A transmission performance optimization method of wireless charging system under adjacent large metal plate environment based on magnetic field aggregation

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ABSTRACT The wireless power transfer (WPT) system will usually contact with the metal environment in military applications. Adjacent large metal plates will result in severe deviation of system parameters and degradation of system performance. Therefore, in order to solve the above problems, an optimization method of additional ferrite is proposed in this paper based on the magnetic field aggregation to decrease the influence of metal plates. Firstly, the characteristic of influence caused by metal plates is analyzed through circuit theory and the optimization goal is pointed out. Then, the influence characteristic of typical metal surface plate and curved plate is obtained by the FEM simulation. Subsequently, the optimization scheme is investigated based on magnetic field aggregation. By analyzing the adjustment rules of multiple design parameters, the optimization scheme is formed ultimately. Based on the optimization scheme, the maximum 33% deviation of system parameter is completely corrected and the transmission performance index parameter is improved according to the simulation. In addition, an improved strategy is proposed to reduce the system eddy current loss. Finally, the influences of metal plates and the beneficial effect of the optimization scheme are verified by the experiment. The effectiveness of the improved scheme for eddy current loss is also verified. The experiment results demonstrate that the deviation of system parameters is completely corrects and the transmission performance index parameter is improved by 5.54%.

INDEX TERMS Wireless power transfer, large metal plate, magnetic field aggregation, transmission performance optimization, eddy current loss reduction

I. INTRODUCTION
The wireless power transfer (WPT) technology has turned into an innovative idea to solve the charging problem in many fields [1-2]. It is widely applied in civil fields such as electric vehicles, mobile phones and implantable medical equipment due to its long transmission distance and high energy transmission efficiency. WPT technology guarantees the rapidity and security of charging the battery and avoids the cumbersome procedure of replacing the battery and the danger caused by the cable [3-7]. In recent years, with the intensive application and research of WPT technology, its application fields have gradually expanded to industrial and military fields, such as ships, airplanes, rockets, etc. When utilizing the WPT technology to supply power for the wireless sensor at the bottom of the ship, it could achieve uninterrupted sea surface monitoring and tracking function [8-10]. WPT technology could effectively avert the danger of personnel caused by cable plugging before the rocket takes off. [11-12]. WPT technology has added new vitality to the development of the military field. We could expect that in the near future, WPT technology will become a significant part of the rational utilization of clean energy in the military field.
In the application process of WPT technology, whether in the civil or military fields, WPT systems will inevitably confront the metal environment. The receiver coil of WPT systems in the military field is generally distributed near the outer surface of industrial shell, which means that the system will operate under the circumstance of metal plates. The relatively large adjacent metal plates will inevitably affect the transmission performance of a coil system, hence it is necessary to carry out the optimization of transmission performance of the coil system under the circumstance of metal plates. The typical military ship WPT system and the rocket WPT system are adopted as the analysis scenario of typical environments. In the past studies, there were some studies on metal plates and metal plates of different shapes. Furthermore, few studies concentrate on the impact of different shapes of large metal plates on the WPT systems and related optimization work. On the one hand, in order to enhance the application value of WPT technology, promote its application in large industrial and military industries, and enhance its energy transmission performance in complex military environments, it is necessary to carry out transmission performance optimization work of WPT system under adjacent large metal plates environment based on Fig.1 and Fig.2. On the other hand, ameliorating the effect of metal plates on WPT system and avoiding the degradation of system performance are similarly important for regular operation of WPT system.

Therefore, this research investigates the influence of large plates of different shapes and proposes a novel optimization method based on magnetic field aggregation to promote transmission performance of the WPT system. Compared with previous studies, the optimization scheme concentrates on the large metal plates and solves the problem of reducing the transmission performance of WPT system under large metal plates. Besides, it has favorable magnetic field aggregation effect and is feasible in practice. The unique distribution and regulation mode of the optimization method in this paper has not appeared before in related researches.

The rest of the paper is arranged as follows. Section II analyzes the influence of different shapes of metal plates on the WPT system from the circuit theory. Then the paper forms the new index of evaluating system transmission performance and analyzes the system impedance formula. Finally the optimization direction is preliminarily
developed. Section III is the simulation part. The optimization system of different shapes of sheet metal is constructed and the specific parameter influences of the metal plate under two shapes on the WPT system are analyzed. Then the optimization scheme is designed based on magnetic field aggregation. In addition, the optimization scheme is improved and the system transmission performance is further improved with the reduction of the system eddy current loss. Section IV is the experimental verification. The physical system of the same size as the simulation is constructed. The experiment verifies the improved effect of system transmission performance indicators before and after optimization, which effectively verifies the correctness of the optimization method.

