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修士論文

A Conductive Obstacle Detection Method Robust to Changes of Receiving Coil Location in Magnetic Resonant Wireless Power Transfer System –Detection Based on Voltage Phase Difference Between a Pair of Symmetrical Search Coils–

受電コイル位置の変化の影響を受けにくい磁界共鳴形非接触電力伝送システムの導電性異物検知法 –対称なサーチコイル対の電圧位相差に基づく検知–

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Abstract

With the advancement of battery technology and concerns about greenhouse gas emissions, electric vehicles(EV) are getting more and more attention. However, the spread of EV is still limited by battery capacity. Long charging time also brings inconvenience to people's lives. The cable may also be damaged by the rain, dust, and snow which will cause electric shock or short circuit ground. Wireless power transmission technology (WPT) can be a good solution to solve these problems. The WPT technology can charge the EV without any line connection, which will avoid the above safety problem by cable. This technology gives a possibility that the EV can be charged whenever it is running or stopped, which will extend the EV's driving distance. There will be no need for a big battery in the car so that people can save costs and space. For these reasons, using WPT technology in EV has a broad future.

The magnetic resonance technology released by the Massachusetts Institute of Technology in 2007 made it possible to transmit kilowatt of energy at the meter distance. Such energy transmission is likely to cause a fire once metal foreign object dropped into the charging area. The previous metal detection method can detect large metal likes pot when the receiving coil is not moving. The results are affected by the receiving coil position and are not sensitive to small metal.

This research will propose a new method used symmetrical coil and phase difference to detect the metal to avoid the effect of receiving coil and try to detect small metal like coins or paper clips.

Mathematical derivation will proof that the phase difference of symmetrical coils and voltage sources should be the same when there is no metal and should not be changed when the receiving coil moves but only change when the metal object appears.

The numerical study will prove that the method can detect a coin shape metal and robust to the receiving coil position. In order to ensure that this achievement can be applied in practice, a series of circuit designs ensure the product will keep low prices and can transfer the metal detection result into an easily detectable voltage change. Finally, the experiment results prove that this method can detect the small metal like a coin and will not fail when the receiving coil moves.

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Chapter 1

Introduction

1.1 Background

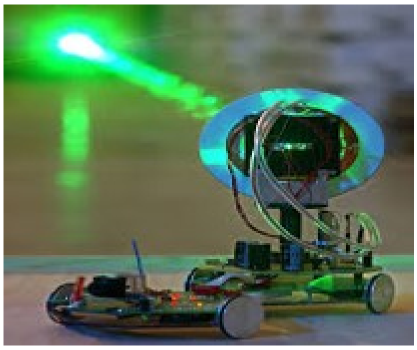
1.1.1 Wireless Power Transfer

The wireless power transfer(WPT) can charge the device without any line connection which has been researched from one hundred years ago by Nikola Tesla [6]. Due to technical constraints, he failed to complete it successfully. So far, research on WPT technology has made a lot of progress. Based on different principles, WPT technology can charge different energy levels at different distances. At the same time, some practical products have entered our lives and slowly changed people's charging habits such as WPT for mobile phones like fig. 1 shows.

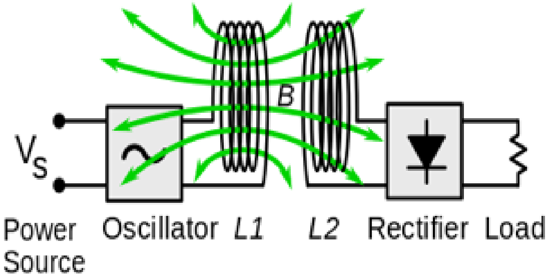
Fig. 1: WPT for mobile phone [1]

With the magnetically resonant couplers(MRC) technology proposed by MIT in 2006, it has become possible to transmit kilowatts of energy at the meter level [7]. People began to try to apply this technology to electric vehicles(EV) [8] [9]. Until now, according to the principle, four technologies can realize the wireless transmission of electric energy. They are Microwave Power Transmission, Laser Power Transfer, Electromagnetic Induction, and Capacitive Power Transmission. The magnetic resonance technology just mentioned is a special case of electromagnetic induction.

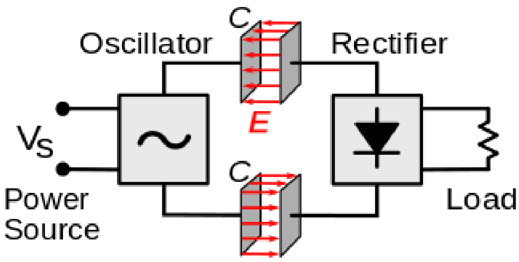
(a) Microwave [10]



(b) Laser [11]



(c) Electromagnetic Inductance [12]



(d) Capacitive Power Transmission [13]

Fig. 2: Four types of WPT technologies

Microwave Power Transmission

By using shorter wavelengths of electromagnetic radiation people can make energy transmission more directional so that energy can be transferred over a longer distance. People tried to apply this technology to artificial satellites and to transfer the energy of solar-powered satellites back to the earth [14]. However, the problem of the oversize of the installation and the loss caused by cloud and rain has not been solved well.

Laser Power Transfer

We can also convert electrical energy into laser light and use photovoltaic panels to receive laser light and convert it into electrical energy to achieve wireless power transmission. The advantage of this method is that laser is less susceptible to interference, so the energy lost in transmission is very small which is suitable for long-distance power transmission. The problem is that this method requires the transmitting side and the receiving side always be aligned. The laser is also a fatal threat to human eyes. In long-distance transmission, any object on the transmission route will interrupt the transmission process and even cause danger.

Electromagnetic inductance

This is the earliest proposed method of wireless power transmission. This method generates an alternating magnetic field through alternating current in the transmitting coil and then causes the magnetic field to generate an induced electromotive force in a receiving coil. The transmission of electric energy is accomplished through alternating magnetic fields. The earliest electromagnetic induction transmission did not add a resonant capacitor, resulting in low transmission efficiency. After adding a resonant capacitor, the transmission efficiency of this method can reach 90%. The advantage of electromagnetic induction is that its receiving side is allowed to have a certain degree of deviation, and it does not need to be completely aligned between the transmitting side and the receiving side. Even if there are non-metallic objects in the transmission path, it will not affect the transmission of electrical energy. The problem of this method is that currently, it can only transfer energy in short and medium distances. Another problem is that if there are metal objects in the transmission path, it may cause a fire.

Capacitive Power Transmission

Capacitive wireless power transmission transfers energy through electric fields. Two electrode plates are respectively placed in the transmitting side and the receiving side to form a large capacitance. Since a single capacitor cannot form a loop, in this way, two sets of electrode plates are generally used to form two capacitors to form a loop. The advantage of this method is to save space and resources. Generally, to increase efficiency, multi-turn coils and iron cores are often used in electromagnetic induction WPT system which will significantly increase the volume. The electrode plate should save a lot of space. The disadvantage is that it is not safe to apply high voltage at both ends of the electrode plate so that this method can only be adapted under short-distance and low-power conditions. This method has been applied to the wireless charging design of some mobile phones.

Among these technologies, the magnetically resonant couplers (a special electromagnetic induction wireless power transmission technology) can transfer kilowatts of energy at a distance of meters with an efficiency of nearly 90%, which is suitable for charging electric vehicles. Nowadays, electric vehicles are still restricted by long charging time and small battery capacity, which makes them unable to effectively compete with gasoline vehicles [15]. The emergence of magnetic resonant couplers provides a simpler and safer way of charging, making the charging of electric vehicles more frequently like fig.3 shows. The transmitting coil (Tx coil) on the ground can charge the receiving coil (Rx coil) under the bottom of the car without any cable connection. Based on this technology, the research of dynamic wireless power transfer can realize that electric vehicles can be charged regardless of parking or driving, which greatly reduces the requirements on the battery capacity of electric vehicles [16]. Therefore, this paper will also focus on the problems in magnetically resonant couplers WPT system.

1.1.2 Safety Problem in WPT System

Generally speaking, there are no exposed high-voltage wires or interfaces in electromagnetic induction wireless power transmission. However, due to the use of a strong alternating magnetic

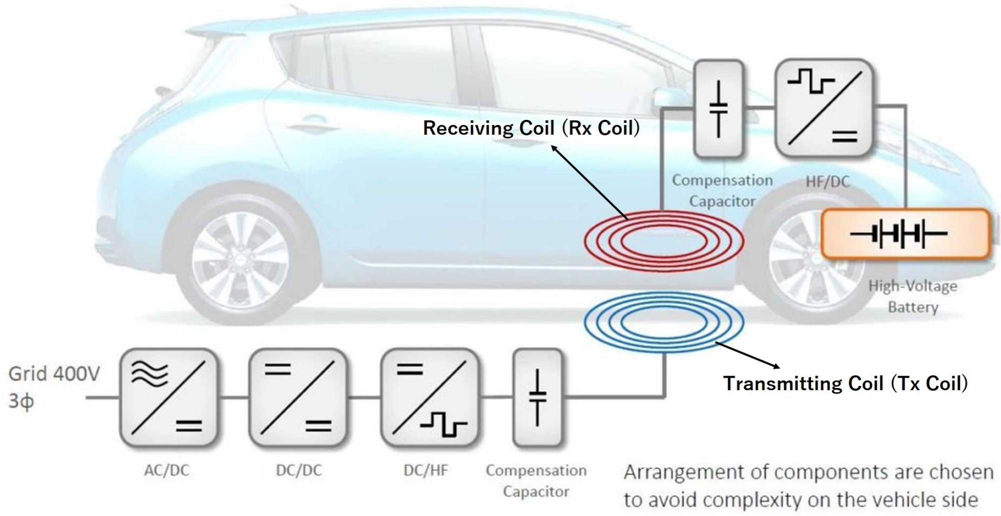


Fig. 3: Conceptual drawing of EV WPT [2]

field for energy transmission, there are still some security risks.

Metal Object

Metal objects between the coil can cause serious overheating problems. Fig.4 shows an experiment about metal object between the coils. In this experiment, the power of the WPT system is 240W, and different metals were put between coils. As Table 1 shows, in only about 30 seconds, these three metals can have at a very high temperature, which will cause a fire accident.

Fig. 4: Metal object experiment [3]

Table 1: Metal temperature rise in WPT ($°C$)

Frequency	Coin	Keys	Compact Disc
kHz	25($°C$)	23($°C$)	0($°C$)
Mhz	1($°C$)	0($°C$)	12($°C$)

Existing metals can also decrease system efficiency. In [17], a copper with 13cm length was put into a 31.57 kHz WPT system and then cause the efficiency decrease from 90% to 57%.

On the other hand, for the EV WPT system, since the power can be kilowatt level, even some small metal can achieve a high temperature in a very short time. Society of Automotive

Engineers (SAE) International has specified experiment criteria to judge whether the metal object will break the WPT system. When putting the metal into the charging area of a system working in normal charging state, if the metal damage to the transmitting coil surface, or charring or ignition, or surface temperature of the Tx coil is above 80 $^{\circ}$C for more than 10 minutes, this metal is considered dangerous and needs to be detected [18]. Based on these criteria, some common metals have been tested. The experiment results and metal shape is shown in Table 2

Table 2: Table of test objects

Sample Objects	Temp Rise	Ignition Test	Notes
Paper Clip	×		Standard size (U.S. #2 (1-1/8 inch or 2.86 cm))
Paper Stack with Paper Clip		×	A4/letter stack of paper (e.g., five sheets with standard size paper clip)
Staple	×		Standard size (Ferromagnetic steel, rectangular wire 0.5 × 0.7 mm, 6 × 12.8 mm) (standardized as "type 24/6 (Number 3)" per DIN 7405:1963)
Paper Stack with Staple		×	A4/letter stack of paper (e.g., five sheets with standard size staple)
Coins	×		2 euro coin, 5 cent coin (U.S cent coin)
Nail	×		Reference size: 10d common steel
Beverage Can	×		Standard U.S. Coke can (12 ounces or equivalent)
Aluminum Sheet	×		5 × 7.5 cm
Steel Sheet	×		5 × 7.5 cm
Wire Loop	×		14 gauge closed ring of wire with 1 cm radius (copper)
Steel Wool	×		Standard steel wool pad (fineness 00, size 40 × 40 × 15 mm)
Foil with Paper Backing	×		Foil with paper backing from food wrappers and cigarette packaging foil (2.5 × 2.5 cm, 30 × 30 cm)
Extension Cord	×		100 feet, 16 gauge, four conditions: straight across pad, coiled in > 25 loops; both conditions tested open ckt., self-plugged

Since the system is working in a normal state of charging, even common small metals cannot pass the test experiment. For the EV WPT system, metal is indeed easy to cause damage to the system.

Active Implantable Medical Devices malfunction

The strong magnetic field may cause the malfunction of the Active Implantable Medical Device (AIMD) , which is a fatal threat to heart patients. Current research shows that for the WPT system below 100kHz used in electric vehicles, no malfunction has been found. But for the WPT system above 100kHz, the pacemaker has malfunctioned [19].

Strong Magnetic Field

The strength of the magnetic field between the coils has been greater than the strength of the magnetic field that is safe for the human body [20]. It will cause damage to the human body, but the impact in this regard is mainly on small animals such as cats and dogs or a baby who wants to pick up a ball fall under the car. Normal activities of adults will not break into this unsafe space. Another problem is the impact on electric vehicle parts. Since the automobile chassis still uses a large amount of metal, a strong magnetic field causes eddy currents in the metal which will reduce the service life of the metal.

1.1.3 Metal Object Detection of WPT System

Since the metal object problem easily causes a fire, there has been some research about metal object detection in the WPT system. According to the principle, these methods can be divided into three categories.

1.Using the circuit parameters.

