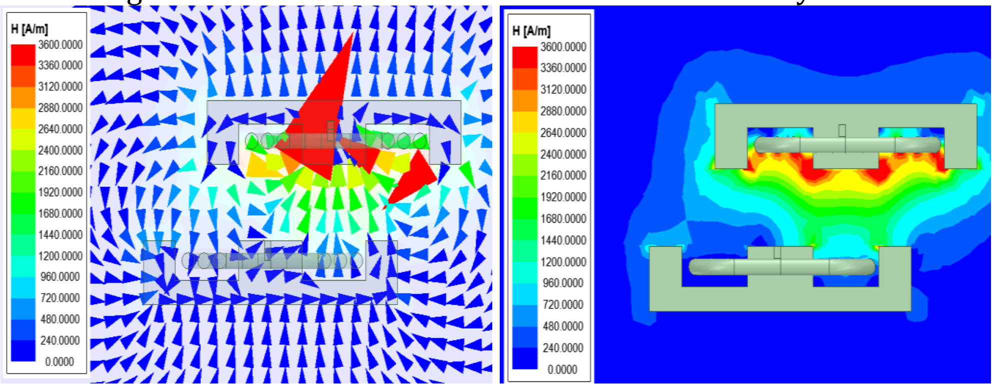
X [mm]	Matrix1.Lnom(Current1,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current1,Current2) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current2) [nH] Setup1 : LastAdaptive
0.000000	580.294474	131.068167	131.068167	567.010613

(c) Induction strength of the coils

Fig. 10 Simulation results when iron core is offset by 5mm



(a) Direction of the magnetic field vector

(b) Distribution of magnetic field strength

X [mm]	Matrix1.Lnom(Current1,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current1,Current2) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current2) [nH] Setup1 : LastAdaptive
0.000000	579.091661	75.541817	75.541817	567.133354

(c) Induction strength of the coils

Fig. 10 Simulation results when iron core is offset by 1cm

To reveal the variation characteristics of magnetic induction intensity, a plot of the coil induction intensity with offset distance before optimization was made as shown in Figs 11-12. As the offset distance increases, the mutual inductance between the coils changes rapidly, which is a decisive parameter for the wireless transmission module, and the variation of it reduces the stability of the device transmission.

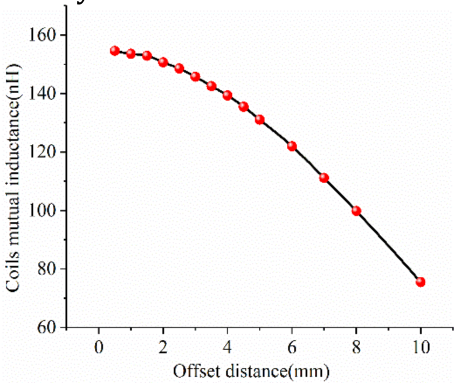


Fig. 11 Variation of coil mutual inductance with offset distance

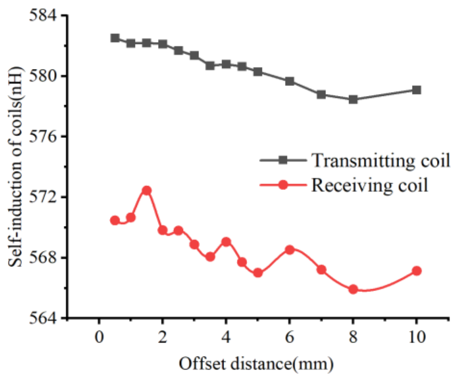
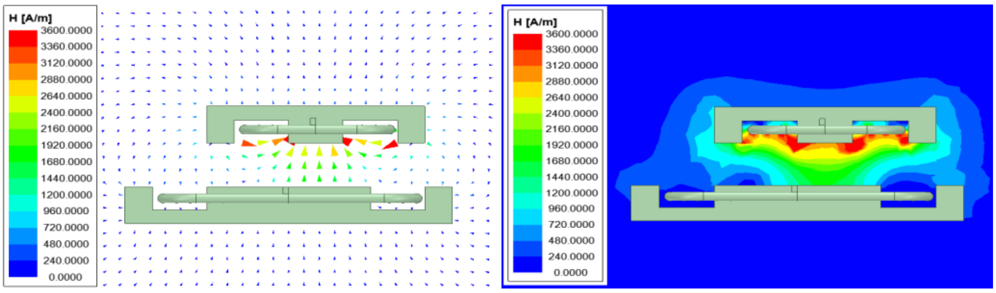


Fig. 12 Variation of coil self-inductance with offset distance

5.2. Optimized analysis

From the model in Figs. 13 and 14, it can be noticed that the middle part of the E-type core at the end of the receiving coil was widened, and the area of the receiving coil was also increased. From the magnetic field strength cloud diagram, it can be seen that the green part of the magnetic field strength is always concentrated on the middle tooth of the receiving coil when the coupling coil is offset for a short distance, which causes the mutual inductance change between the coils to be very small.