II. CIRCUIT SYSTEM ANALYSIS IN LARGE METAL ENVIRONMENT

This part mainly shows the influence of large metal on WPT system from the perspective of circuit, which highlights the necessity and importance of this study.

According to the description in the introduction and Fig.1 and Fig.2, the circuit model under complex metal environment needs to be built, so the circuit equivalence of adjacent metal plates is required. In the process of building rockets, the exterior skin usually use aluminum alloy material. The materials of ships mainly include non-ferromagnetic metals such as titanium alloy, copper alloy and aluminum alloy. These non-ferromagnetic metals have identical characteristics of electromagnetic field, which means that their relative permeability is close to 1 and electrical conductivity is high. Because the construction of the rocket usually adopts aluminum alloy materials that can also be used in ship construction, this paper chooses the aluminum alloy as the material for adjacent large metal plates.

When the WPT system is in an aluminum alloy metal environment as shown in Fig.3, a high-frequency current is added to the coil and then the current will motivate an alternating magnetic field which will generate electromagnetic induction with the non-ferromagnetic metal. Afterwards, due to the high conductivity of non-ferromagnetic metal, the metal plate will generate an induced eddy current, and the eddy current will also generate the corresponding induced magnetic field to affect the original magnetic field, which will cause the deviation of entire resonant circuit parameters. According to eddy current loosely coupled transformer model, the eddy current induced on the non-ferromagnetic metal plate can be equated into a short-loop current with internal resistance, coupled with the coil system. The non-ferromagnetic metal plate is distributed on the receiver coil side, and its coupling degree with the transmitter coil is small and can be approximately neglected [20-21], so the equivalent circuit of the whole system is shown in Fig.4.

\[ Z = Z_1 + j\omega M_{12} + Z_2 + j\omega M_{20} \]

where

\[ Z_1 = R_1 + j\omega L_1 + 1/(j\omega C_1), \]
\[ Z_2 = R_2 + j\omega L_2 + 1/(j\omega C_2), \]
\[ I_1, I_2, I_3 \]

represent the current of the transmitter coil, the receiver coil and the metal plate, respectively. Based on equation (1), the system efficiency \( \eta \) of the WPT system in the resonant state and the equivalent impedance of the secondary side \( Z' \) under the metal plate environment can be derived as

\[ \eta = \frac{(\omega M_{12}^2)^2 R_2}{R_{rec}[R_0 R_{rec} + (\omega M_{12}^2)^2]} \]  

\[ Z' = R_{rec} + j(\omega L_2 - \frac{\omega^2 M_{20}^2}{R_0^2 + \omega^2 L_0^2} I_0 - \frac{1}{\omega C_2}) \]
where \( R_{sec} = R_0 + \frac{\omega^2 M_{20}^2}{R_0^2 + \omega^2 L_0^2} R_0 + R_1 \).

According to [21], once the metal plate is large, the number of eddy current loops induced on the metal plate will increase, which signifies that there will be multiple circuits like \( L_0 \) and \( R_0 \) as shown in Fig.4 affecting the secondary side circuit. However, every eddy current field generated by coil current on the metal plate basically does not change because of the constant current. The equivalent resistance, self-inductance and mutual inductance with receiver coil of multiple eddy current circuits (number is assumed as \( k \)) are denoted as \( R_{0(1,2...k)} \), \( L_{0(1,2...k)} \) and \( M_{20(1,2...k)} \) respectively. The equivalent impedance of the receiver side under the large metal plate \( Z''_2 \) is shown as (4),

\[
Z''_2 = R_{sec} + \sum_{n=1}^{k} \frac{\omega^2 M_{2n}^2}{R_{0(n)} + \omega^2 L_{0(n)}} R_{0(n)} + j(\omega L_{0} - \frac{\omega^2 M_{20}^2}{R_0 + \omega^2 L_0} L_0 - \sum_{n=1}^{k} \frac{\omega^2 M_{2n}^2}{R_{0(n)} + \omega^2 L_{0(n)}} L_{0(n)} - \frac{1}{\omega C_2})
\]  

(4)

Therefore, the self-inductance of the receiver coil will be significantly decreased from (4). However, the capacitance of the system is mostly lumped, which is difficult to change after it is equipped, so the secondary circuit will deviate severely from the resonant state under the large metal plate. When the system is deviated from the resonant state, from the energy point of view, the system loss resistance only increases the values of eddy current resistances, so the efficiency of the system will not be dropped sharply based on (2). Nevertheless, the deviation from the resonant state makes part of power to reactive power. Although reactive power does not dissipate energy, it also weakens the transmission performance of the whole system. From the perspective of the grid, reactive power is also part of the energy output from the grid. When evaluating the transmission performance of the system, reactive power also needs to be considered. Therefore, the efficiency equation (2) is inadequacy to evaluate the non-resonant system. The reference [22-23] use the output power divided by the total power to represent the energy transmission performance of the system, hence the \( \beta \) parameter is analogously defined to represent the transmission performance of the system in the case of the large metal plate. The calculation method is shown as (5), and \( \beta \) also represents the active transmission capability of the system.

