Research on the Characteristics of Wireless Power Transfer in Non-ferromagnetic Metal Pipe

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Abstract. With the development of various electronics, the way of transmitting energy by wire has brought increasingly negative effects on the operability and convenience of products. As wireless power transfer (WPT) technology requires no transmission lines, it has received increasingly wide attention. Most of the previous research on the technology of magnetic resonant coupling WPT mainly focused on the transmission of energy in the air. This paper establishes the wireless power transfer system model under non-ferromagnetic metallic environment and studies the effect of non-ferromagnetic metallic environment on coil self-inductance L, mutual inductance M and coil resistance R of WPT system. On this basis, the study on the relationship between coil diameter and mutual inductance is carried out for aluminium pipe, and the relationship between coil diameter and diameter of metal pipe at the maximum mutual inductance is fitted. Besides, experimental verification is conducted for the change of mutual inductance between the coils of WPT system in the aluminium pipe, presenting that the actual measurement results of mutual inductance in the aluminium pipe are consistent with the theory.

1. Introduction

With the application of various electronic products, people's requirements for products is increasingly high. WPT has flexible power supply mode and no mechanical loss, and enjoys the advantages of long service life and being applicable to special occasions[1]. Therefore, it has become a hot research topic at home and abroad, and a growing number of new methods and concepts have been developed. With few years of development, this technology has been widely used in different fields such as electric vehicles, portable mobile devices, medical devices, submarines[2-4]. At present, the research at home and abroad mainly focuses on free space, liquid and other environments. However, when there are metal objects in the transmission space, metal will have a great impact on the magnetic field, changing the distribution of the magnetic field, affecting coil coupling, and even destroying the transmission state.

With the experimental method, Kenichiro Ogawa et al. approach the small-sized aluminium sheet to the transfer coil to observe the decrease in transfer efficiency of the system[5]. Yang Qingxin et al. of Tiangong University analysed the change rule of equivalent parameters of iron, aluminium and copper, and studied the influence of different metal obstacles on the system when placed inside the system[6]. Jae Hee Kim et al. studied adding metal plates to the WPT system, slotting on the metal plates to maximize the transfer efficiency[7]. Feng Wen et al. discussed the method of reducing negative effects by shield slotting. However, the influence of metal objects around the transmission system on the
transmission characteristics of the system still needs to be further studied. Jiacheng Li et al. analysed
the influence of the distance between the shield plate and coil on parameters of coil, resonance
frequency and transfer efficiency\[9\]. On this basis, this paper studies the influence of non-
ferromagnetic metallic environment on WPT system. The system simulation model is established.
Based on the simulation model, we learned the influence of metal pipe conductivity on system
parameters, the influence of non-ferromagnetic metallic environment and relative distance on coil
mutual inductance and the condition of the maximum value of coil mutual inductance. Finally, the
correctness and accuracy of the simulation model are verified by experiments.

2. Eddying Effect of Metals
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2.1. Formatting the title
When the conductor is in a changing magnetic field or moving in a magnetic field, there will be eddy
induced current inside the conductor. This current is called eddy current, which is called eddy for short,
and this induced phenomenon is called eddying effect.

In a WPT system in a metallic environment, its receiving and transmitting coils in a metal pipes
are as shown in Fig.1. The metal pipe is regarded as a collection of infinite conductive rings with a
small thickness. When a high-frequency alternating current is introduced into the wireless transfer coil,
an alternating electromagnetic field will be generated around the coil. According to Faraday's law of
electromagnetic induction, a tiny conductive ring will generate induced electromotive force $\varepsilon$.

![Fig. 1 Eddying Effect of Wireless Transfer Coil in Metal Pipe](image)

Inductive current $i$ will be generated in the tiny metal conductive ring, and its magnitude can be
expressed as below:

$$i = \varepsilon \frac{\sigma \cdot r^2}{2R}$$  (1)

$R$ refers to the radius of the tiny metal conductive ring, $r$ refers to the cross-sectional radius of the tiny
conductive ring, and $\sigma$ refers to the conductivity of the metal material.