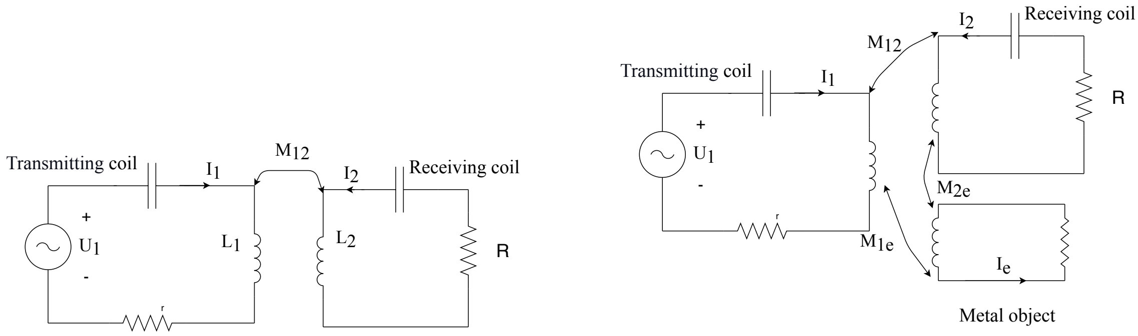
2.Using the magnetic information.

3.Using other sensors.

The circuit parameter

When the metal gets into this area, two phenomena will occur. The first one is the magnetization of ferromagnetic materials. When the ferromagnetic material gets into the alternating magnetic field, the magnetizing current will occur in the surface of the metal and change the magnetic field distribution which is called magnetization. This is caused by the more ordered arrangement of the nucleus and its extranuclear electrons in the metal when they are in the magnetic field. One thing to note that is the magnetizing current will not consume power but just change the magnetic field distribution. From the circuit model point of view, this phenomenon will lead to changes in the self-inductance and mutual inductance in the loop. For example, in fig.5(a), the magnetization of ferromagnetic materials will only affect self-inductance L_1 and L_2 and mutual inductance M_{12}, but not affect other parameters.

The second one is the eddy current. This is caused by the electromotive force generated by the



(a) Magnetization model (b) Eddy current model

Fig. 5: Circuit model of the metal in the system

alternating magnetic field. Another thing to note is that the eddy current will consume power. So judging from the circuit model, this will add a new coupling loop between the original transmitting coil(Tx coil)and receiving coil(Rx coil) loop. This loop is used to describe eddy currents in metal and will change the equivalent resistance and equivalent inductance of the primary side. At the same time, the energy emitted by the transmitting coil will not only be received by the receiving coil but also absorbed by the metal which changes the transmission efficiency. magnetizing current means the change of self -inductance and mutual inductance. This is the principle of metal detection based on circuit parameters. It should be noted that due to the size of the metal, the placement direction, the location, and the material will affect the resistance, mutual inductance, and self-inductance in the equivalent circuit which is uncontrollable. So if we use the method of monitoring circuit parameters, we can only judge whether there is metal or not by observing clear changes in the parameters. For example, in fig.5(b), the eddy current in the metal will bring another loop.

Based on these changes, we can determine whether there is a metal object by monitoring the voltage and current in the loop, or other values calculated based on the voltage and current. For example, paper [21] measures the voltage of the coil, paper [22] measures the quality factor, paper [23] measure the power, paper [24] measure the resonance frequency.These methods have succeeded in detecting small metal in the WPT system. However, they still have some problems.

Paper [22] who uses the quality factor of Rx coil can only detect the metal near the Rx coil and need a communication system between Tx coil and Rx coil. In addition, the metal is usually dropped on the ground means more near to the Tx coil.

Paper [24] which uses the resonance frequency can only detect the metal when there is no Rx coil.

In paper [23], the power loss will increase with the increase of Rx coil offset. Paper [25] also proved that this method can only worked when the receiving coil don't move.

In the WPT system, since the Rx coil and the Tx coil have a better coupling, the influence from the Rx coil side is easier to feedback to the Tx coil side. Among them, the change in the displacement of the Rx coil is the most common because we cannot guarantee that the Rx coil is in the same position every time it is charged. Especially for dynamic WPT systems, a large range of displacement of the receiving coil is very common which will also cause changes in loop parameters. Table3 shows the simulation of the voltage and current parameter value changes in the loop when the coil moves. It can be seen that the voltage and current changes caused by small metals are much smaller than the changes caused by coil displacement, so if we use loop parameters to detect metals, it is often necessary to fix the position of the Rx coil or to do the detection when there is no receiving coil.

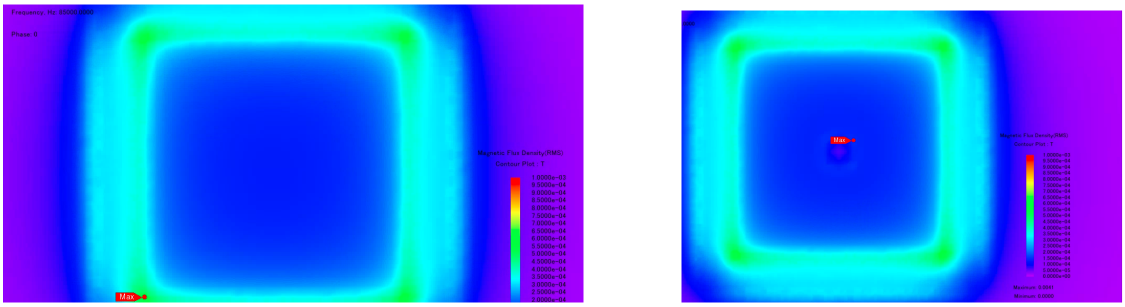
Table 3: Simulation results of coil parameter changed by Rx coil offset and metal

Simulation situationl	Voltage in Tx coil (V)	Current in Tx coil (A)	Voltage in Rx coil (V)	Current in Rx coil (A)	Power loss (W)
Rx coil alignment	43.7	2.5	49.6	2.9	0.07
Rx coil 2 cm offset	46.2	2.6	51.1	2.9	0.08
Rx coil 4 cm offset	55.3	3.18	56.1	3.2	0.1
Rx coil 6 cm offset	74.2	4.22	65.2	3.8	0.2
Rx coil 8 cm offset	111.4	6.4	80.2	4.6	0.3
Rx coil 10 cm offset	191.1	11	105.2	6.0	0.8
Metal	43.7	2.5	50.2	2.9	0.1

Magnetic Information

Both the magnetization of ferromagnetic materials and the eddy currents in metals change the magnetic field distribution in space. If the information of the magnetic field can be detected, the presence of metal can also be detected by observing the change of the magnetic field.

Paper [26] introduced a method using Tunneling magnetoresistive (TMR) sensors to detect the magnetic field strength. The small sensors were put under the Rx coil to measure the magnetic field strength of a series of independent points to get the approximate distribution of the magnetic field on a plane. This method can detect a coin shape metal and can know the misalignment of Rx coil. However, this method can only detect metal when there is no Tx coil. fig.6 (a) shows the magnetic field simulation results of no metal but Tx coil is charging and fig.6 (b) shows the results of a coin shape metal, the magnetic field nearly not change. That is because when the Tx coil charges the Rx coil, the magnetic field strength caused by the coil is too strong that the magnetic field strength changes caused by the eddy current cannot cause enough magnetic field distribution change.



(a) No Metal (b) Metal Exists

Fig. 6: Simulation results of TMR sensors

Paper [4] introduced another method using small search coils to get the magnetic information. In the search coil, the alternating magnetic field will cause induced electromotive force. Changes in the magnetic field distribution will also cause changes in electromotive force. As mentioned in the previous analysis, the change in the magnetic field caused by the metal is too small compared to the magnetic field caused by the coil. If you use a small coil directly, we can't get the information of the magnetic field change effectively.To solve this problem, this article proposes a new coil arrangement

The arrangement of the coils is as shown in Fig.7 When there is no metal, this symmetrical arrangement causes the voltages of the two coils induced by the main magnetic field to be uniform. But when the metal dropped into the area, for example in the Q-coil, the magnetic field caused by the eddy current will have a different distribution in two coils which will cause the inductive voltage different. By measure the voltage difference of Q-coil and D-coil, the metal can be detected.

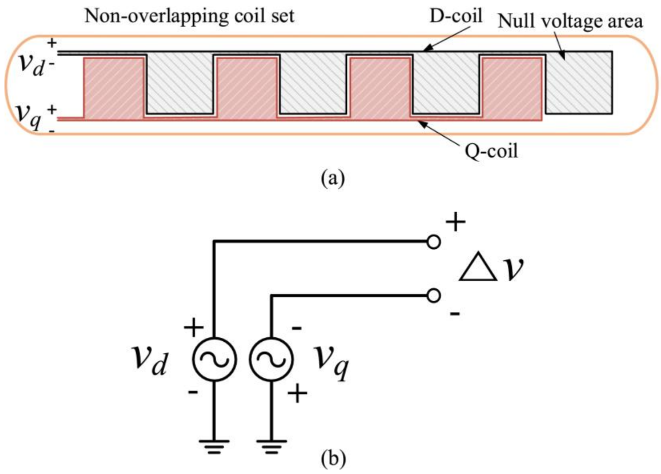


Fig. 7: Non-overlapping coil sets [4]

This method can detect some metal because the small metal will break the balance of two coils. However, this method is also affected by the coil misalignment since the misalignment will cause the main magnetic field unevenly distributed in the two coils. Besides, since the metal dropped in the middle of two coils will cause the same magnetic field to change, this method has an area where the metal cannot be detected as Fig.8 shows. It is called Dead Zone.

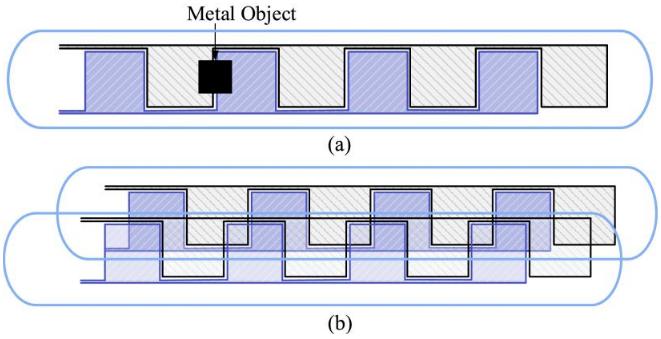


Fig. 8: Dead zone of non-overlapping coil sets [4]

To solve the dead zone problem, at least three-layer coil which is on some surface and with no connection with each other. This will make the coil complexed.

Obviously, this method can detect smaller metals than direct measurement of loop parameters, but when the coil is misalignment, there is also a voltage change in search coil. Moreover, when the metal was put into the dead zone, the voltage is as same as there is no metal. In conclusion, this method has dead zone and cannot distinguish metal and misalignment.

Other sensors

The third method is using other sensors like the camera [27] or radar [28] or X-Ray [29]. The biggest advantage of using other sensors is that the methods mentioned before judge whether there is metal by observing the change of the parameter or magnetic field after the metal enters the charging area. The eddy currents in the metal are already heating the metal. But other sensors such as cameras can monitor a wider area that includes the charging area, which can ensure that early warning can be done before the metal enters the dangerous charging area, which improves the safety of the system. The disadvantage is that other sensors are more expensive. On the other hand, the camera cannot distinguish mixed foreign objects. For example, the camera can detect a plastic bag, but cannot detect whether there are metal objects in the bag. Non-conductive plastic bags will not affect the system, only some metals will affect it. If we want to distinguish between mixed foreign objects, an X-ray-based system is needed, which is too expensive.

As other sensor is significantly more expensive than the other two methods (the camera is more than 30,000 JP). This paper will only introduce the first two methods which use electromagnetic detection.

1.2 Target of Research

From the summary of the past metal detection methods in the previous section, it can be seen that the loop parameters and magnetic field information methods are more susceptible to the position of the receiving coil compared to small metal, and it is difficult to judge whether there is really metal when the position of the Rx coil moves. Other sensors are more expensive. Therefore, my research aims to propose a new method that can detect some small metals. This method will not be disturbed even when the coil has a certain displacement. At the same time, this method should be able to achieve metal object detection with a cheaper method.

1.3 Outline of Research

The first chapter introduces the WPT system and the metal object problem in the WPT system, and summarizes the problems of the previous metal detection methods. The second chapter will introduce the structure and principle of the proposed new method, as well as the changes in the results in the case of system resonance and non-resonance. Chapter 3 uses numerical simulation to verify that this method can detect small metal and is robust to the Rx coil offset. The fourth chapter introduces a series of circuit designs to ensure that the method is practical in a cheaper way. At the same time, the experimental results prove the effectiveness of the design. The fifth chapter introduces summary and future prospects.

Chapter 2

Structure and Principle of Symmetrical Coil Phase Detection

2.1 Structure of Symmetrical coil

2.1.1 Advantage of Search Coil

The presence of metal will inevitably cause changes in the magnetic field. However, when we try to detect changes in the magnetic field with loop parameters, we essentially transform a spatial vector into a scalar change, and a lot of information will be lost in the process. Therefore, the use of loop parameters can only obtain a small amount of metal information, and it is easy to be disturbed by other information. If we want to know all the vector information of a whole space, we need enough detectors, which will increase the size and cost of the system. Therefore, the second best thing is to use some small search coils to obtain part of the magnetic field information to distinguish whether there is metal.

In order to obtain better information and increase sensitivity,paper [5] [30] introduced a pair of balance coil structure which is used in finding landmines as figure shows. The two search coils(Receive 1 and Receive 2 in Fig.9) are put above and under the transmitting coil. The current in the transmitting coil will produce a symmetrical magnetic field in two search coils. When there is no metal, the symmetrical magnetic field will produce same inductive voltage in the two search coils so that the difference of two search coil voltage should be near zero. When there is metal on one side, the eddy current in the metal will change the distribution of magnetic field, so that the magnetic field in two search coil is not the same. The inductive voltage in two search coils will also change. The difference between the two search coil voltage will not be zero. By measure the change of difference of two search coil voltage, this method can find the metal.