\[
\beta = \frac{(\omega M'_{12})^2 R_1}{Z''_2[Z'_2 + (\omega M'_{12})^2]}
\]  

(5)

Once the metal plate is large, the overall equivalent resistance of the receiver coil will increase according to (4), and the imaginary part of \( Z''_2 \) will increase due to the decrease of the self-inductance of the receiver coil. These factors lead to an increase in the denominator in (5), and \( \beta \) consequently decreases. In addition, the non-ferromagnetic metal is extremely inferior in magnetic permeability, so the metal plate on the back of the receiver coil will hinder the closing of the magnetic flux lines. Hence, the mutual inductance \( M'_{12} \) will inevitably decrease. Since the derivative of \( \beta \) with respect to \( M'_{12} \) is more than zero, \( \beta \) will decrease with the decrease of \( M'_{12} \).

From the perspective of impedance, the existence of the large metal plate makes the equivalent impedance of secondary side become \( Z''_2 \). However, the input impedance of the entire system is

\[
Z''_m = R_1 + j\omega L_1 - 1 + \frac{\omega M'_{12}}{R_{sec} + j(\omega L_2' - \frac{1}{\omega C_2})}
\]  

(6)

where \( L_2' = L_2 - \frac{\omega^2 M_{20}^2}{R_0 + \omega^2 L_0} L_0 - \sum_{n=1}^{k} \frac{\omega^2 M_{2n}^2}{R_{0(n)} + \omega^2 L_{0(n)}} L_{0(n)} \). The imaginary part of (6) is

\[
\text{Im}(Z''_m) = \omega L_1 - \frac{\omega M'_{12}^2}{\omega C_2} - \frac{1}{\omega C_2} R_{sec} + \left( \frac{\omega L_2' - \frac{1}{\omega C_2}}{\omega C_2} \right)^2
\]  

(7)

The denominator of the last term in (7) is larger, so the value of the last term is extraordinarily smaller than the first two terms. Therefore, the resonant frequency point of the entire system will only change slightly and the resonant frequency has almost no offset. However, due to the variation of the resonant frequency at the secondary side, the system has incomplete energy exchange and transmission. In addition, the reduction of mutual inductance further reduces the ability of energy exchange.

It can be summarized from the above analysis that under the action of the large non-ferromagnetic aluminum alloy plate, the transmission performance \( \beta \) of the system is affected and interfered to a large extent. The essential problems are the decrease of the self-inductance of the receiver coil and the mutual inductance of the system, accompanied by the eddy current loss. Therefore, the optimization strategy is necessary to improve the self-inductance of the receiver coil and mutual inductance to minimize their deviation and the eddy current electromagnetic field without changing the parameters of the coil system.

As for ferromagnetic materials, the electromagnetic field effect for the coil system is more obvious than the non-ferromagnetic material due to its large magnetic permeability and small electrical conductivity. However, owing to the nonlinearity of the magnetic material, the calculation manifests extremely complicated and difficult to formulate [25]. The influence characteristic can be known by finite element simulation and experiment. According to [24], [28], the addition of ferrite ferromagnetic material can improve the self-inductance of the coil system and significantly improve mutual inductance of the WPT system. Moreover, the eddy current effects it brings can be reduced by corresponding
measures [25-28]. Therefore, this paper will implement the optimization in the form of additional ferrite.

III. SIMULATION OPTIMIZATION

This part confirms the circuit analysis from the perspective of simulation. With the help of magnetic field distribution figures, this part puts forward a unique optimization method and its characteristic distribution and regulation mode. The improved optimization scheme is proposed to reduce eddy current loss.

A. simulation model

In this paper, the high-coupling coil system model is firstly established as shown in Fig.5. Due to the requirement of the coil system, the coil system is equipped with matched ferrite. The assembly parameters are shown in Table I.

Table I Parameters of high-coupling coil system

<table>
<thead>
<tr>
<th>Object</th>
<th>Parameters</th>
<th>Value/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coils</td>
<td>external diameters</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>length</td>
<td></td>
</tr>
<tr>
<td></td>
<td>external diameters</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>width</td>
<td></td>
</tr>
<tr>
<td></td>
<td>turn spacing</td>
<td>10</td>
</tr>
<tr>
<td>Ferrite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>length</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>width</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>thickness</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>distance from coil</td>
<td>1</td>
</tr>
</tbody>
</table>

The large surface plate and curved plate of aluminum alloy are constructed as shown in Fig.6, whose covered area is more than 10 times the covered area of the coil. The curved plate is a hollow hemispheric sphere.