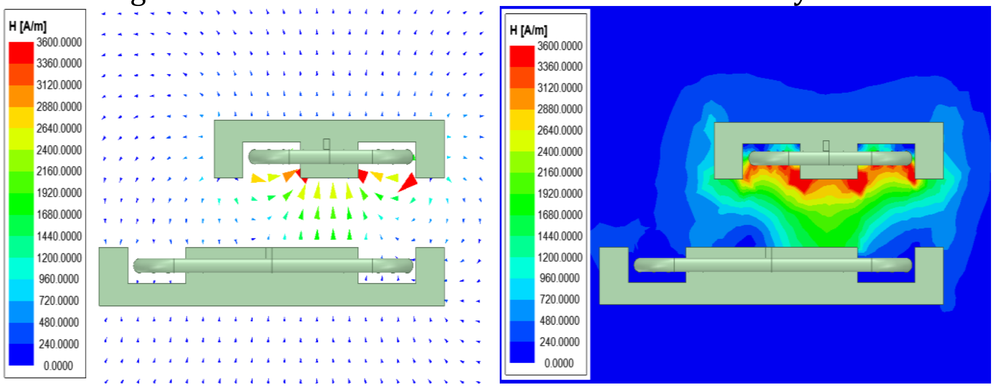


(a) Direction of the magnetic field vector (b) Distribution of magnetic field strength

X [mm]	Matrix1.Lnom(Current1,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current1,Current2) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current2) [nH] Setup1 : LastAdaptive
0.000000	595.808142	167.857874	167.857874	845.680119

(c) Induction strength of the coils

Fig.13 Simulation results when iron core is offset by 5mm



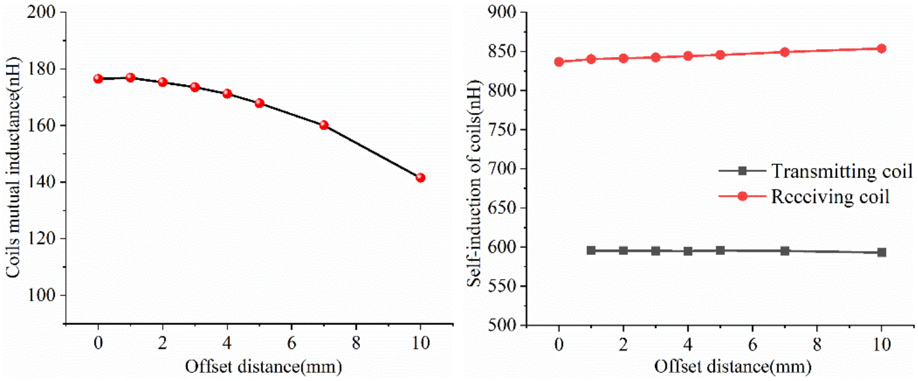
(a) Direction of the magnetic field vector (b) Distribution of magnetic field strength

X [mm]	Matrix1.Lnom(Current1,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current1) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current1,Current2) [nH] Setup1 : LastAdaptive	Matrix1.Lnom(Current2,Current2) [nH] Setup1 : LastAdaptive
0.000000	593.089664	141.519103	141.519103	853.777343

(c) Induction strength of the coils

Fig. 14 Simulation results when iron core is offset by 1cm

In order to verify the validity of this optimization from the data, a plot of the variation of coil inductance with offset distance after optimization is made as shown in Fig. 15, in which the vertical coordinate in Fig. 15(a) is the same scale as Fig. 11, and the maximum offset of the horizontal coordinate is also 10 mm. Therefore, it can be intuitively seen that the variation of coil mutual inductance under the optimized model is much slower than the results shown in Fig. 11, reflecting the superiority of the optimization.



(a) Variation of coil mutual inductance (b) Variation of coil self-inductance

Fig. 15 Variation curve of induction intensity versus offset distance after optimization

6. Conclusion

1. When designing a short distance wireless power transmission device, the magnetic field distribution can be optimized by placing iron cores, and the optimization effect is different for different core shapes, with the law: EE>UU>II>None.

2. The inductive strength of the EE core-wound coupling coil shows a parabolic downward trend with the increase of the installation distance, and the self-inductance and mutual inductance of the two coils exhibit the same law.

3. The inductive strength of the EE core-wound coupling coil tends to decrease as an exponential function with increasing offset distance, while the coil self-inductance tends to decrease irregularly.

4. Equipment tolerance for installation errors can be enhanced by widening the width of the E-type core and coil at the receiving end.

Declarations

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] D.A.G. Pedder, A.D. Brown and J.A. Skinner: A contactless electrical energy transmission system[J], IEEE Transactions on Industrial Electrions, Vol. 46 (1999) No.1, p.23-30.

[2] N. Tesla: The Transmission of Electrical Energy without wires as a means for furthering peace[J], Electrical World and Engineer, Vol. 1905 (1905), p.21-24

[3] D. Kacprzak, G.A. Covic, J.T. Boys: An improved magnetic design for inductively coupled power transfer system pickups[C], Power Engineering Conference, 2005. IPEC 2005. The 7th International. IEEE, Vol. (2005), p.1133-1136.

[4] S. Covic, G.A. Boys, G.H. Lu: A three-phase inductively coupled power transfer system[C], Industrial Electronics and Applications, 2006 1ST IEEE Conference on. IEEE, Vol. 2006 (2006), p.1-6.

[5] S. Covic, G.A. Boys, J.T. Pennalligen, C. Shekar: Practical considerations in the design of multiphase pick-ups for contactless power transfer systems[C]. Industrial Electronics, 2009. IECON '09. 35th Annual Conference of IEEE, Vol. 2009 (2009), p.753-758.

[6] Eber A, Nagel A: Contactless high speed signal transmission integrated in a compact rotatable power transformer[C], Power Electronics and Applications, 1993.Fifth European Conference on. IET, Vol. 1993 (1993), p.409-414.

[7] H. Sakamoto, K. Harada, S. Washimiy: Large Air-Gap Coupler for Inductive Charger[J], IEEE Transactions on Magnetics, Vol. 35 (1999) No.5, p.3526-3528.