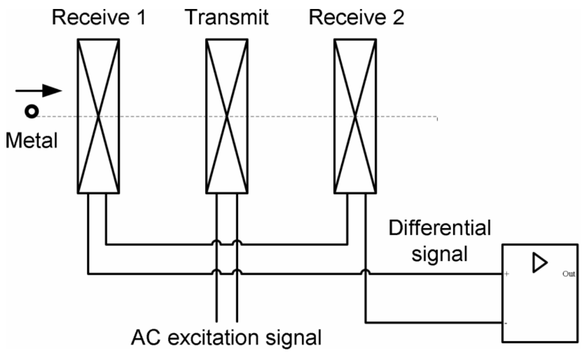
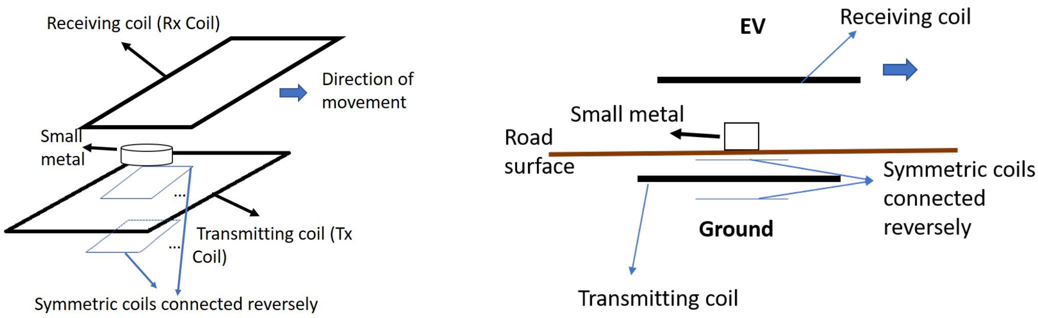


Fig. 9: Structure figure of balance coil [5]

2.1.2 Structure

However, this method is only used in normal metal detection. For the WPT system, due to the exists of receiving coil in EV, the magnetic field above and under the transmitting coil is asymmetric. The inductive voltage of two search coils should be different. So we made following improvements. First, we used smaller search coil. Two same search coil was put above and under the Tx coil as Fig.10 shows.



(a) One Search Coil Structure View (b) One Search Coil Front View

Fig. 10: Search coil structure

The two blue coils are used as search coils and the black coil are the transmitting coil and receiving coil of WPT system. This model is a test model with only one pair of search coils. In the future, the real device will be full of these pairs of search coils as fig.11 shows. Here only one set of coils is taken for illustration. The search coil has the same width of 5mm from the transmitting coil. Different coils on the same plane are not connected, and the coils that are symmetrical up and down in the same horizontal position are reversely connected.

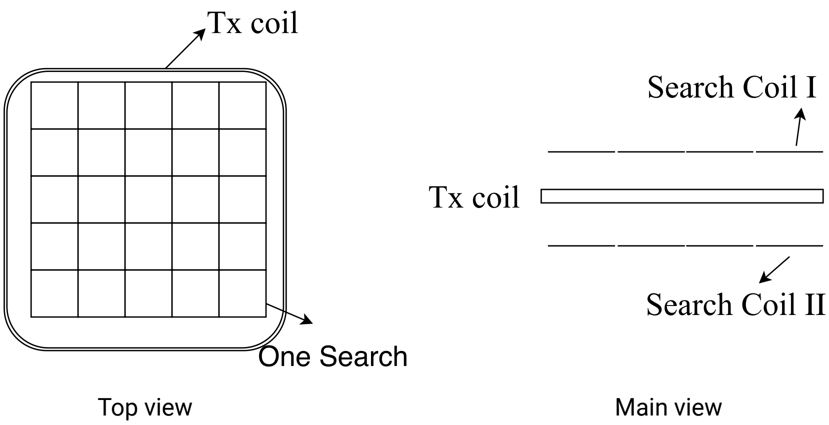


Fig. 11: Concept figure of whole structure

2.2 Principle

2.2.1 Resonance State

The second improvement is that we did not use voltage difference, but phase difference to detect the metal.

Here we use the loop and mutual inductance model for derivation. The equivalent circuit of the system is shown in Fig. 12

Table 4: The meaning of parameter

Parameter	Meaning
I_1	The current in the Tx coil
I_2	The current in the Rx coil
M_{12}	The mutual inductance between Tx coil and Rx coil
M_{1s1}	The mutual inductance between Tx coil and search coil I
M_{2s1}	The mutual inductance between Rx coil and search coil I
M_{es1}	The mutual inductance between metal object and search coil I
U_1	Voltage source
U_s	Voltage of search coil I

In order to facilitate understanding, first introduce the equivalent circuit diagram of one search coil. Table.4 shows the meaning of each parameter. The mutual inductance will describe the relationship between metal and each coil.

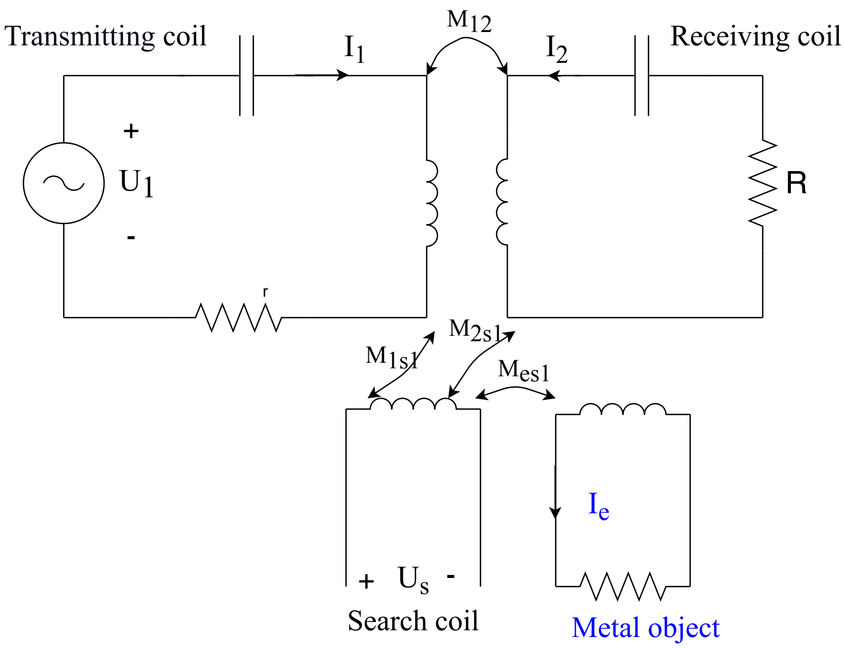


Fig. 12: Equivalent circuit

Then we can get the voltage function of search coil I. The voltage was affected by three aspects, Tx coil Rx coil and metal. Here U_{s1} means the voltage of search coil I.

$$U_{s1} = I_1 j\omega M_{1s1} + I_2 j\omega M_{2s1} + I_e j\omega M_{es1} \tag{2-1}$$

Since only the voltage value of the coil is measured here (in practice, an operational amplifier will be connected here), the coil can be regarded as an open circuit, so it will not be interfered by search coil II. When the system is working on the resonance frequency, there is a relationship between current in Tx coil and current in Rx coil.

$$I_2 = -\frac{j\omega M_{12}}{r+R} I_1 \tag{2-2}$$

R means the load and r means the resistance of the receiving coil. So the voltage function can be written as

$$U_{s1} = I_1\omega^2 \frac{M_{12}M_{2s1}}{r+R} + j(I_e\omega M_{es1} + I_1\omega M_{1s1}) \tag{2-3}$$

Based on the same principle, we can write the voltage function of search coil II

$$U_{s2} = I_1\omega^2 \frac{M_{12}M_{2s2}}{r+R} + j(I_e\omega M_{es2} + I_1\omega M_{1s2}) \tag{2-4}$$

Here, M_{2s2} means the mutual inductance between Rx coil and search coil II. M_{es2} means the mutual inductance between metal and search coil II. $M1s2$ means the mutual inductance between

Tx coil and search coil II.

The search coil I and search coil II are put in symmetrical positions above and below the Tx coil, and they are of the same shape. So M_{1s1} is approximately equal to M_{1s2}. Two search coils are connected in reverse series, so the total voltage of two search coils is there difference. The total voltage is:

$$\begin{aligned}\Delta U_s &= U_{s1} - U_{s2} \\ &= I_1\omega^2\frac{M_{12}}{r+R_L}(M_{2s1} - M_{2s2}) + jI_e\omega(M_{es1} - M_{es2})\end{aligned} \tag{2-5}$$

The real part of the total voltage ΔU_s is only affected by the Rx coil position, and the imaginary part is only affected by the metal. If there is a metal in the charging area, there will be an imaginary part in the total voltage ΔU_s. That means the phase of total voltage and current in Tx coil are the same when there is no metal. And when there is metal, the phase of voltage ΔU_s and current I_1 will be different. Because the system is working in a resonance state, the current in Tx coil has the same phase as the voltage source. By measuring the phase of ΔU_s and voltage source, it is possible to detect the metal without the affected by the position of Rx coil.

2.2.2 Non-resonant State

The necessary condition for the establishment of this method is 2-2 must be satisfied which means the WPT system must work in resonance. However, it is very hard to make the system work in perfect resonance due to the device error. As a result, it is necessary to discuss the non-resonant state. When the system is not working in the resonance. Formula 2-2 will change to

$$I_2 = -\frac{j\omega M_{12}}{r+R+j(\omega L_2 - \frac{1}{\omega C_2})}I_1 = -\frac{j\omega M_{12}}{R_x + jX_2}I_1 \tag{2-6}$$

Here, L_2 means the self-inductance of Rx coil. C_2 means the resonance capacitance in Rx coil side. To simplify the formula, replace $r+R$ with R_x and replace $(\omega L_2 - \frac{1}{\omega C_2})$ with X_2.

The voltage function of search coil when the system is working in non-resonance is changed to:

$$U_{s1} = I_1 j\omega M_{1s1} + I_1\omega^2\frac{M_{12}M_{2s1}}{R_x + jX_2} + I_e j\omega M_{es1} \tag{2-7}$$

$$U_{s2} = I_1 j\omega M_{1s2} + I_1\omega^2\frac{M_{12}M_{2s2}}{R_x + jX_2} + I_e j\omega M_{es2} \tag{2-8}$$

The total voltage of search coil when there is no metal is

$$
\begin{aligned}
\Delta U_s &= U_{s1} - U_{s2} \\
&= I_1\omega^2 \frac{M_{12}R_x}{{R_x}^2 + {X_2}^2}(M_{2s1} - M_{2s2}) + jI_1\omega\left[(M_{1s1} - M_{1s2}) - \frac{\omega M_{12}X_2}{{R_x}^2 + {X_2}^2}(M_{2s1} - M_{2s2})\right]
\end{aligned} \tag{2-9}
$$

When the system is working on a non-resonant state, the phase of the voltage source and current in Tx coil is different. So the following discussion will focus on the phase difference between Tx coil current I_1 and total voltage of symmetrical search coil ΔU_s. The phase difference between I_1 and ΔU_s in formula 2-9 is

$$
\begin{aligned}
\theta &= arctan\left(\frac{(M_{1s1} - M_{1s2}) - \frac{\omega M_{12}X_2}{{R_x}^2+{X_2}^2}(M_{2s1} - M_{2s2})}{\frac{\omega M_{12}R_x}{{R_x}^2+{X_2}^2}(M_{2s1} - M_{2s2})}\right) \\
&= arctan\left(\frac{(M_{1s1} - M_{1s2})}{\frac{\omega M_{12}R_x}{{R_x}^2+{X_2}^2}(M_{2s1} - M_{2s2})} - \frac{X_2}{R_x}\right)
\end{aligned} \tag{2-10}
$$

As the Rx coil moves far away from Tx coil, the mutual inductance between Tx coil and Rx coil M_{12} becomes smaller. The difference between mutual inductance of the Rx coil and two search coils $M_{2s1} - M_{2s2}$ also becomes smaller. Other parameters will not change and the phase difference between ΔU_s and I_1 will become smaller. When the metal exists, the total voltage of search coil is

$$
\begin{aligned}
\Delta U_s &= U_{s1} - U_{s2} \\
&= I_1\omega^2 \frac{M_{12}R_x}{{R_x}^2 + {X_2}^2}(M_{2s1} - M_{2s2}) + jI_e\omega(M_{es1} - M_{es2}) + \\
& jI_1\omega\left[(M_{1s1} - M_{1s2}) - \frac{\omega M_{12}X_2}{{R_x}^2 + {X_2}^2}(M_{2s1} - M_{2s2})\right]
\end{aligned} \tag{2-11}
$$

Most of the metal is dropped on the ground which means the metal is closer to the Tx coil than the Rx coil. If we ignore the effect of the Rx coil. The relationship of eddy current in metal and current in Tx coil is

$$
I_e = -\frac{j\omega M_{e1}}{R_e + jX_e} I_1 \tag{2-12}
$$

M_{1e} means the mutual inductance of metal and Tx coil, R_e means the resistance of the metal,

X_e means the self-inductance of metal. Formula 2-11 can change to:

$$
\begin{aligned}
\Delta U_s &= U_{s1} - U_{s2} \\
&= I_1 \left[\omega^2 \frac{M_{12} R_x}{{R_x}^2 + {X_2}^2}(M_{2s1} - M_{2s2}) + \omega^2 \frac{M_{e1} R_e}{{R_e}^2 + {X_e}^2}(M_{es1} - M_{es2})\right] + \\
& jI_1\omega \left[(M_{1s1} - M_{1s2}) - \frac{\omega M_{12} X_2}{{R_x}^2 + {X_2}^2}(M_{2s1} - M_{2s2}) - \omega \frac{M_{e1} X_e}{{R_e}^2 + {X_e}^2}(M_{es1} - M_{es2})\right]
\end{aligned}
\tag{2-13}
$$

The metal parts $(M_{es1} - M_{es2})$ will increase the real part and reduce the imaginary part as compared to the original system. So the phase will decrease when metal exists.