B. Analysis of metal impact on WPT system

The magnetic field strength around the coil system under different conditions is shown in Fig.7 utilizing ANSYS Maxwell magnetic field simulation tool. Fig.7(b) and Fig.7(c) demonstrate that whether the WPT system is in the presence of aluminum alloy surface or curved plate, the value of the induced magnetic field strength on the back side of plates is extremely low, which means that the aluminum plate completely blocks the magnetic flux lines. Compared with the surface plate, the area of the curved plate whose magnetic field strength value is high is large, so the degree of influence of the curved plate is smaller than that of the surface plate. Table II shows the influence of the surface and curved plate on the parameters of the WPT system under simulation conditions, and confirms the above analysis, which also verifies the analysis of circuit in section II.

Table II Influence of the large metal plate on system parameters

<table>
<thead>
<tr>
<th>Condition</th>
<th>Primary coil inductance</th>
<th>Secondary coil inductance</th>
<th>Self-inductance deviation (maximum)</th>
<th>Mutual inductance</th>
<th>Mutual inductance deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>95.99μH</td>
<td>95.95μH</td>
<td>0%</td>
<td>24.57μH</td>
<td>0%</td>
</tr>
<tr>
<td>Surface plate</td>
<td>91.25μH</td>
<td>77.87μH</td>
<td>-18.84%</td>
<td>16.26μH</td>
<td>-33.82%</td>
</tr>
<tr>
<td>Curved plate</td>
<td>93.56μH</td>
<td>88.67μH</td>
<td>-7.59%</td>
<td>20.62μH</td>
<td>-16.08%</td>
</tr>
</tbody>
</table>

The β value of the system before and after the effect of the metal plate is calculated by MATLAB simulation combined with (5). The simulation frequency is set to 85kHz, and the circuit parameters adopt the parameters in Table II. The AC power supply voltage is 200V, and the resistance of transmitter and receiver coil is 0.1Ω from ANSYS simulation. The effect of eddy current loss is temporarily ignored. In order to prevent frequency and power splitting under low load and high coupling, the load value is set to 25 Ω. The calculation results are shown in Table III.
Tables II and III indicate that in the presence of the large surface plate, the self-inductance deviation maximum is 18.84%, and the mutual inductance is reduced severely by 33.82%. As for the $\beta$, the maximum deviation is 14.77%. However, the effect of curved plate is relatively mild. The mutual inductance is reduced by 16.08% and the value of $\beta$ is only decreased by 1.32%. The magnitude of parameter deviation determines the strength of the plate’s influence.

Therefore, the optimization goal of the paper is to amend the deviations of self-inductance and mutual inductance and ensure the value of $\beta$ as large as possible to guarantee the transmission performance of the system.

C. Formation of optimization scheme

From the perspective of magnetic field aggregation, in whatever circumstances, the more magnetic flux lines of self-inductance and mutual inductance passing through the coil loop area, the larger value of corresponding self-inductance and mutual inductance. Therefore, the magnetic field distribution in free space and different metals environment are shown in Fig.8.

![Magnetic field distribution under different conditions](image)

**FIGURE 8. Magnetic field distribution under different conditions**

Fig.8(b) and Fig.8(c) show that the magnetic flux lines of self-inductance from the transmitter coil are basically unaffected, and few flux lines sent to distant place are blocked. Nevertheless, the mutual inductance flux lines generated by the transmitter coil are blocked at the aluminum plate and can’t form a closed loop. The flux lines of self-inductance from receiver coil are also affected. When it is in the curved plate situation, due to the existence of some gaps between receiver coil and plate, there are several flux lines of self-inductance and mutual inductance going across the receiver coil through the gaps. Therefore, the influence of curved plate is slightly smaller than that of surface plate.

According to the optimization direction in Section II, we add a ferrite plate to the secondary coil for magnetic field aggregation. Firstly, the ferrite can’t block the distribution of flux lines, so it is required to avoid distributing in the middle of the coil transmission path. Then, when the ferrite is arranged along with magnetic flux lines, it has a better effect on magnetic field aggregation from our diversified tests, and the improvement effect of the coil parameters is also better. However, it is worth noting that the scheme needs avoiding excessive correction of self-inductance, which also leads to a deviation from the resonant state of secondary circuit. Considering the above requirements, this paper forms a preliminary optimization scheme by measuring the direction of magnetic flux lines of the receiver coil in Fig.8. We add a pair of ferrite plate of the same size at a horizontal distance ($x$ mm) from short edge of receiver coil (adding the ferrite on the long edge of the coil will result in excessive self-inductance correction), and its length $F_1$ is the same as the width of the coil. The thickness of ferrite $F_3$ is 5 mm, and the width is set to $F_2$. The angle between the distribution direction of the ferrite plate and the vertical line is set to $\alpha$. We form a ferrite optimization scheme as shown in Fig.9.

