Research on the Characteristics of Wireless Power Transfer in Ferromagnetic Metal Pipe

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Abstract: With the development of society, radio energy transmission technology has been paid more and more attention. However, in the actual application environment, the surrounding metal environment has a significant impact on the radio energy transmission performance. Based on the technology of MRR radio energy transmission, this paper establishes a two coil radio energy transmission model, and analyzes the influence of metal environment on the coil self inductance L, mutual inductance m and coil resistance R of the radio energy transmission system by finite element simulation. On this basis, aiming at the ferromagnetic metal environment, the steel pipe is selected as the research object to study the relationship between coil diameter and mutual inductance in the metal pipe, and the relationship between coil diameter and metal pipe diameter when the maximum mutual inductance is obtained through fitting analysis. At the same time, through the experiment, the mutual inductance between the coils of the wireless energy system in the steel tube is verified, and the experimental results are very consistent with the theory.

1. Introduction

Nowadays, magnetic resonant wireless power transfer technology, which was first proposed by MIT scientists in 2007[1], is a hot research topic among domestic and overseas researchers. Scientists and engineers have devoted to this field, leading more and more new methods and new ideas emerging. 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]. Most researches at home and abroad are focusing on the power transfer in free space. However, when there is any metal object enclosing the system, the high-frequency alternating magnetic field in the coil will induce eddy current in the surface of the metal object, ① causing power loss of the system; and ② effecting a reactive magnetic field which will generate scattered field impedance in the coil loop through coupling mapping to change equivalent parameters of the coil loop and even cause the failure of wireless energy transfer.

The Reference [5] analyzes the effect of proximal metal on the transfer efficiency of WEVC system which is based on WPT technology, and the relationship among system frequency, copper plate height and transfer efficiency. The results show that the system must recognize whether there is any metal object near the receiving coil to ensure high transfer efficiency. The Reference [6] analyzes the effect of external metal objects on the transfer efficiency of the system through experimental methods: the transfer efficiency of the system decreases when a small-sized aluminum plate is placed close to the transmitting coil. The Reference [7] discusses the method of reducing negative effects by shield slotting. The effect of metal objects surrounding the transfer system on the transfer characteristics of the system shall be further studied to reveal the fundamental factors causing the changes in transfer power, efficiency and resonant frequency. However, the existing references are still at the level of experimental
simulation and simulation analysis, and fail to research deeply on the effect of metal environment on transfer parameters; the researches on the effect of metal environment on wireless energy transfer characteristics have no accurate theoretical models. In addition, it is necessary to further analyze the effect law \[8-9\].

With the specific metal environment of inner ferromagnetic metal pipe, this paper establishes a wireless power transfer system model, and studies the effect of metal pipe permeability on coil self-inductance L, mutual inductance M and coil resistance R of the system and analyzes the effect of magnetic permeability on system parameters and the conditions for obtaining the maximum mutual inductance of coils through simulation.

2. Magnetization of Metals

The material in the magnetic field will be magnetized. Then, the magnetized material will form an additional magnetic field in the space around, which will cover the original magnetic field and change the entire magnetic field. The vector sum of the material's magnetic dipole moments \(m_i\) per unit volume is:

\[
P_m = \lim_{\Delta V \to 0} \frac{1}{\Delta V} \sum_{i=1}^{N} m_i
\]

In the equation, \(N\) is the number of magnetic dipoles in volume of \(\Delta V\), \(m_i\) is the magnetic moment of the \(i\)th magnetic dipole in \(\Delta V\), and \(P_m\) is the bulk density of the magnetic dipole moment. As for linear media, the magnetization intensity \(P_m\) is proportional to the magnetic-field intensity \(H\):

\[
P_m = \chi_m H
\]

In the equation, \(\chi_m\) is called magnetic susceptibility. For ferromagnetic materials, \(\chi_m\) is a complicated function of \(H\), so there is no linear relation between \(P_m\) and \(H\). For both linear and ferromagnetic materials, the equation below can be satisfied:

\[
B = \mu_0 \left(1 + \chi_m\right) H
\]

In the equation, \(\left(1 + \chi_m\right)\) can be expressed as \(\mu_r\), a dimensionless constant called the relative permeability.