2.2.3 Improved Method of Non-Resonance

Formula 2-5 has proved that the phase difference between the voltage of search coil and current in Tx is robust to the Rx coil location. For the resonance state, the voltage source has the same phase as current in Tx coil. However, when the system is working in a non-resonance state, the phase between the voltage source and current in Tx coil is not the same. This phase difference is uncontrolled since the reactance of the Rx coil can be bigger or smaller. The improved method uses the current in Tx coil instead of a voltage source. Since the current is not an easily detectable quantity like voltage. We use the voltage of capacitance instead of current because there is always a 90-degree phase difference from the current.

Chapter 3

Discussion on Sensitivity to Metal and Robustness to Receiving Coil Position

3.1 Numerical Study Model

The numerical study model built in the JMAG-Designer and its size is shown in Fig.13. The electrical parameter is shown in Table5. In this study, only one pair of search coil is built to verify the validity of this method. In the future, the charging area could be filled with pairs of symmetrical coils. In the numerical study, the Rx coil was first put in the alignment position to the Tx coil without other metal objects and moved horizontally. Then a coin shape steel was put above search coil I and was put at the center of the search coil, on the edge of search coil, and at the corner of the search coil. In the simulation, the phase difference between the voltage

Table 5: Electrical parameter

Parameter	Value
Voltage source	7 V
Frequency	85 kHz
Receiving Coil and Trans-mitting coil turns	10
System load	3 Ω
Receiving Coil Misalign-ment	0 mm, 20 mm, 40 mm, 60 mm, 80 mm, 100 mm
Metal material	Steel

source and the voltage difference of two search coils has been calculated. The metal position is

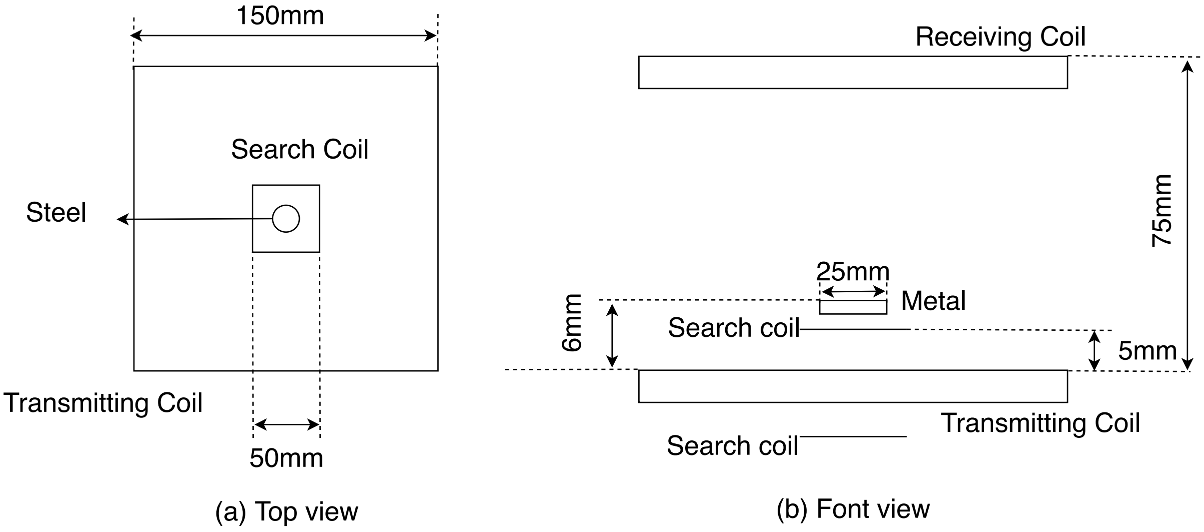


Fig. 13: Nnumerical study model

shown in Fig.14.

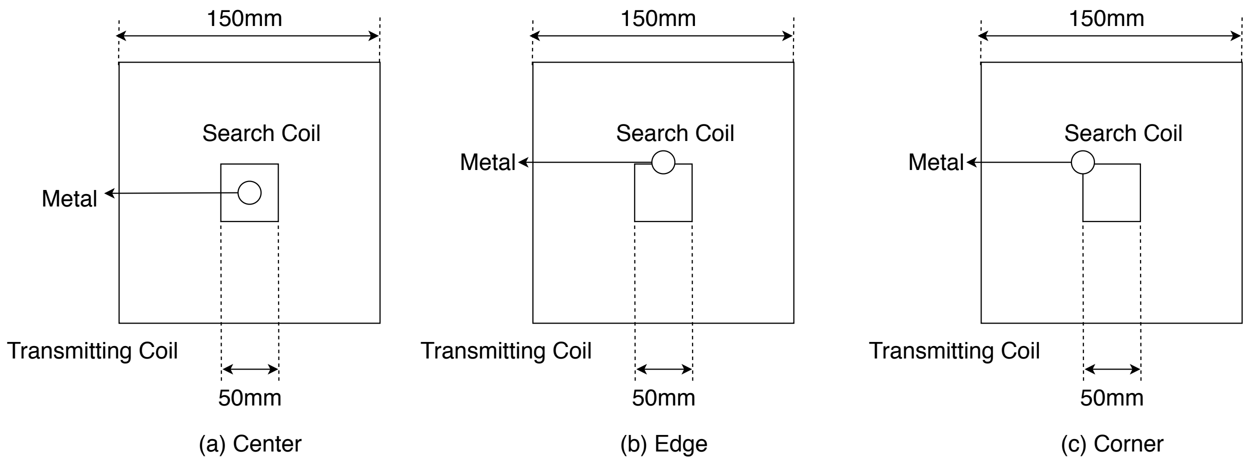


Fig. 14: Metal positions

3.2 Discussion of Resonance State

3.2.1 Robustness to Location and Sensitivity to Metal

Fig.15 shows the phase difference of the voltage source and the total voltage of search coil. As Fig.15 shows that when there is no metal above the search coil, the phase difference is under 5 degrees until the Rx coil moves 10 cm which is two-thirds of the coil length. When the metal is put above the search coil, the phase difference decreases nearly 9 degrees, and as the coil is misaligned, the phase difference decreases quickly. This result shows that the coil position does not cause a large phase change but metal can. Therefore, the phase difference of voltage source and search coil can detect small metals without Rx coil positional interference. Fig.15 also shows that metal at the edges and corners will cause greater phase changes than metal in the center. The phase change caused by the metal in the center is sufficiently larger than the phase change caused by the Rx coil position, so it can be said that the metal can be detected in all the area surrounded by the coil. Fig.16 shows the phase change of Rx coil vertical movement. The height

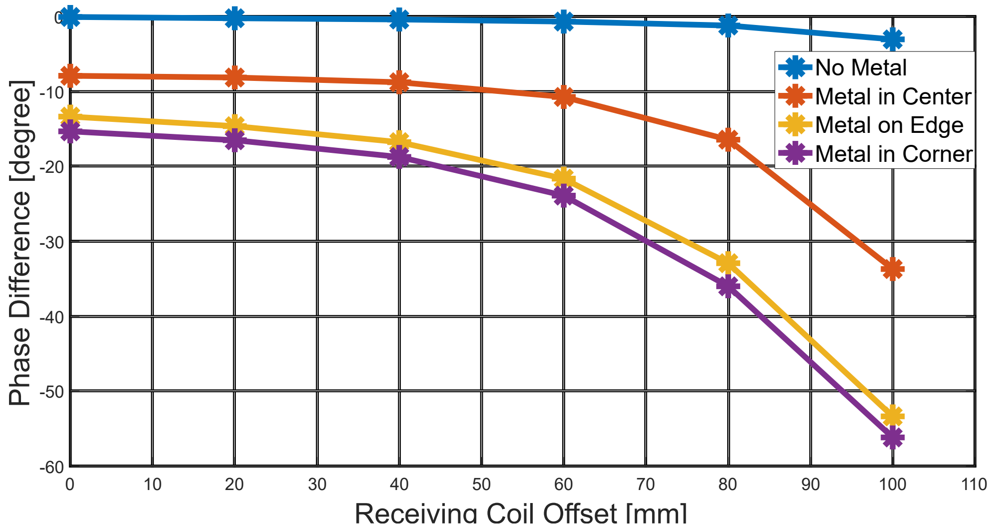


Fig. 15: Phase change of metal and Rx coil movement

of the chassis of an electric vehicle will move slightly with the load, and this movement is not large within a safe range. Therefore, we simulate that the Rx coil moves up and down 2cm in the vertical direction, which is about a quarter of the coil height. Fig.16 shows the phase

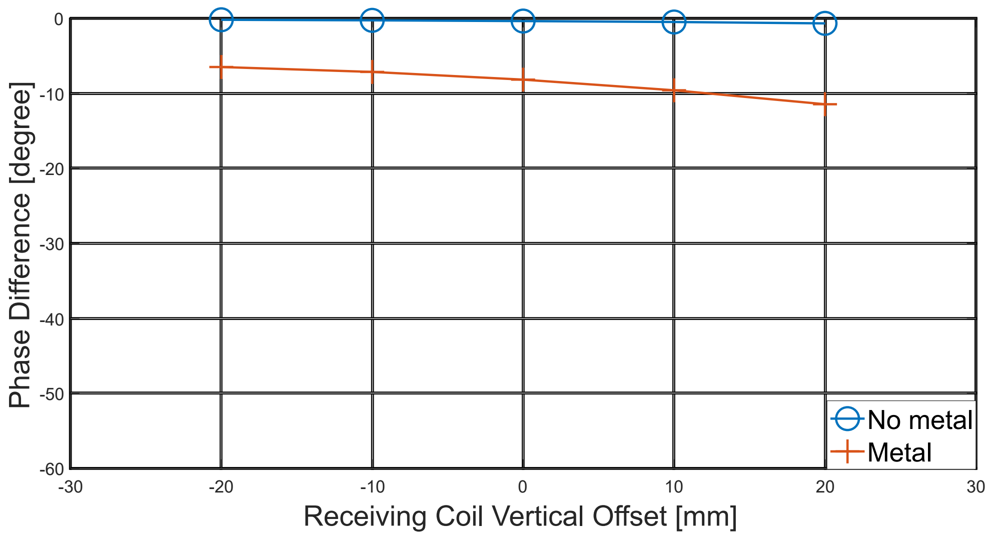


Fig. 16: Phase change of Rx coil vertical movement

change of Rx coil vertical movement. In fig.16 the phase changed caused by the Rx coil vertical movement is always under 1 degree, while the phase change caused by the metal is at least 6 degrees. This result proves that the vertical movement also cannot cause enough phase change compared to the metal. In conclusion, fig.15 and fig.16 prove the robustness of the method to Rx coil position and the sensitivity to metals.

3.2.2 Influence of Search Coil Size

In the previous discussion, the size of the coils is set to a square with a side length of 50mm. In the design, the actual system will densely cover these coils in the dangerous charging area. The larger size means fewer coils and lower costs. A smaller coil means more cost. In principle, the influence of the size of the coil on this method is mainly the influence of two kinds of mutual inductance, the mutual inductance of search coil and the receiving coil in equation2-5 $(M_{2s1} - M_{2s2})$, and the mutual inductance of the search coil and metal $(M_{es1} - M_{es2})$. Since the size of the coil will affect the change of the integration path in the calculation of mutual inductance, It is difficult to theoretically calculate the relationship between size and mutual inductance. Here again, using the numerical study to find the effect of search coil size. In fig.17,

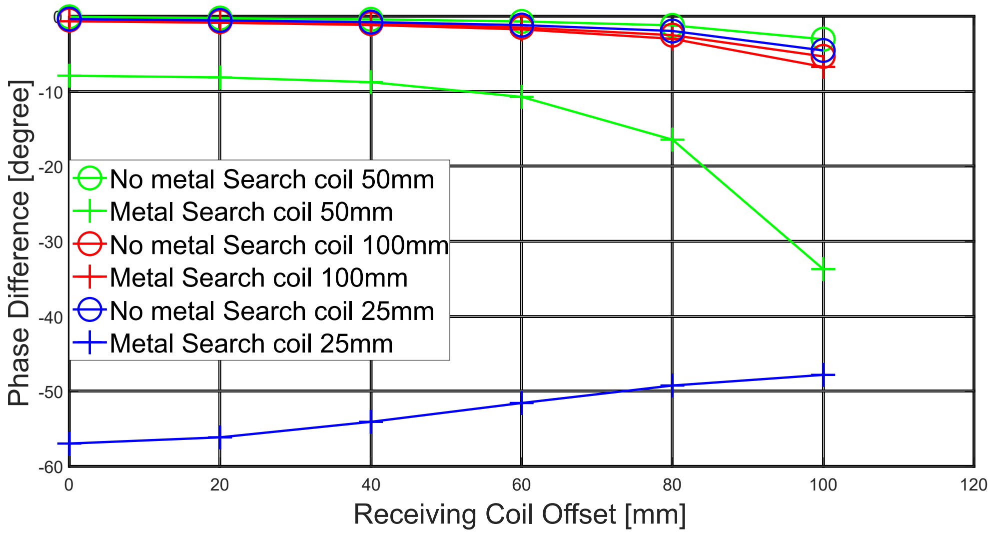


Fig. 17: Phase change of different search coil size

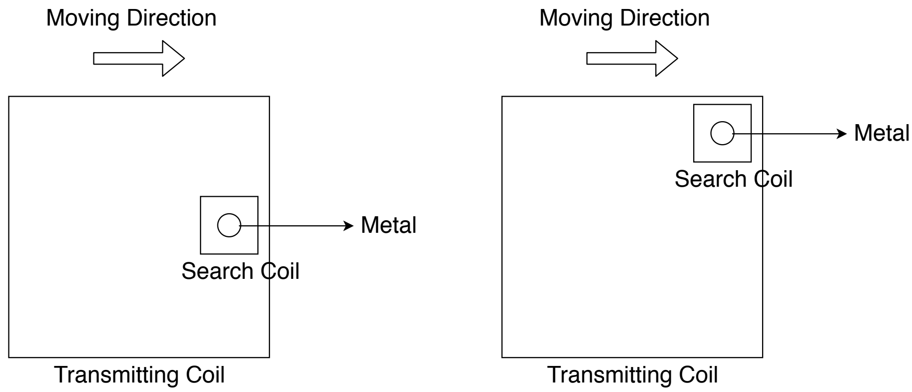
the same color means the same search coil size, the signal 'o' means there is no metal the signal '+' means there is metal. When the length of search coil is 100 mm, the phase change of metal and no metal is nearly the same. The system cannot distinguish the metal or Rx coil offset. For other size search coil, the phase change caused by the metal is significantly bigger than the phase change by the Rx coil movement. The different trends of phase change when the search coil is 25 mm and have metal is because this time, the search coil size is bigger than the metal.