![The parameters setting of ferrite optimization scheme](image)

**FIGURE 9. The parameters setting of ferrite optimization scheme**

Next, the regulation rules of parameters in the optimization scheme are analyzed. The variation curves of self-inductance and mutual inductance between transmitter and receiver coils under different metal plates are obtained by changing the values of $\alpha$, $x$ and $F_2$ as shown in Fig.10-12.
while the effect is weak under the curved plate. Whether the system is under the surface plate or curved plate, the augmentation of \( F_2 \) has the identical enhancement effect of the mutual inductance. Therefore, we can reduce the deviation of the metal plate on the self-inductance and mutual inductance of coils by increasing \( F_2 \). The augmentation of \( \alpha \) will result in a sharp decrease in the self-inductance of the receiver coil and a moderate increase of mutual inductance. Hence, the adjustment of \( \alpha \) can be used to avoid excessive modification of self-inductance in the optimization scheme. The regulation rule of \( x \) parameter for self-inductance of the receiver coil and mutual inductance is similar to \( \alpha \) parameter, except that the increase of \( x \) will also bring the decline of mutual inductance. The adjustment of \( x \) can also avoid excessive modification of self-inductance.

Considering the requirement for maintaining high mutual inductance, the value of \( x \) should not be high. Under different coil systems, the above three parameters can also be adjusted to reduce the influence of metal plates, which indicates that the method in this paper has universality. The optimization scheme of ferrite is finally formed by adjusting the values of \( F_2 \), \( \alpha \) and \( x \), and the parameters are tabulated in Table IV. The adjustment effect is shown in Fig.13. The regulation rule of parameter \( F_2 \) (\( \alpha = 30^\circ \), \( x = 0 \)mm) is shown in Fig.10, the regulation rule of parameter \( \alpha \) (\( F_2 = 130 \)mm, \( x = 0 \)mm) is shown in Fig.11, and the regulation rule of parameter \( x \) (\( F_2 = 130 \)mm, \( \alpha = 30^\circ \)) is shown in Fig.12.

**TABLE IV**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Length ( F_1 )(mm)</th>
<th>Width ( F_2 )(mm)</th>
<th>Thickness ( F_3 )(mm)</th>
<th>Angle ( \alpha )</th>
<th>Horizontal offset distance ( x )(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface plate</td>
<td>500</td>
<td>130</td>
<td>5</td>
<td>30(^\circ)</td>
<td>0</td>
</tr>
<tr>
<td>Curved plate</td>
<td>500</td>
<td>100</td>
<td>5</td>
<td>30(^\circ)</td>
<td>2</td>
</tr>
</tbody>
</table>

**FIGURE 10.** The regulation rule of parameter \( F_2 \) (\( \alpha = 30^\circ \), \( x = 0 \)mm)

**FIGURE 11.** The regulation rule of parameter \( \alpha \) (\( F_2 = 130 \)mm, \( x = 0 \)mm)

**FIGURE 12.** The regulation rule of parameter \( x \) (\( F_2 = 130 \)mm, \( \alpha = 30^\circ \))

Fig.10-12 indicate that the variation of the three parameters has little effect on the self-inductance of the transmitter coil. The augmentation of \( F_2 \) has a prominent effect on improving self-inductance under the surface plate, while the effect is weak under the curved plate. Comparing the magnetic flux lines in Fig.13 and Fig.8, we clearly obtain that in the case of a surface plate, the extra

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ferrite plate aggregates the magnetic flux lines which was shielded initially. In the case of the curved plate, additional ferrite plate will provide a new loop path for the original magnetic flux lines. The correction results of the parameters and the improvement results of the β are shown in Table V.