3. Influence of Medium Conductivity on WPT System
Metal mainly affects the transfer performance of the WPT system by influencing the electromagnetic
field. According to the equations of electromagnetics, conductivity $\sigma$ is an important parameter. It is
necessary to understand the influence of conductivity on system performance. Table 1 Model Parameter
Setting in Metallic Environment
The electromagnetic field is studied by ANSYS Electronics Desktop simulation software. The system simulation model is established by two-dimensional axial symmetry, as shown in Fig. 2. Refer to Table 1 for model parameters.

The operating frequency is 1MHz, and the conductivity $\sigma$ of the metal pipe is 1, 1000, 10000 and 100000(S/m) respectively. The magnetic field intensity maps and magnetic induction line distribution simulated by the system are shown in Fig. 3.

![Finite Element Simulation Model in Metallic Environment](image)

**Fig. 2. Finite Element Simulation Model in Metallic Environment**

### Table 1. Model Parameter Setting in Metallic Environment.

| Parameters of Coil | Parameters of Metal Pipe |
|--------------------|-------------------------|
| Coil Diameter R_Coil1, R_Coil2/mm | 80 | 125 |
| Wire Diameter $r$/mm | 1 | Wall Thickness of Metal Pipe $t$/mm | 5 |
| Distance Between Coils $d_{12}$/mm | 30 | Length of Metal Pipe $h$/mm | 200 |
| Coil Material Cu | Relative Permeability $\mu_r$ | 1 |
| Coil Turns $N_1, N_2$ | 10 | Conductivity $\sigma$/S·m-1 | Variables |

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![Distribution of Magnetic Field and Magnetic Induction Line in Metallic Environment](image)

**Fig. 3 Distribution of Magnetic Field and Magnetic Induction Line in Metallic Environment with Different Medium Conductivity**

As can be seen from Fig.3, when the conductivity of the external metal pipe $\sigma$=1S/m, the electromagnetic field distribution between the two coils is not affected by the metal pipe. When the conductivity $\sigma$ of the metal pipe increases to 1000S/m, the electromagnetic field between the coils begins to penetrate into the metal pipe. This is because of the eddying effect in the metal pipe. When the conductivity $\sigma$ increases to 10000S/m, the magnetic field strength in the inner wall of the metal pipe increases significantly, the magnetic field depth in the metal pipe decreases, the skin effect of the eddy begins to be obvious, and the magnetic induction line has been completely bound in the inner wall of the metal pipe. When the conductivity $\sigma$ increases to 100000S/m, the magnetic field on the inner wall of the metal pipe reaches to the maximum strength, the magnetic induction line is
completely bound in the metal pipe, the magnetic induction phenomenon in the metal pipe is basically concentrated on the surface of the inner surface wall, and the skin effect of the eddy reaches to the strongest.

For the purpose of further exploring the influence of metal pipe conductivity on coil parameters of WPT system, the relationship between mutual inductance M, self-inductance L, resistance R and metal medium conductivity σ is studied respectively.

In Fig.4(a), with the conductivity of the metal pipe increases, the mutual inductance of the coil decreases rapidly first, then it reaches to the minimum, and remains unchanged finally. In Fig.4(b), with the increase of the conductivity of the metal pipe, the self-inductance L of the coil rapidly decreases from 14.697μH of the maximum value to 12.75μH, and remains basically unchanged finally. In Fig.4(c), with the increase of the conductivity of the metal pipe, the resistance R of the coil will increase from 0.04387 Ω to the peak value of 5.698 Ω rapidly (the conductivity is 1200S/m at this time), and then gradually decrease to about 1 Ω.

In conclusion, the greater the conductivity of the metal pipe, the smaller the mutual inductance M between the receiving and transmitting coils and the self-inductance L of the coils. At the initial stage of conductivity change, mutual inductance M and self-inductance L of the coil decrease rapidly. However, when the conductivity of the metal pipe exceeds a certain value, the decrease of the coil parameters trended slowly. The resistance R of the coil increases sharply with the increase of metal conductivity and then decreases rapidly after reaching the peak value. The influence of metal conductivity parameters on the parameters of the wireless transfer coil reaches the peak with the change of the metal conductivity, and the M, L and R of the coil will tend to be stable.