Fig.17 also proves that the smaller of the search coil size, the more sensitive to metal the search coil is. The coil size will not break the robustness to the Rx coil position.

Therefore, for the manufacturer, the choice of coil size depends on how small the metal wants to be detected, and the price considerations. The simulation results verify that the small coil can better distinguish between the metal and the coil movement, but the small coil means that more sets of coils need to be tiled. In the subsequent chapters, it can be proved that for each set of symmetrical coils, related circuits are needed to detect phase change. Therefore, not only the manufacturing cost of the coil, but also the data processing cost will increase with the increase of the coil.

3.2.3 Influence of Search Coil Position

In the original idea of this research, the charging area should be covered by a group of such symmetrical coils. However, the previous discussion mainly focused on the sensitivity of the coil to metal and the robustness to the Rx coil position when the coil is in the center position. The central location is too special. In order to verify the effectiveness of the method, other generalized locations must be discussed to check whether this method can be sensitive to the metal in other positions and robust to the Rx coil movement. Here are two positions for discussion, one is the discussion on the edge position of the Tx coil, and the other is the discussion on the corner position of the Tx coil. It should be noted that for the center position, due to the symmetry of the structure, the front and back movements and left and right movements of the coil are the same. When the coil is at the edge and corner position, this symmetry will no longer exist, so the changes caused by the displacement of the coil in different directions need to be investigated in these two positions. Fig.18 shows the direction of Rx coil motion and the position of the



(a) Search Coil on Edge (b) Search Coil in Corner

Fig. 18: Phase change of search coil position and Rx coil lateral displacement

coil. This time the coil moves laterally. Fig.19 shows the results of Rx coil lateral movement. In

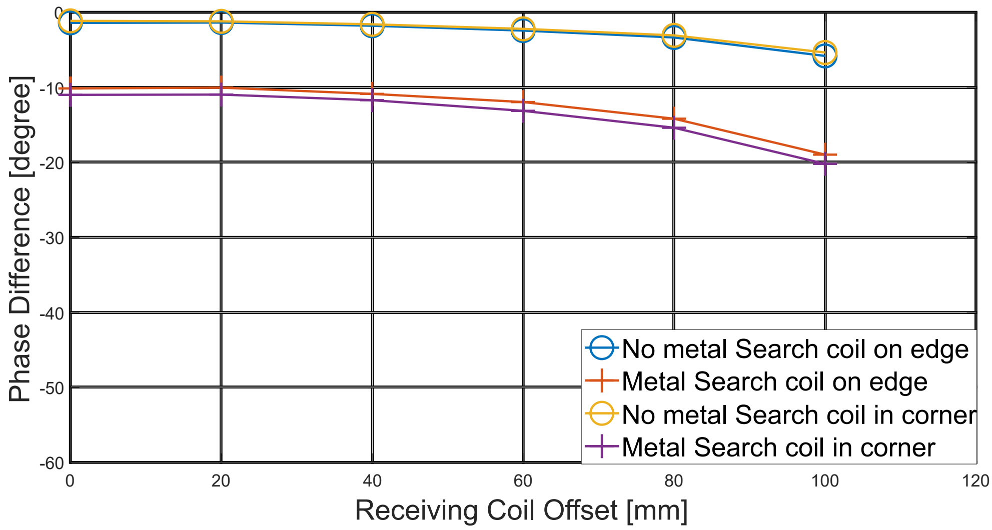
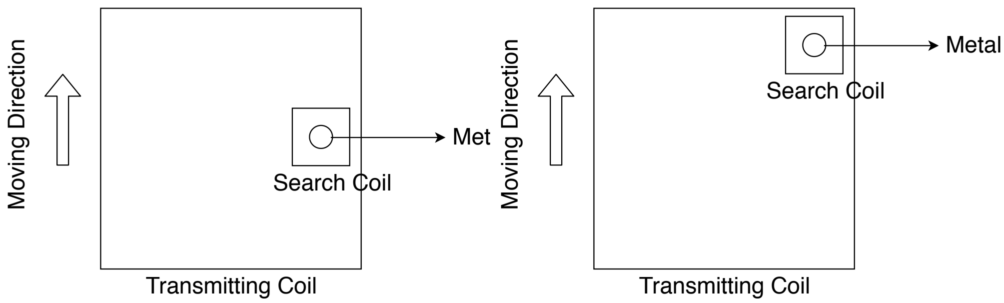


Fig. 19: Phase change of different search coil position and Rx coil moves laterally

fig.19 the symbol 'o' means there is no metal, the symbol '+' means there is metal. It is cleared that when the Rx coil moves lateral, wherever the search coil is put on edge or in the corner, the phase difference does not change too much. At the same time, the metal can still cause enough phase change.



(a) Search coil on edge (b) Search coil in corner

Fig. 20: Phase change of search coil position and Rx coil longitudinal displacement

In fig.20, this time the Rx coil moves longitudinally. Fig.21 shows the results of Rx Coil longitudinal movement. It can be seen that when the coil movement exceeds 80mm, at this time, the phase change caused by the Rx coil offset is greater than the phase change caused by the metal, which means that the system cannot distinguish well whether the coil displacement occurs or the metal exists in this area.

Fortunately, through the analysis in 3.2.2, we already know that shrinking the coil can increase the sensitivity of the coil to metal and displacement, and the increase in sensitivity to metal is much greater than the sensitivity to coil displacement. Therefore, we can put a smaller coil on the edge area to increase the sensitivity to the metal falling on the edge area.

Fig.22 and Fig23 show the results of using a search coil with a side length of 30mm. The coil

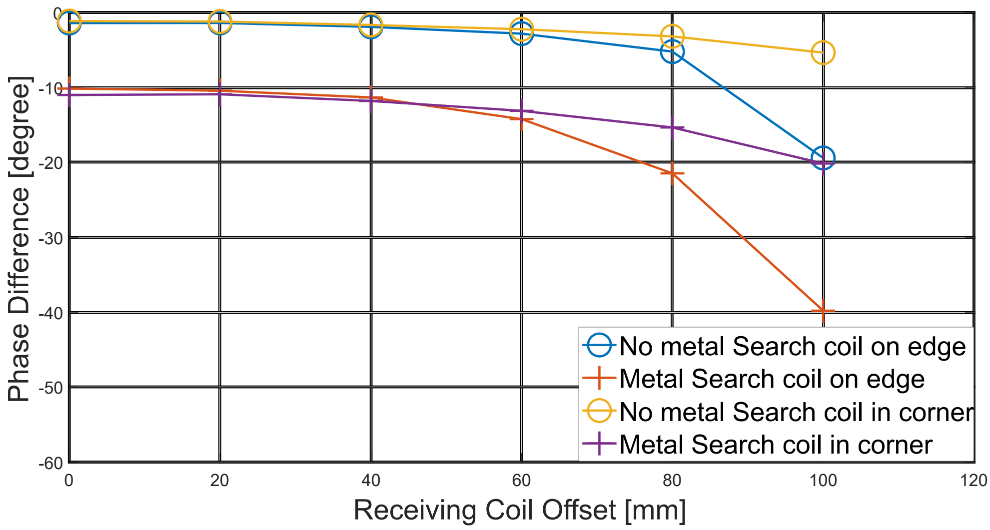


Fig. 21: Phase change of different search coil position and Rx coil moves longitudinally

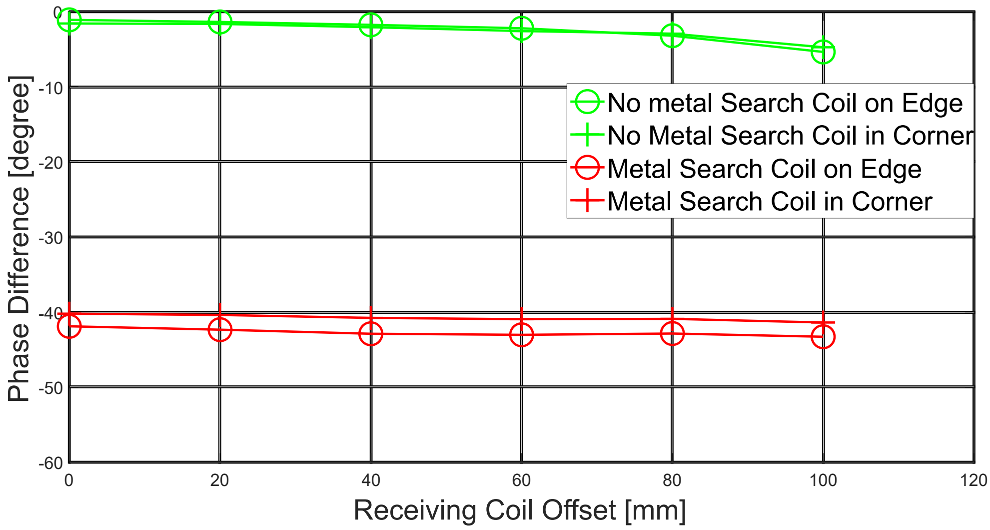


Fig. 22: Phase change of small search coil and Rx coil moves laterally

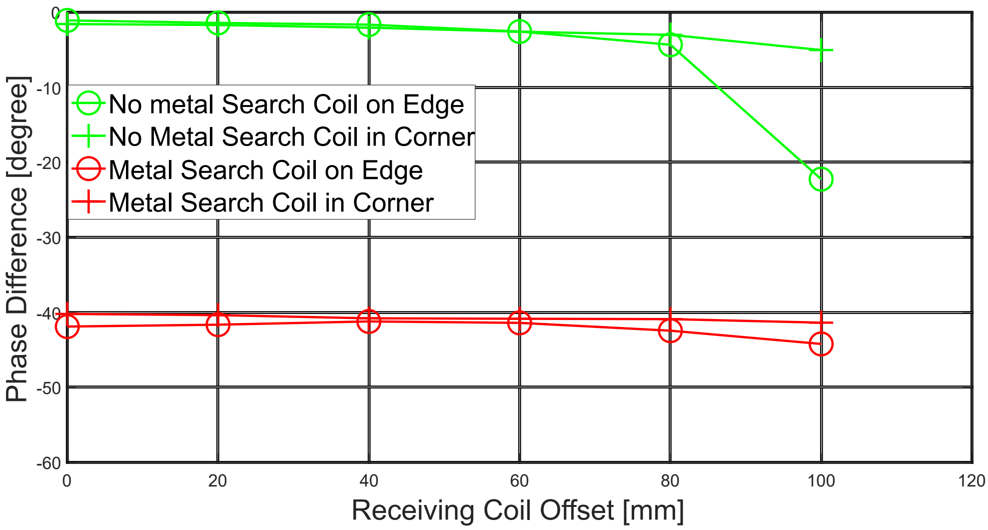


Fig. 23: Phase change of small search coil and Rx coil moves longitudinally

is also put on the edge and in the corner of Tx coil. The tx coil also moves laterally as fig.18 shows. Obviously, when using a smaller coil, the phase change caused by the metal is far greater than the change caused by the displacement. At this time, the system can detect the metal when the coil position changes. Therefore, it is suggested that a larger coil can be used at the center of the coil to reduce costs, and a smaller coil can be used at the edge of the system to improve the sensitivity to the metal of this area.

3.3 Results of Non-Resonance State

3.3.1 Phase Change of Non-Resonance State

This design is aimed to metal object detection in the magnetic resonance WPT system, and the theory is also derived based on the resonance conditions. But in the actual process, it is difficult for us to achieve a perfect resonance state. Due to the error of the device and the voltage source, the actual WPT system will always have a slight deviation from the resonance point which is inevitable. In order to ensure that this method can effectively detect metals in the actual system, it is necessary to discuss whether this method is still effective in a non-resonant system.