<table>
<thead>
<tr>
<th>Condition(simulation)</th>
<th>Transmitter coil inductance</th>
<th>Receiver coil inductance</th>
<th>mutual inductance</th>
<th>The value of β</th>
<th>optimization effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>95.99μH</td>
<td>95.95μH</td>
<td>24.57μH</td>
<td>98.17%</td>
<td>0%</td>
</tr>
<tr>
<td>Surface plate</td>
<td>91.25μH</td>
<td>77.87μH</td>
<td>16.26μH</td>
<td>83.67%</td>
<td>+13.15%</td>
</tr>
<tr>
<td>Surface plate (after optimization)</td>
<td>94.27μH</td>
<td>95.93μH</td>
<td>22.79μH</td>
<td>96.82%</td>
<td></td>
</tr>
<tr>
<td>Curved plate</td>
<td>93.56μH</td>
<td>88.67μH</td>
<td>20.62μH</td>
<td>96.87%</td>
<td></td>
</tr>
<tr>
<td>Curved plate (after optimization)</td>
<td>94.42μH</td>
<td>95.37μH</td>
<td>22.90μH</td>
<td>97.19%</td>
<td></td>
</tr>
</tbody>
</table>

Table V effectively proves the remarkable optimization effect of the optimization scheme. The optimization effect of curved plate’s condition is inferior to surface plate’s condition, which may be due to the fact that the curved plate essentially has less impact on the system. The optimization effect on the surface plate is more evident. Even in the most severe surface metal plate environment, the maximum deviation value 14.77% of transmission performance measurement parameter β has been increased by 13.15%, and the maximum deviation of self-inductance 33.82% has been completely corrected, which represents that the whole system has returned to resonant operation state.

D. Improvement of optimization scheme

The above schemes temporarily ignore the eddy current loss, and extra ferrite plate will bring extra eddy current loss. Therefore, the optimization scheme needs to be improved to reduce the eddy current loss without affecting the optimization effect. The possible improvement strategies are set up as shown in Fig.14, and Maxwell eddy current loss calculation tool is utilized to measure the loss.

![FIGURE 14. The improvement strategies: different distributions of the ferrite](image)

The whole ferrite under large curved plate is divided into n=1,4,8,16 ferrites and distributed in equal distance. The eddy current loss of the system under different quantity schemes is obtained as shown in Fig.15.

According to Fig.15, when n is 4, the overall eddy current loss is reduced to the minimum, and the improvement effect of self-inductance and mutual inductance of the system is basically unchanged in the case of 4 ferrites distribution according to additional testing. Fig.14(b) is determined as the final scheme. We add the additional eddy current loss to the calculation of β, and we obtain that the value β of the improved optimization result is 96.75%. The β of original scheme is 95.89% after adding the eddy current loss, which verifies the improved scheme.

![FIGURE 15. The distribution of eddy current loss results](image)

IV. EXPERIMENTAL VERIFICATION

This part verifies the improvement effect of the optimization scheme on different metal plates and effectively verifies the feasibility and novelty of the optimization scheme in this paper.

Two experimental coils with nearly the same size as the simulation are fabricated. Coil winding and ferrite layouts are modeled in strict and accurate accordance with the sizes of Fig.5 and Table I. Coil winding and the whole system are shown in Fig.16.

![FIGURE 16. The physical layout of coil system](image)
The experiment utilizes LCR meter 3522-50 LCR HiTESTER (Hioki E.E. Corporation, Nagano Prefecture, Japan) to implement the measurement of self-inductance and mutual inductance of coils. The oscilloscope is used to measure the primary and secondary current, voltage and transmission performance parameter $\beta$. In addition, it also includes high frequency power source, coil system (including transmitter and receiver coils, coil system ferrite), compensation capacitor, AC resistance load, current detector, voltage detector and isolating probe. Complete set of experimental measurement equipment distribution is displayed in Fig.17.

![Experimental equipment distribution](image)

**FIGURE 17.** The experimental measurement equipment distribution

To highlight the consistency between simulation and experiment, the resonant frequency of the system is set to 85kHz, and the system equivalent load is set to 25Ω. The inductance parameters are measured and the capacitances are rational allocated. Basic experimental parameters in free space are shown in Table VI. Experimental waveforms of primary input voltage, current and load voltage, current in free space are shown in Fig.18.

![Experimental waveforms](image)

**FIGURE 18.** The experimental waveforms in free space

Comparing the free space parameters in Table VI and Table V, the self-inductance value of the constructed physical coil has nearly 10% error compared with the simulation value, which may be caused by the winding technology and is within the acceptable range. Fig.18(a) shows that the primary voltage and current are in phase and have a phase difference of 90° from the secondary voltage. Fig.18(b) shows the load voltage and current are in phase and have a phase difference of 90° from the primary input voltage, which is consistent with the state of the circuit at resonance. It is worth noting that due to the large setting of the load resistance, the reflection impedance of the circuit is small. Therefore, the input voltage will generate a ringing overshoot phenomenon at the end of the rising phase and the end of the falling phase, but its effect on the $\beta$ can be ignored. The system $\beta$ in the free space is calculated as 96.96%.