3. Effect of Medium Permeability on WPT System

The metal environment will change the electromagnetic field around the WTP (Wireless Transfer Power) system, so the transfer efficiency of the WTP system in different metal pipes is very different. The relative permeability \(\mu_r\) of metal is controlled by simulation analysis and its effect on WTP is also studied.

| Table 1 Simulation Model Parameters of WPT System in Metal Environment |
|------------------------|------------------------|------------------------|------------------------|
| Parameters of Coil     | Parameters of Metal Pipe | Parameters of Metal Pipe | Parameters of Metal Pipe |
| Coils Diameter R_Coil1, |
| R_Coil2/mm            |                         | Inner Diameter of Metal Pipe |
|                       |                         | R_Pipe/mm                 |
| Wire Diameter r/mm     | 1                       | Wall Thickness of Metal Pipe |
|                       |                         | t/mm                      |
| Distance between Coils |
| d_{12}/mm             | 30                      | Length of Metal Pipe h/mm |
|                       |                         | 200                      |
| Coil Material          | Cu                      | Relative Permeability \(\mu_r\) |
|                       | Variables               | Variables                |
| Coils Turns N1, N2     | 10                      | Variables                |
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. 1. For model parameters, see Table 1.

The relative permeability parameters $\mu_r$ of the metal pipe are 1, 100, 1000 and 10000 respectively, and other parameters of the system can be referred to Table 1. See fig 2(a)–(d) for the magnetic-field intensity nephogram and magnetic induction line distribution of the system.

From fig 2, the magnetic field between two coils will not be affected when the relative permeability of the metal pipe $\mu_r=1$; when $\mu_r=100$, the magnetic field between the coils is attracted by the inner wall of the metal pipe and the magnetic induction line obviously bends into the metal pipe due to the smaller magnetic-field intensity of the pipe's inner wall, which shows the effect initially; when $\mu_r=1000$, the magnetic-field intensity of the metal pipe's inner wall is obviously enhanced, and the magnetic induction line is completely bound in the metal pipe; when $\mu_r=10000$, the situation of magnetic-field intensity of the metal pipe's inner wall and the binding of the magnetic induction line in the metal pipe is similar to those when $\mu_r=1000$, and the metal pipe's capacity of binding magnetic force has reached saturation.

The $\mu_r$-$M$, $\mu_r$-$L$ and $\mu_r$-$R$ curves are obtained as shown in Fig. 3 to further explore the effect of metal pipe permeability on the coil parameters of WPT system.

From Fig. 3, as the relative magnetic permeability of the metal pipe is increasing, the mutual
inductance between the coils and the self-inductance of the coils are increasing rapidly and then remain stable at the maximum value. The change of metal pipe's permeability has no effect on the resistance of coils.

To sum up, the permeability parameter of the metal pipe will affect the wireless transfer system. When the relative permeability of the metal pipe is larger, the mutual inductance \( M \) and self-inductance \( L \) between receiving coil and transmitting coil of WPT system will be larger; but when the relative permeability of the metal pipe exceeds a certain value, the influence will reach the limit, and the mutual inductance \( M \) and the self-inductance \( L \) will remain stable. The impedance \( R \) of the coil itself will not be affected by the permeability of the metal pipe.

4. Conditions for Maximum Mutual Inductance of Coil in Ferromagnetic Metal Pipe

The size of metal pipe in practical WPT system is often already determined, so it is very meaningful to study the effect of the structural parameters of the coils in metal pipe on WPT system. The relationship between coils and steel pipe is shown in Fig. 4 with steel pipe as the research object. The relative permeability of ordinary carbon steel is 500. When the coils' mutual inductance \( M \) of the WPT system in the steel 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.

![Fig. 4 Position Relationship between Coils and Steel Pipe](image)

When the metal pipe enclosing the receiving coil and transmitting coil is made of ferromagnetic material (such as carbon steel), the coil will not only generate eddy current on the surface of the metal pipe, but also magnetize it. When the metal pipe is magnetized, its internal magnetic field will combine the magnetic field of WPT system's receiving and transmitting coils with the magnetic field of magnetized metal pipe. In this case, the ferromagnetic metal pipe will also affect the parameters of the wireless transfer coil. Moreover, metal pipes made of different materials have different influences on the receiving and transmitting coils of the internal WPT system.

When we study the condition for obtaining maximum value of the mutual inductance of WPT system's coils in ferromagnetic materials, the relative magnetic permeability \( \mu_r \) should be set as a fixed value to simplify the finite element model. The metal pipe in WPT system model is made of ordinary carbon steel, and the relative permeability \( \mu_r=500 \) which ignores the nonlinear hysteresis of ferromagnetic materials. See Table 2 for the various parameters in the model.