Non-resonance may be caused by component errors and power supply errors. Either way, it will cause the reactance of Rx or Tx coil not to be zero. So here, the capacitance is changed to simulate the non-resonance state. In the resonance system, the capacitance is 108 nF. Here the value is changed by 5%. Fig.24 shows the results of changing capacitance in the Tx coil and Fig.25 shows the results of changing capacitance in Rx coil. Fig.24 and Fig.25 show that the

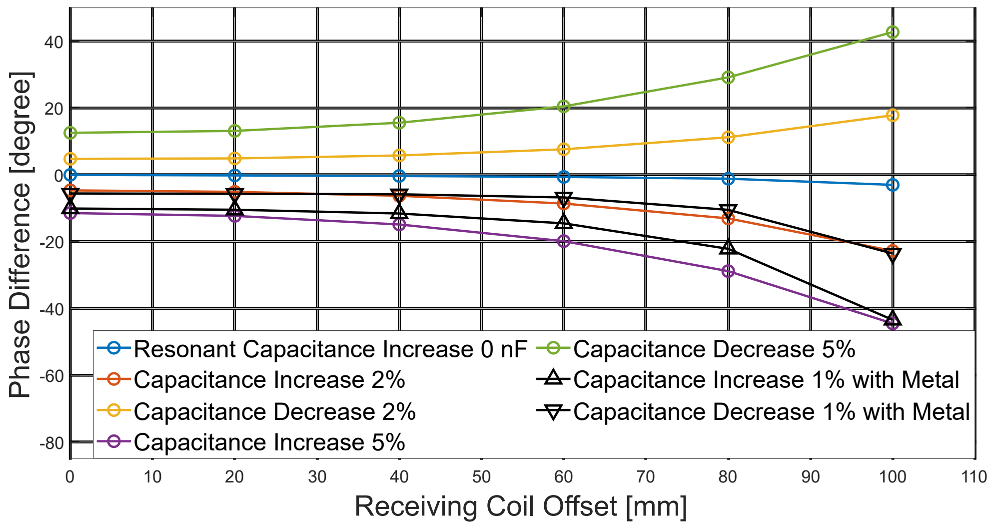


Fig. 24: Phase change in the non-resonant state of Tx coil

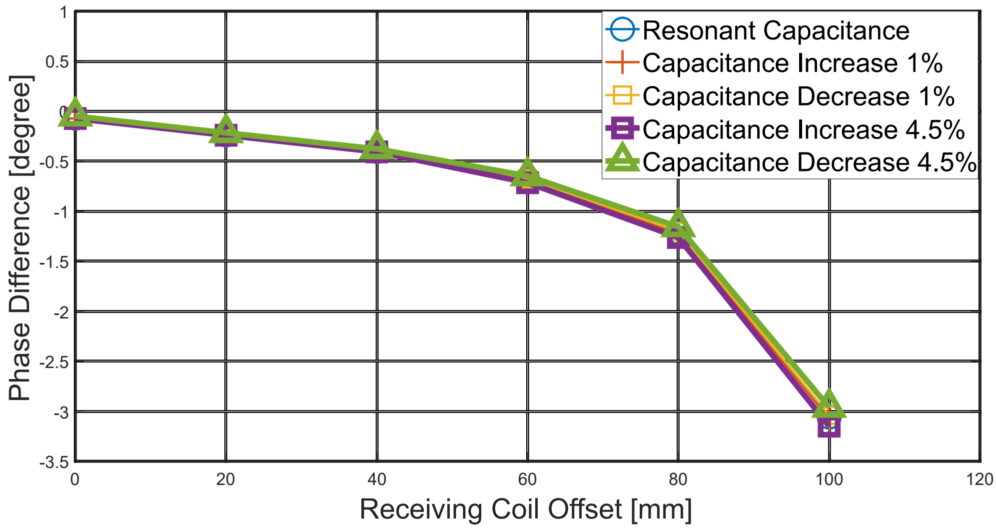


Fig. 25: Phase change in the non-resonant state of Rx coil

change in capacitance of Tx coil will make the system sensitive to the Rx coil location while the capacitance change in Rx coil did not affect too much. And at this time, a small capacitance error in Tx coil side will make the phase change caused by the movement of the Rx coil to greatly exceed the phase change caused by the metal. Therefore, the original method will fail when the Tx coil is not resonant. It is still effective when the Rx coil is not resonant.

3.3.2 Improved Method

The main reason for failure is that the current in the Tx coil is no longer in phase with the voltage source so that the phase difference of the voltage source and search coil will change significantly. To solve this problem, the voltage of capacitance in the Tx coil side can be used instead of the voltage source since it always has a 90-degree phase difference with the current in Tx coil. Fig.26 shows the results of using capacitance voltage and search coil voltage. This time the phase difference caused by the metal is still bigger than the phase difference caused by the Rx coil offset. This method can still detect the metal object without the effect from Rx coil position.

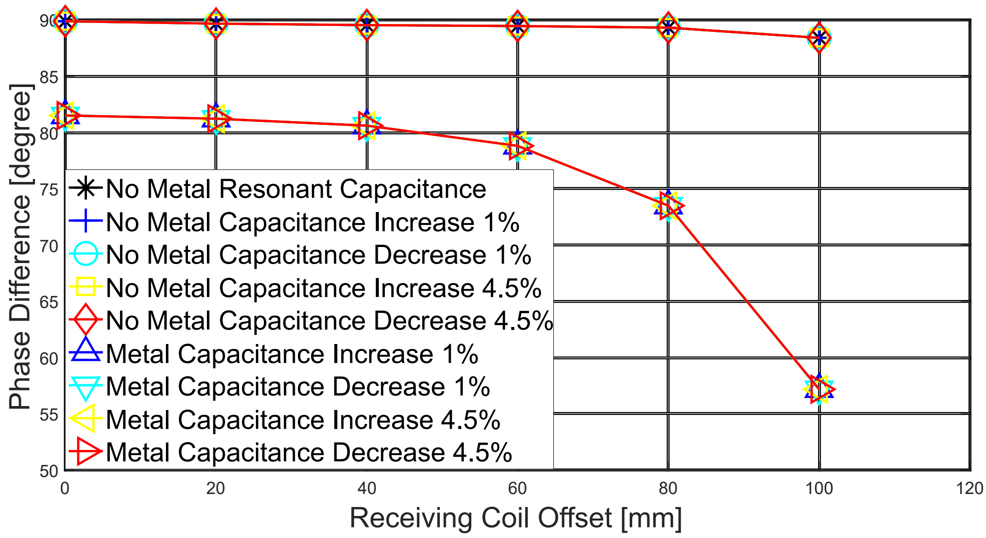


Fig. 26: Results of improved method for the non-resonant state of Tx coil

3.4 Experimental verification

3.4.1 Experimental Device

Here, we built a small WPT system to verify the validity of this method. The equipment is shown in the fig.27 The red coils are the transmitting coil and receiving coil. In order to make the same type and same size search coil, we use the PCB board to print the search coil. The search coil is shown in fig.28 The black terminal can be used to adjust the number of turns of the coil. Two PCB boards will put above and under the Rx coil. The geometric dimensions and electrical parameters refer to the previous simulation condition settings.

The metal is a steel coin which has a 2cm radius as fig.29 shows.

3.4.2 Discussion of Preliminary Experimental Results

For the first step, we just use the oscilloscope to measure the wave of current in Tx coil and the total voltage of two search coils. We try to get the value of the phase change by observing the oscilloscope. The results are shown in fig.30.

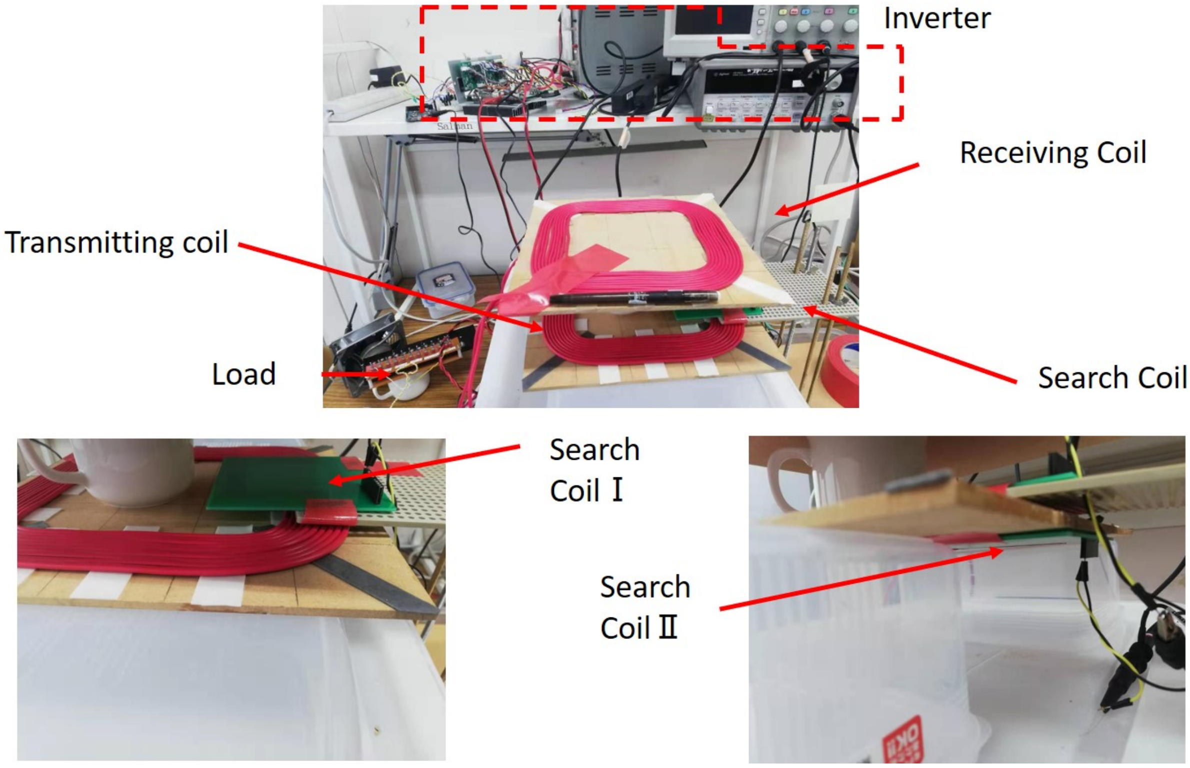


Fig. 27: Experiment device

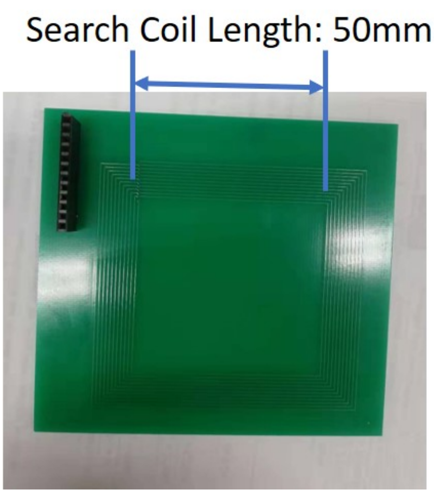


Fig. 28: Search coil photo

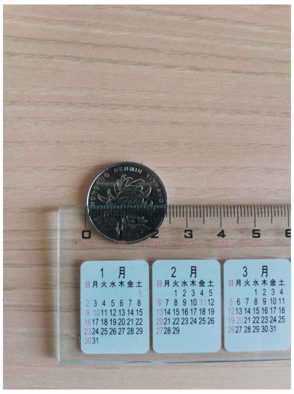
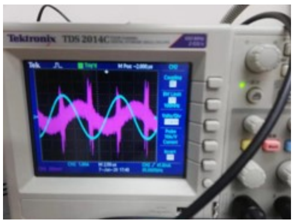


Fig. 29: Metal



(a) No netal and Rx coil alignment

(b) Rx coil misalignment

(c) Metal

Fig. 30: Waveforms in different situations

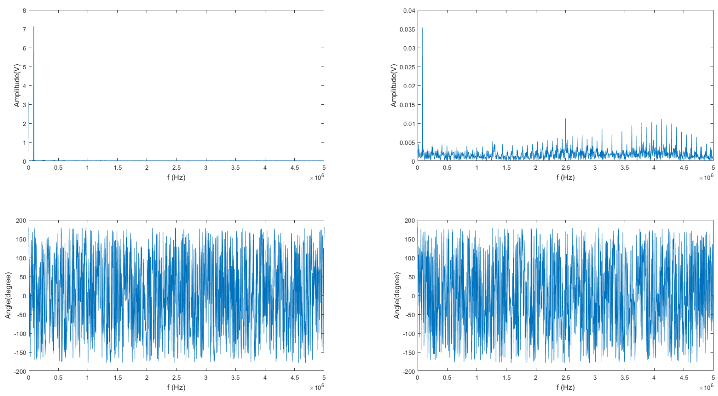


Fig. 31: DFT of Tx current and search coil voltage when coil is alignment

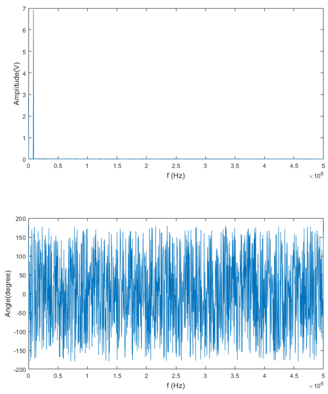


Fig. 32: DFT of Tx current and search Coil voltage when coil is misalignment

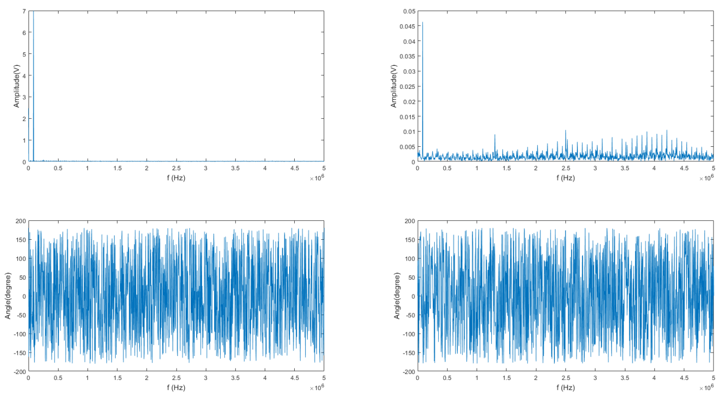


Fig. 33: DFT of Tx current and search coil voltage when metal exists

The blue line is the waveform of the current in Tx coil and the pink line is the waveform of the voltage in search coil. Unfortunately, because the pink waveform is too thick, neither the metal nor the coil movement can cause enough phase changes to be observed. Therefore, we take out the waveform data of the oscilloscope and perform Discrete Fourier Transformation(DFT).