**TABLE VI**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>Transmitter coil self-inductance</td>
<td>111.52μH</td>
</tr>
<tr>
<td></td>
<td>Receiver coil self-inductance</td>
<td>111.14μH</td>
</tr>
<tr>
<td></td>
<td>Mutual inductance</td>
<td>27.29μH</td>
</tr>
<tr>
<td></td>
<td>The value of $\beta$</td>
<td>96.96%</td>
</tr>
<tr>
<td></td>
<td>Transmitter capacitance</td>
<td>31.44nF</td>
</tr>
<tr>
<td></td>
<td>Receiver capacitance</td>
<td>31.55nF</td>
</tr>
<tr>
<td></td>
<td>load resistance</td>
<td>25Ω</td>
</tr>
</tbody>
</table>
The surface plate and the curved plate are established as shown in Fig.19. The surface plate area is about 9 times of the coil, and the curved plate area is about 5 times more than the coil. Due to the fixed problem in reality, the curved plate is composed of several surface plates which are bent at an angle and fixed by human power (not shown in Fig.19), and the coil parameters and $\beta$ are measured as shown in Table VII.

![Large surface plate and Coil system](image)

**FIGURE 19.** Experimental configuration of surface and curved plate

<table>
<thead>
<tr>
<th>Condition (experiment)</th>
<th>Transmitter coil inductance</th>
<th>Receiver coil inductance</th>
<th>Mutual inductance</th>
<th>The value of $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>111.52(\mu)H</td>
<td>111.14(\mu)H</td>
<td>27.29(\mu)H</td>
<td>96.96%</td>
</tr>
<tr>
<td>Surface plate</td>
<td>111.10(\mu)H</td>
<td>97.102(\mu)H</td>
<td>22.745(\mu)H</td>
<td>90.18%</td>
</tr>
<tr>
<td>Curved plate</td>
<td>111.30(\mu)H</td>
<td>106.75(\mu)H</td>
<td>24.59(\mu)H</td>
<td>94.75%</td>
</tr>
</tbody>
</table>

Comparing Table VII with Table II and Table III, it can be found that the variation tendency is basically the same, and the self-inductance of receiver coil is reduced by 18%, which can effectively verify the correctness of the corresponding simulation. The difference is that the influence of the surface plate and the curved panel moderately declines in practice compared with the simulation results. Besides, the influence on the $\beta$, mutual inductance and self-inductance of the secondary coil declines. The reason is that the actual surface and curved panel are smaller than the simulation due to the actual condition.

As shown in Fig.20, the ferrite is assembled and fixed with the same parameters $F_1$-$F_3$ as the optimization scheme on the plastic plate, and the plastic plate is slanted on the short side of the receiver coil to construct the corresponding angle $\alpha$. A plastic foam sheet of corresponding thickness $x$ is added to the short side of the receiver coil. Eventually, the distribution of the ferrite is consistent with the setting of the optimization scheme.

![Ferrite assembly in surface plate and curved plate](image)

**FIGURE 20.** Parameters setting of the optimization scheme

The primary and secondary waveforms are measured before and after optimization. The corresponding $\beta$ is calculated to observe the optimization effect. The typical waveform diagram is shown in Fig.21.
Before the optimization, the metal plate makes the primary side voltage waveform appear more severe distortion, and the primary side voltage and current have a certain phase angle, which means that the circuit enters the non-resonant state. At the same time, due to the peak shift of the input voltage, we compare the half cycle of the input voltage and load voltage. Fig.21(a) demonstrates that the first half of the input voltage is less than 180° while the second half is greater than 180°, and the input voltage and load voltage no longer exhibit a 90° phase angle difference. Fig.21(b) shows that after applying the optimization scheme, the primary voltage is basically in phase with the primary current, and has a phase angle of 90° with the load voltage, which is basically consistent with the waveform in Fig.18. Therefore, after applying the optimization scheme, the system returns to the resonant state and maintains normal operation. The optimization scheme is reasonable and effective. The transmission performance parameter results are recorded in Table VIII. The results comparisons of receiver coil inductance between simulation and experiment are illustrated in Fig.22.

![Image](image_url)

**FIGURE 21.** The optimization effect of the optimization scheme

Before the optimization, the metal plate makes the primary side voltage waveform appear more severe distortion, and the primary side voltage and current have a certain phase angle, which means that the circuit enters the non-resonant state. At the same time, due to the peak shift of the input voltage, we compare the half cycle of the input voltage and load voltage. Fig.21(a) demonstrates that the first half of the input voltage is less than 180° while the second half is greater than 180°, and the input voltage and load voltage no longer exhibit a 90° phase angle difference. Fig.21(b) shows that after applying the optimization scheme, the primary voltage is basically in phase with the primary current, and has a phase angle of 90° with the load voltage, which is basically consistent with the waveform in Fig.18. Therefore, after applying the optimization scheme, the system returns to the resonant state and maintains normal operation. The optimization scheme is reasonable and effective. The transmission performance parameter results are recorded in Table VIII. The results comparisons of receiver coil inductance between simulation and experiment are illustrated in Fig.22.