| Parameters of Coil | Parameters of Metal Pipe |
|--------------------|--------------------------|
| Coil Diameter \( R_{\text{Coil1}}=R_{\text{Coil2}}/\text{mm} \) | Variable 1 |
| Inner Diameter of Metal Pipe \( R_{\text{Pipe}}/\text{mm} \) | Variable 2 |
| Wire Diameter \( r/\text{mm} \) | 1 |
| Wall Thickness of Metal Pipe \( t/\text{mm} \) | 5 |
| Distance between Coils \( d_{12}/\text{mm} \) | 30 |
| Length of Metal Pipe \( h/\text{mm} \) | 200 |
| Coil Material | Copper |
| Relative Permeability \( \mu_r \) | 500 |
| Coil Turns \( N_1, N_2 \) | 10 |

When the working frequency is 1MHz, the 3D surface as shown in Fig. 5(a) can be obtained after applying Parameter Sweep to the above two independent variables respectively through finite element analysis.
In Fig. 5(a), the X and Y planes represent the diameter of coil and the inner diameter of the metal pipe respectively, and the ordinate represents the mutual inductance M of the coils; when the diameter of coil is fixed, the larger the inner diameter of the metal pipe, the larger the mutual inductance. This shows that when the coil is far away from the ferromagnetic metal pipe, the influence of the metal pipe would be reduced; when the inner diameter of the metal pipe is fixed, the mutual inductance between the coils has a peak value showing a single peak curve; when the inner diameter of the metal pipe is 125mm, the maximum mutual inductance of the wireless transmitting and receiving coils (R coil=82.5 mm) is 847.9nH. Fig. 5(b) is a scatter diagram showing the relationship between the coil diameter R_Coil and the inner diameter of the metal pipe R_Pipe in case of reaching peak point, and the R_Coil coordinate corresponding to the peak point of mutual inductance. The relation curve formula of coil diameter and inner diameter of metal pipe is as follows:

$$R_{\text{Coil}} = 0.6563 \times R_{\text{Pipe}} - 0.5375$$  \hspace{0.5cm} (4)

Through the above formula, the conditions for obtaining the maximum mutual inductance of WPT system's receiving and transmitting coils in ferromagnetic metal pipe can be figured out. When ferromagnetic metal pipe and the inner diameter of the steel pipe are determined, the coil diameter at the peak point of mutual inductance value can be obtained according to the above formula.

5. **Experiment on Mutual Inductance of Coils in Metal Pipe**

Based on the theory in Section 4, the mutual inductance M of the coils is measured by HIOKI 3532-50 LCR analyzer when the diameters of metal pipes are 70, 80, 90 and 100mm, and the diameters of coils are 36, 46, 56, 66 and 76mm. The experiment conditions are shown in Fig. 6.

Measure the mutual inductance between coils with different diameters in steel pipes with different inner diameters respectively. Table3 shows the theoretical and experimental data of mutual inductance of coils in steel pipes.
Table 3 Theoretical and Experimental Values of Coils' Mutual Inductance M in Ordinary Carbon Steel Pipe (Unit: μH)

| Type       | R_Coil  | 76mm | 66mm | 56mm | 46mm | 36mm |
|------------|---------|------|------|------|------|------|
| 70mm       | —       | —    | 0.0583 | 0.0839 | 0.0676 |
| 80mm       | —       | 0.0932 | 0.1496 | 0.1452 | 0.0965 |
| 90mm       | 0.1334  | 0.2312 | 0.2527 | 0.2031 | 0.1214 |
| 100mm      | 0.3254  | 0.3853 | 0.3496 | 0.2529 | 0.1417 |

The experimental results in table3 should be compared with the variation curve of mutual inductance in Section 4 to simplify the comparison of the experiment and the conditions of the simulation model in Section 4. Select the corresponding curves when the inner diameter of the metal pipe is 70mm, 80mm, 90mm and 100mm, and draw the comparison diagram of experimental results, as shown in Fig. 7.

![Fig. 7 Theoretical Mutual Inductance and Experimental Mutual Inductance between Coils in Steel Pipe](image)

The four curves in the Figure represent the theoretical value of mutual inductance of the coils when the inner diameter of the metal pipe is 70, 80, 90 and 100mm respectively, and the discrete points represent the actual value of mutual inductance measured in the experiment. 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 (WPT) system model in ferromagnetic metal pipe and studies the influence of metal environment on the electrical parameters of WPT system. The simulation analysis and experiments show that: ① The larger the permeability of the medium, the greater the mutual inductance and self-inductance of the coils. But the value will remain stable eventually. The coil...
resistance will not be affected by the permeability of the medium. As the permeability of the medium increases, the influence gradually tends to peak and the electrical parameters tend to be stable. ② This paper figures out the conditions for obtaining the maximum value of the coils' mutual inductance of WPT system in ferromagnetic metal pipe. When the mutual inductance is maximum, the mutual inductance is proportional to the inner diameter of the metal pipe. ③ The experiment verifies the correctness and accuracy of the simulation model and simulation method.

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