Fig.31 shows the results of DFT of the current in Tx coil and voltage of search coil when there is no metal and Rx coil is alignment. Fig.32 shows the results of DFT of the current in Tx coil and voltage of search coil when Rx coil is misalignment. Fig.33 shows the results of metal exists. For fig.31 and fig.32 and fig. 33, the right two figures show the result of the current in the Tx coil and the left two figures show the result of search coil voltage. We can find the phase of the 85 kHZ waveform from the figure and calculate the phase difference between the current and the voltage. The phase difference in fig.31 is -7.6481 degrees. The phase difference in fig.32 is -6.8579 degrees. The phase difference in fig.33 is -1.9510 degrees. The results show that it is true that the phase difference between the Tx coil current and the voltage of search coil changes less when the coil is moving and has a greater change when there is metal.

3.5 Conclusion

In this chapter, the numerical study first verified that the phase of the symmetrical search coil voltage and the voltage source in the magnetic resonant WPT system was easily changed by the influence of metal. At the same time, the phase difference was not easily affected by the position of the Rx coil. This chapter also proved that metal can be detected within the range enclosed by the search coil. The simulation results showed that smaller coils are more sensitive to metals. At the edge of the Tx coil, the sensitivity of the coil to metal decreased. Therefore, this chapter recommended using a smaller Tx coil at the edge and verifies the effectiveness of the method. This chapter discussed the effectiveness of the method in non-resonant systems and proposed an improved method of using capacitor voltage instead of voltage source in non-resonant systems. The experiment results also proved that this method can be sensitive to the metal object but robustness to the Rx coil position.

Chapter 4

Economic Optimization

4.1 Circuit Design

4.1.1 Background of Circuit Design

The simulation software can easily calculate the phase of the voltage source and the search coil. However, in reality, the phase difference of two signals is not easy to detect. The previous chapter introduced that the phase difference can be obtained through the DFT. But this method asks people to use A/D converter(ADC) to input the signal into the microprocessor and then get the phase information. This method not only needs high-precision ADC but also needs a microprocessor to do DFT all the time which will consume more power. Furthermore, the whole system needs to cover the dangerous charging area with pairs of the symmetrical search coil, which means each pair of coil need an ADC and microprocessor to calculate the phase difference. Since most of Operational Amplifier is under 1.5 dollars, the ADC is about 20 dollars. As the introduction said in the beginning, this research is committed to solving metal detection problem in a cheap way, but using too many ADC and microprocessors will obviously increase costs.

The ideal way is to change the phase difference to amplitude value and input into a microprocessor so that each pair of search coils will only occupy one channel.

4.1.2 Phase Detector

In order to convert the phase difference into something easier to measure, a phase detector is used here. Phase detector can help to transform phase difference of two signals to voltage change since the voltage is easier to measure. Suppose the current of capacitance in Tx coil side and voltage of search coil is

$$U_a = Asin(\omega t) \tag{4-1}$$

$$I_b = Bsin(\omega t + \theta) \tag{4-2}$$

U_a means the voltage of search coil and I_b means the current in Tx coil. Since the voltage of capacitance has a 90-degree phase difference with the current in Tx coil, the voltage of capacitance is

$$U_b = Bsin(\omega t + \theta - 90) = Bcos(\omega t + \theta) \tag{4-3}$$

U_b means the voltage of capacitance. The product of these two signals is

$$\begin{aligned} U_a \cdot U_b &= Asin(\omega t) \cdot Bcos(\omega t + \theta) \\ &= \frac{1}{2}AB\left[-sin(2\omega t + \theta) + sin(\theta)\right] \end{aligned} \tag{4-4}$$

In formula 4-4, the product has a high-frequency part and a constant part, and the constant part is the sine of the phase difference of two signals. If we use a low pass filter here, we can get the phase information of two signals.

4.1.3 The Requirements of Circuit Design

The multipier will product a higher frequency signal and a constant part will be produced in their result. And this constant is related to the trigonometric function of the phase difference of two signals. This brings us to the first and second circuit design requirements, an analog multiplication circuit for multiplication calculation and a low-frequency filter that only allows constant parts to pass. The previous analysis has said that the perfect resonance state is difficult to achieve in practice, so the experiment here defaults to the non-resonance state. Therefore, the capacitor voltage and the total voltage of search coil are selected as the first signal and the second signal in the subsequent analysis.

Formula 4-4 only considers ideal signals. But fig.33 and fig.32 and fig.31 tell us that the actual signal contains a lot of clutter. Therefore, the actual signal should be written in the following form.

$$U_a = A_1sin(\omega_1 t) + A_2sin(\omega_2 t) + A_3sin(\omega_3 t) + ... \tag{4-5}$$

$$U_b = B_1cos(\omega_1 t + \theta_1) + B_2cos(\omega_2 t + \theta_2) + B_3cos(\omega_3 t + \theta_3) + ... \tag{4-6}$$

If we multiply such two signals, the answer should be

$$\begin{aligned} U_a \cdot U_b = &\frac{1}{2}A_1B_1 \left[-sin(2\omega_1 t + \theta_1) + sin(\theta_1)\right] + \frac{1}{2}A_2B_2 \left[-sin(2\omega_2 t + \theta_2) + sin(\theta_2)\right] \\ &+ \frac{1}{2}A_3B_3 \left[-sin(2\omega_1 t + \theta_3) + sin(\theta_3)\right] + ... \end{aligned} \tag{4-7}$$

It can be seen that every multiplication of the same frequency waveform will add a constant term, and among them, only the result of the multiplication of the power frequency is what we want. The other constant terms are all errors. In order to reduce the influence of other frequency waves on the results, the two signals must be filtered before multiplication. Here comes the third circuit design requirement, designing a filter for the signal.

In formula 4-4, the constant part is not only affected by the phase difference but also affected by the amplitude of two signals. Especially, when the Rx coils move, the current in Tx coil will also get changed. If we cannot separate a value from the product with a circuit, we must at least know the magnitude of this value so that we can divide the result by this value. Here comes the fourth circuit design requirement, getting the signal amplitude. In this research, we use a rectifier circuit to get the amplitude.

The previous discussion talked about using voltage source voltage or capacitor voltage for phase comparison. When we use capacitor voltage, we must consider separating the signal circuit from the WPT power circuit. Otherwise, we will not only damage the signal circuit, but also destroy the resonance state of the system, and reduce efficiency, which must be absolutely avoided. Here comes the fifth circuit design requirement, designing a voltage follower for the signal.

4.1.4 Multiplier

The multiplier is the core component of the loop. The analog multiplier can multiply two signals to achieve our goal. In this research, AD633 analog multiplier of Analog Devices company is selected. This kind of multiplier circuit is simple, only need to configure the power supply according to the requirements of the data manual [31], no additional external circuit is needed.

4.1.5 Filter

The analysis in the previous section said that a total of three filters are required in the circuit, one for filtering the capacitor voltage signal, one for filtering the search coil voltage, and one for filtering the output of the analog multiplier.

The first is the capacitor voltage filter. Since only the waveform of the power supply voltage frequency is what we want, a bandpass filter is needed here. At the same time, the capacitor voltage in the circuit will be greater than the power supply voltage. In order to protect the device, we use a passive filter here to avoid the use of op-amps.

The circuit of the capacitor filter is shown in the fig.34.The design of the parameters takes into account the frequency of the power supply voltage. On the other hand, the amplitude of the signal is reduced because the capacitor voltage is often too large. The amplitude-frequency

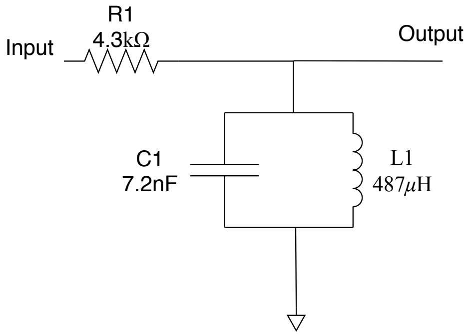


Fig. 34: Capacitor voltage filter circuit Diagram

curve and phase-frequency curve of the filter are shown in the fig.35.

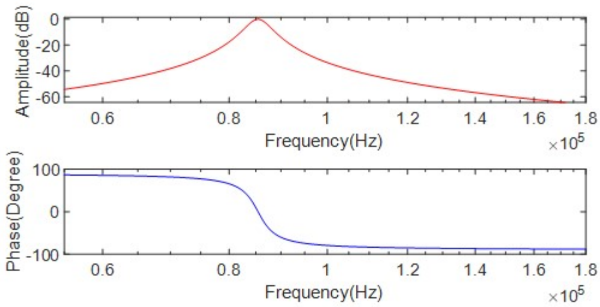


Fig. 35: Amplitude-Frequency curve and Phase-Frequency curve of capacitor filter

The second filter is for the search coil. It is also a bandpass filter and the pass frequency is also as same as voltage source. Since the total voltage of search coil is always too small. Here an active bandpass filter is used to amplify the value of signal. With the help of filter wizard [32], the second filter is designed as fig36 shows.

The amplitude-frequency curve and phase-frequency curve of the filter are shown in the fig.37.

Since we use phase to judge metal, we need to discuss the phase shift of the filter. The original two signals have a phase difference of 90 degrees. The capacitor voltage filter will increase the phase of the 85khz waveform by 9.5 degrees, and the search coil filter will increase the phase of the waveform by 190 degrees. After passing through the filter, the phase difference between the

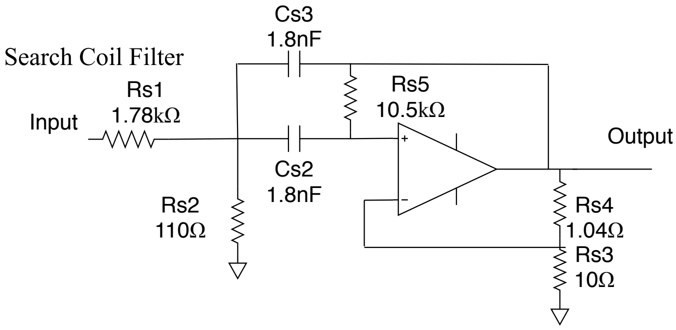


Fig. 36: Search coil filter circuit diagram

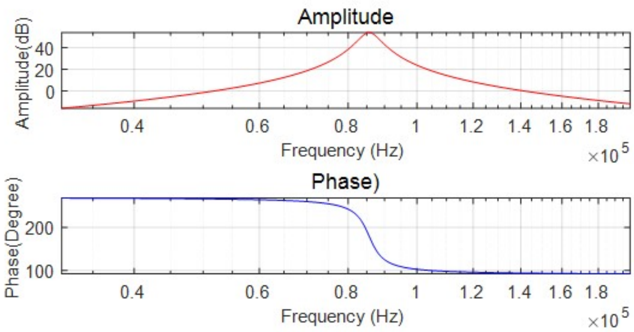


Fig. 37: Amplitude-Frequency curve and Phase-Frequency curve of search coil filter

two is still around 90 degrees, but the direction is opposite. This will only add a negative sign in the multiplication operation, and will not change the nature of the circuit.

The last filter is to pass only the constant component in the product of formula 4-4, and cut off all other frequency waveforms as much as possible, so its cut-off frequency should be as small as possible. With the help of filter wizard, the circuit figure is shown in fig.38.

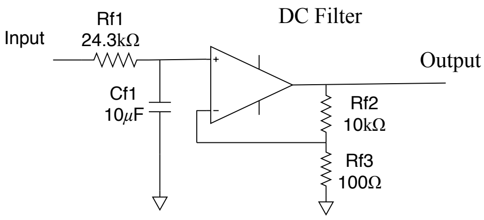
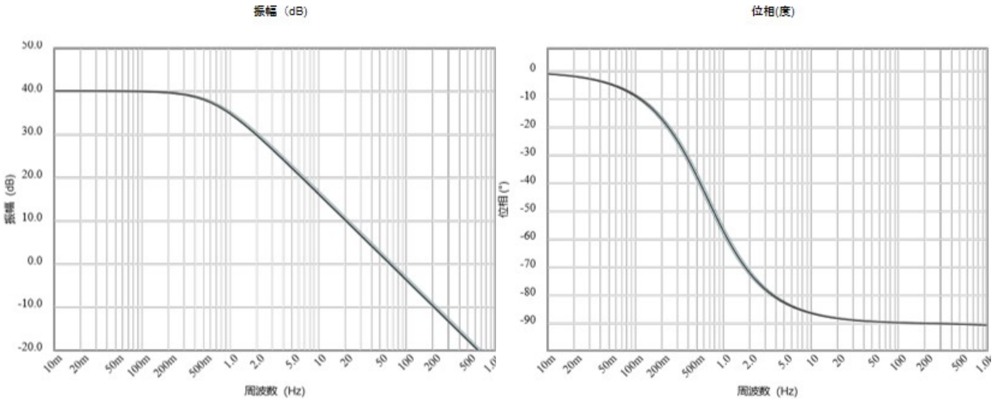


Fig. 38: Low pass filter circuit diagram

The amplitude-frequency curve and phase-frequency curve of the filter are shown in the fig.39.

4.1.6 Voltage Follower

The voltage follower is used to isolate the signal circuit and the WPT power circuit. Here, an operational amplifier is used to isolate the two circuits because the internal resistance of the operational amplifier is very large and hardly affects the power circuit and the signal of the



(a) Amplitude-Frequency curve (b) Phase-Frequency curve

Fig. 39: Amplitude-Frequency curve and Phase-Frequency curve of low pass filter

capacitor voltage can be obtained in real time. The circuit diagram is shown in the fig.40. Since

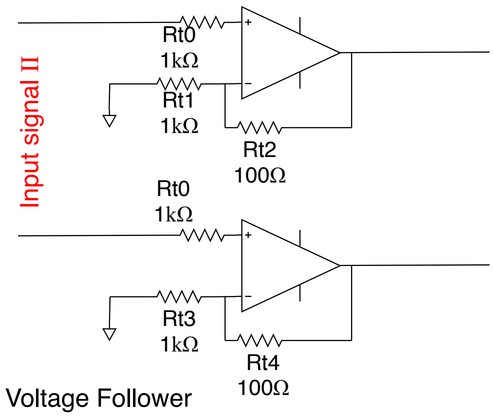


Fig. 40: Voltage follower circuit diagram

an operational amplifier is used here, this circuit is not suitable for high-power WPT systems, because the voltage of the high-power WPT system is much higher than the safe working voltage of the operational amplifier, so the method of directly connecting the operational amplifier into the working circuit is only suitable for low-power WPT systems. Regarding this aspect, a voltage divider circuit can be used to obtain a voltage signal, but the resistance used in the voltage divider circuit is generally not greater than the internal resistance of the op-amp. It may affect the original power circuit.