**TABLE VIII**

<table>
<thead>
<tr>
<th>Condition (experiment)</th>
<th>Transmitter coil inductance</th>
<th>Receiver coil inductance</th>
<th>Mutual inductance</th>
<th>The value of $\beta$</th>
<th>Optimization effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>111.52μH</td>
<td>111.14μH</td>
<td>27.29μH</td>
<td>96.96%</td>
<td>0%</td>
</tr>
<tr>
<td>Surface plate (before optimization)</td>
<td>111.10μH</td>
<td>97.102μH</td>
<td>22.745μH</td>
<td>90.18%</td>
<td>+5.54%</td>
</tr>
<tr>
<td>Surface plate (after optimization)</td>
<td>111.75μH</td>
<td>110.50μH</td>
<td>25.60μH</td>
<td>95.72%</td>
<td></td>
</tr>
<tr>
<td>Curved plate (before optimization)</td>
<td>111.30μH</td>
<td>106.75μH</td>
<td>24.59μH</td>
<td>94.75%</td>
<td></td>
</tr>
<tr>
<td>Curved plate (after optimization)</td>
<td>112.42μH</td>
<td>111.50μH</td>
<td>22.90μH</td>
<td>95.80%</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 22.** The results of receiver coil inductance in simulation and experiment

Table VIII and Fig.22 effectively verifies the feasibility and correctness of optimization scheme. Even in the most severe surface metal plate environment, transmission performance measurement parameter $\beta$ increased by 5.54%. The improvement effect is slightly lower than the corresponding value 13.15% of the simulation. Fig.22 demonstrates that the optimization scheme has restored the WPT system to resonant state both in simulation and in experiment. The correction effect of the experiment is inferior to the simulation whether under surface plate or curved plate, because the influence of the actual metal plate is smaller than that of the simulation, so the improvement
effect of optimization scheme is not absolutely manifested. The eddy current improved scheme is subsequently verified. In the background of the curved plate, a ferrite plate with \( n=4 \), \( n=8 \) and \( n=16 \) as shown in Fig.23 is built for verification. Since the eddy current can’t be measured in practice, the value of \( \beta \) under the different numbers of ferrite plates is recorded to evaluate the improvement effect in Table IX, and the improvement effect of the eddy current improved scheme is consistent with the simulation.

![Figure 23](image)

**FIGURE 23.** Different distributions of the ferrite in the experiment

**TABLE IX**

<table>
<thead>
<tr>
<th>Ferrite quantity</th>
<th>The value of ( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>95.80%</td>
</tr>
<tr>
<td>4</td>
<td>96.20%</td>
</tr>
<tr>
<td>8</td>
<td>95.12%</td>
</tr>
<tr>
<td>16</td>
<td>95.30%</td>
</tr>
</tbody>
</table>

Moreover, in order to make the proposed method more practical, we suggest that in the practical applications, the ferrite plate can be installed by an auxiliary plastic frame. The frame is shown in Fig.24, which can be expediently placed above the receiver coil.

![Figure 24](image)

**FIGURE 24.** The installation method of the proposed ferrite

V. CONCLUSIONS

In this paper, an optimization method using additional ferrite with unique distribution and regulation methods is proposed to solve the influence problem of large metal plate on WPT system. Moreover, the eddy current improved scheme is proposed to further improve integrity and availability of optimization method. Firstly, the influence of metal plate on WPT system is analyzed based on the circuit model and is verified through the simulation and experiment. We conclude that the large metal will result in the serious deviation of self-inductance and mutual inductance of coil system. The maximum deviation can be nearly 33%. Subsequently, the specific optimization scheme is obtained by analyzing the magnetic flux lines based on magnetic aggregation. We conclude that the optimization scheme has great improvement effect on magnetic field and transmission performance parameter. The transmission performance parameter can be increased by 5.54% according to the experiment and the distortion of waveforms is basically eliminated. Finally, the eddy current improved scheme is obtained by analyzing various schemes. In summary, by using the proposed method, the WPT system could operate normally in large metal environment such as ship or rocket, and the coil parameters will be corrected to the values in free space. The transmission performance will also be improved. Moreover, the proposed method is verified to be effective and available through experiment. In addition, for different WPT systems, once it is in a complex metal environment, we can adjust the distribution parameters in the paper to achieve the same improvement effect.

REFERENCES