4. Mutual Inductance of Coils in Aluminium Pipes
As the coupling coils of WPT system are widely distributed in the metal pipe, the coil structure in different situations is shown in Fig. 5. The larger the coil diameter is, the closer it is to the inner wall of the metal pipe, the more obvious the influence of the metal pipe will be. The smaller the coil diameter is, the less the influence of the metal pipe will be, but the mutual inductance of the coil will be reduced, and the coupling coefficient of the coil itself will be smaller. Therefore, it is necessary to study the influence of the structural parameters of the coil in the metal pipe on the WPT system.

In this paper, the metal pipe is made of aluminium. The conductivity of aluminium pipes is 33 million S/m. When the coils' mutual inductance M of the WPT system in the aluminium pipe reaches
the maximum, the relationship between the coil diameter \( R_{\text{Coil}} \) and the inner diameter \( R_{\text{Pipe}} \) of the metal pipe can be studied.

The mutual inductance between the structure of the receiving and transmitting coils is one of the decisive factors of the coupling degree between the transmitting and the receiving end of the system, and it is the key parameter affecting the transfer performance of the system. When the mutual inductance is small, the coupling coefficient between the transmitting and the receiving end of the system will be small and the performance of the system will decrease. Therefore, the increase of the mutual inductance between the transmitting and receiving coils in the system can improve the transfer performance of the system. As the mutual inductance of the coil in the aluminium pipe will be affected by the aluminium pipe, the mutual inductance between the coils will not increase with the increase of the coil diameter. On the contrary, the larger the coil, the more obvious the influence of the aluminium pipe. Therefore, for the WPT system operated in the aluminium pipe, there must be a maximum value of mutual inductance between the coils. When the maximum value of mutual inductance is taken, it's expected to make clear the relationship between coil diameter \( R_{\text{Coil}} \) and inner diameter \( R_{\text{Pipe}} \) of the aluminium pipe during research, design, and optimization of WPT system. The relationship between the diameter of the coil and the inner diameter of the aluminium pipe is also the condition for the maximum mutual inductance of the coil in the WPT system in the aluminium pipe.

The working frequency of 1MHz is set. For other parameters, refer to Table 2. Based on the use of the finite element analysis software ANSYS Electronics Desktop, the coil diameter and the inner diameter of aluminium pipe are scanned respectively, presenting the three-dimensional surface as shown in

### Table 2 Parameters of WPT System Simulation Model in Aluminium Pipe

| Parameters of Coil | Parameters of Aluminium Pipe |
|-------------------|-----------------------------|
| Coil Diameter \( R_{\text{Coil1}}=R_{\text{Coil2}} \)/mm | Variable 1 | Inner Diameter of Aluminium Pipe \( R_{\text{Pipe}} \)/mm | Variable 2 |
| Wire Diameter \( r \)/mm | 1 | Wall Thickness of Aluminium Pipe \( t \)/mm | 5 |
| Distance between Coils \( d_{12} \)/mm | 30 | Length of aluminium pipe \( h \)/mm | 200 |
| Coil Material | Copper | Relative Permeability \( \mu \) | 1.000021 |
| Coil Turns \( N_1, N_2 \) | 10 | Conductivity \( \sigma \)/S·m | 33000000 |

Fig. 6 (a) Change of Mutual Inductance Between Receiving and Transmitting Coils in Aluminium Pipe

In Fig. 6(a), the XY plane corresponds to the coil diameter \( R_{\text{Coil}} \) and the inner diameter of the aluminium pipe \( R_{\text{Pipe}} \) respectively, and the vertical scale corresponds to the mutual inductance \( M \) of the coil. For coils with the same diameter, the larger the inner diameter of the aluminium pipe is, the larger the mutual inductance is, indicating that the influence on the aluminium pipe can be reduced when the coil is away from the aluminium pipe. In an aluminium pipe with the same inner diameter, there is a peak value for the mutual inductance between coils, which is a curve of single peak. When the inner diameter of the aluminium pipe is 125 mm, the maximum mutual inductance of the receiving
and transmitting coil is 771.5nH, and the diameter of the coil $R_{\text{Coil}}$ is 80 mm at this time. Fig. 6(b) is a scatter diagram showing the relationship between the coil diameter $R_{\text{Coil}}$ and the inner diameter of the aluminium pipe $R_{\text{Pipe}}$ in case of reaching peak point. According to Fig.6(b), the relationship curve expression between coil diameter and inner diameter of aluminium pipe can be as follows:

$$R_{\text{Coil}}=0.64757 \times R_{\text{Pipe}} – 1.89714$$

The above formula refers to the conditions when the mutual inductance of the receiving and transmitting coil of the WPT system in the aluminium pipe reaches to the maximum value. When the inner diameter of the aluminium pipe is determined, the coil diameter at which the peak point of mutual inductance is obtained can be worked out according to the above formula.

5. Experiment on Mutual Inductance of Coils in Aluminium Pipe

For the purpose of the verification of the theory in Section 4, the analyser of HIOKI 3532-50 LCR is adopted to measure the mutual inductance $M$ of the coil. The inner diameters of aluminium pipes are 70 mm, 80 mm, 90 mm and 100 mm respectively, and the diameters of coils are 36 mm, 46 mm, 56 mm, 66 mm and 76 mm respectively. The experiment conditions are shown in Fig. 7.

![Fig. 7 (a) Aluminium Pipes and Coils in Experiment](image)

The measurement of mutual inductance between coils with different diameters in aluminium pipes with different inner diameters is carried out respectively. Table 3 shows the theoretical and experimental data of mutual inductance of coils in aluminium pipes.

| Type   | $R_{\text{Coil}}$/ $R_{\text{Pipe}}$ | 76mm | 66mm | 56mm | 46mm | 36mm |
|--------|-----------------------------------|------|------|------|------|------|
| Theoretical Value | 70mm | --- | --- | 0.0369 | 0.0646 | 0.0571 |
|             | 80mm | --- | 0.0599 | 0.1161 | 0.1241 | 0.0867 |
|             | 90mm | 0.0868 | 0.1815 | 0.2171 | 0.1835 | 0.1131 |
|             | 100mm | 0.2566 | 0.3323 | 0.3170 | 0.2363 | 0.1349 |
| Experimental Value | 70mm | --- | --- | 0.0368 | 0.0658 | 0.0534 |
|             | 80mm | --- | 0.0618 | 0.119 | 0.129 | 0.089 |
|             | 90mm | 0.0858 | 0.1828 | 0.2178 | 0.1845 | 0.1088 |
|             | 100mm | 0.267 | 0.333 | 0.318 | 0.2428 | 0.1358 |

The theoretical and experimental curves corresponding to the inner diameters of 70 mm, 80 mm, 90 mm and 100 mm of aluminium pipes in Table 3 are drawn, as shown in Fig. 8.
The four curves in the figure represent the theoretical value of mutual inductance of the coils when the inner diameter of the aluminium pipe is 70 mm, 80 mm, 90 mm and 100 mm respectively, and the discrete points represent the experimental value of mutual inductance of coils. It can be seen from the Figure that the experimental results of mutual inductance are very close to the theoretical simulation results. Statistics show that the error between all experimental measurement results and theoretical simulation results is between -6.4% and 4.05%. The experimental results are consistent with the theoretical simulation, which attests the correctness and accuracy of the simulation model and simulation method in Section 4.

6. Conclusion
This paper establishes the wireless power transfer system model under non-ferromagnetic metallic environment and studies the effect of non-ferromagnetic metallic environment on parameters of WPT system. The simulation analysis and experiments show that: ① The larger the medium conductivity, the smaller the mutual inductance and self-inductance of the coils. But the value will remain stable eventually. The coil resistance increases dramatically to the peak value and then decreases rapidly. As the medium conductivity increases, the influence gradually tends to peak and the electrical parameters tend to be stable. ② The condition for the maximum value of the system coil's mutual inductance under the non-ferromagnetic metallic environment. When the mutual inductance of the coil reaches to the maximum, the diameter of the coil is directly proportional to the inner diameter of the aluminium pipe. ③ An accurate simulation model and method are obtained.

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