4.1.7 Rectifier Circuit

The rectifier circuit is used to obtain the amplitude of the signal. Here, a full bridge circuit is used to obtain the amplitude of the signal. The selection of the resistance value of the capacitor is determined by the frequency. The circuit diagram is shown in the fig.41. The disadvantage of this method is that it is difficult for the rectifier circuit to obtain a very smooth waveform. If

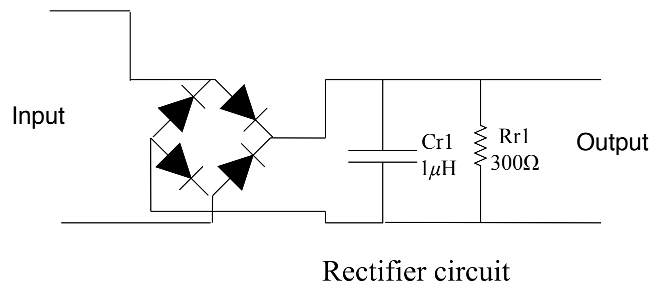


Fig. 41: Rectifier circuit diagram

we use a division circuit to divide the output result of the analog multiplier by the output result of the rectifier circuit, this unsmooth waveform will be amplified and seriously affect the result. The current method is to read the average value of the output waveform of the rectifier circuit to obtain the signal amplitude. Finally, the output result of the analog multiplier is divided by the amplitude of the signal by manual calculation.

4.1.8 Whole Circuit

Based on the above analysis, the logic diagram of the circuit was first drawn as shown in the fig.42.

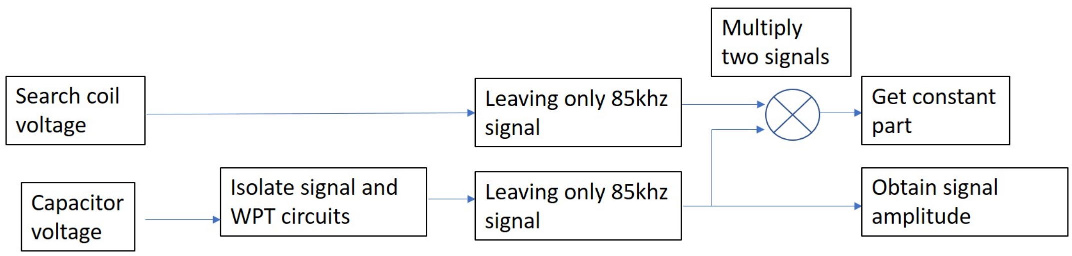


Fig. 42: Logically circuit diagram

The whole circuit is shown in fig.43. The voltage follower obtains the voltage across the capacitor and sends it to the filter for filtering. At the same time, the search coil voltage is directly sent to the filter for filtering. On the one hand, the filtered capacitor voltage is multiplied by the filtered search coil voltage and sent to the rectifier circuit on the other hand. The reason why the capacitor voltage is selected here is because it is found in actual experiments that when the coil is displaced, the amplitude of the capacitor voltage tends to change greatly and the coil voltage amplitude changes less. After the two signals are multiplied, the result is sent to the low-pass filter. The whole circuit has two outputs, one is the constant component mentioned in the formula4-4, the other is the amplitude of the capacitor voltage, and finally, the constant component is divided by the capacitor voltage. The result is a certain multiple of the sine of the phase difference between the two signals

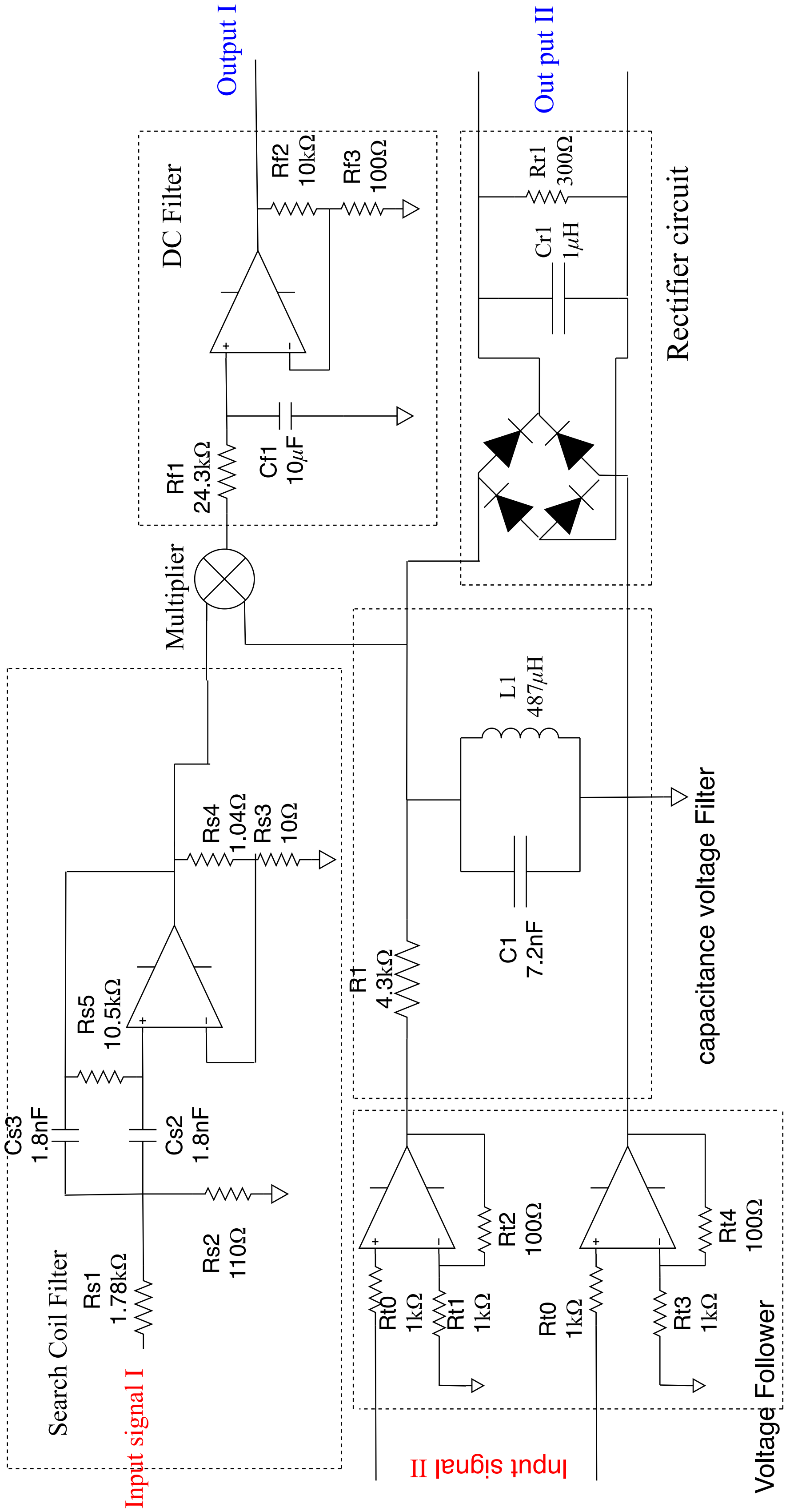


Fig. 43: Whole circuit diagram

4.2 Experiment Results

The experiment used the coin in fig.29. The output I and output II in fig.43 is measured. Then divide output I by output II to get the final result. In each case, three sets of experiments were done and the average of the three sets of experimental data was taken. The results of verfication experiment are shown in fig.44.

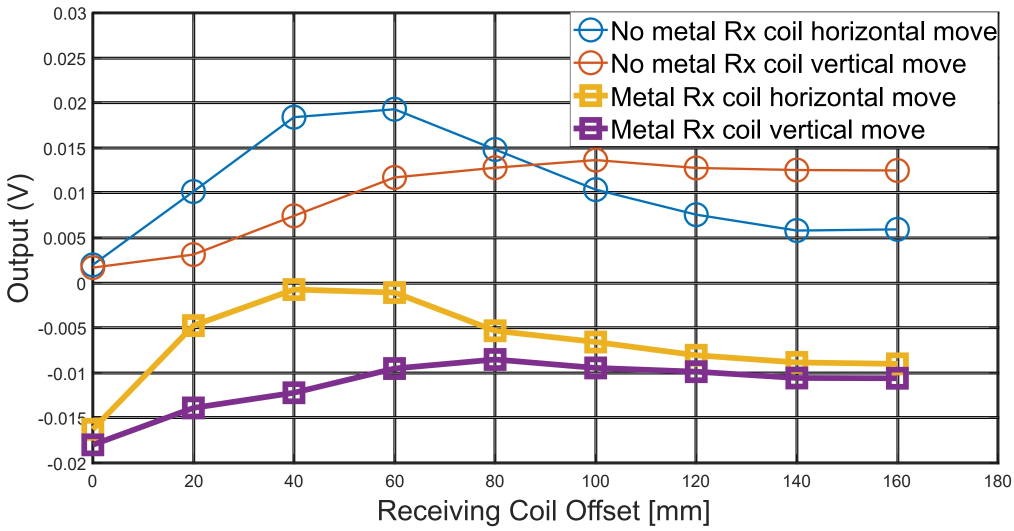


Fig. 44: Verfication experiment results

The coin was put above the search coil. We can see that when there is no coin, although the output will change with the lateral or longitudinal displacement of the Rx coil, the range of output change is always outside the range of change when there is a coin. Once a coin appears above the search coil, the output will drop significantly, even if the coil is displaced laterally or longitudinally, the output value cannot return to the time when there is no coin. Therefore, the output of this system when a coin appears has a completely different value than when there is no coin. Although this value will also change, the changed area will not cross, so the system will not produce misjudgments. Experiments have proved that this method can detect metals and is robust to the Rx coil position.

Table 6: Experiment results of metal in different position

Position	Center	Edge	Corner
Output(V)	-0.0072	-0.00941	-0.00875

Table6 also shows that the metal will cause similar output changes regardless of whether it is in the center, edge, or corner of the search coil. This indicates that in the area covered by the search coil, there is no detection dead zone, and the metal can be detected in any area covered by the search coil. Table 7 shows that this method can detect metal at a certain height from

Table 7: Experiment results of metal in different height

Metal Height	0mm	5mm	10mm	25mm
Output(V)	-0.00722	-0.00516	-0.0035	0

the coil. In practice, the detection system and the transfer coil will be packaged together, so the metal often does not fall directly on the surface of the coil. It must be a certain height from the coil. Table 7 proves that at least 1.5cm away from the coil, the metal can be detected as well.

4.3 Conclusion

This chapter first introduced a series of analog circuit designs to convert the phase difference of the two signals into easily detectable voltage changes. Secondly, this chapter proved that the phase of the symmetrical search coil voltage and the capacitor voltage was indeed susceptible to the influence of metal and was robust to the Rx coil position through experiments. Experimental results showed that this method can detect an iron coin size metal within the range of the coil's lateral or longitudinal offset by one Rx coil length. The experimental results also showed that metal can be detected within the range enclosed by the search coil. The experimental results also proved that the coin can be detected within 1.5cm above the search coil.

Chapter 5

Conclusion

5.1 Conclusions

This research first introduced the previous metal object detection methods in WPT system and their inability to distinguish between coil misalignment and metal object in Chapter One.

In Chapter Two, this research proposed a new method using the phase difference of a pair of symmetrical search coils voltage and voltage source to detect the metal. The theoretical deduction proved that this method is robust to coil misalignment in the metal detection of magnetic resonance WPT systems. This research also proposed the improvement methods when the system deviates from the resonance point.

The simulation results in Chapter Three showed that the system can detect metal well and is not affected by Rx coil position when the coil displacement did not exceed two-thirds of the coil length. This study also proved that metal falling on the search coil can be detected everywhere. Aiming at the problem that the search coil at the edge of the Tx coil cannot detect metal well, this research proposed a method of arranging a small search coil on the edge of the Tx coil and a large search coil in the center, which takes into account the production cost and detection sensitivity. This study also proved that even if the system does not work in a perfect resonance state, the robustness of the coil displacement can be achieved by using capacitor voltage.

In Chapter Five, a series of analog circuits were designed to convert the phase difference into voltage values that are easier to detect. Based on this circuit, this study proved that this method can detect coin-sized conductors, and within the range of the coil length moving of the receiving coil, metal can be detected without the interference of the coil position in experiments. Experiments also demonstrated that this method can detect metals at least 1.5cm above the coil.

In conclusion, this research proved that this method can detect a steel coin shape metal. The results were robust to the Rx coil two-thirds of the coil length moving. This method can detect metal at 1.5 cm higher than the search coil. There is no dead zone in the area covered by the search coil. For one search coil, the cost is under 3000 JPY. It is expected to solve the problem that the detection of metal objects in electric vehicles WPT system is susceptible to the position of Rx coil in a cheap way.

5.2 Future Plan

Noise in the circuit is a big problem, and the source of these noises has not been fully understood. These noises will mainly increase the sensitivity of this method to the coil, making the output result easily affected by the position of the Rx coil. At present, there are two main problems with noise. One problem is that before the multiplication operation, the effects of the two bandpass filters are not always ideal, and the amplitude of some high-frequency signals is not significantly reduced. Another problem is that there is a clutter with a frequency of about 600kHZ in the oscilloscope display loop, the amplitude of which is relatively large, and this clutter cannot be removed by the bandpass filter. Even if the circuit is completely wrapped with tin foil, this clutter cannot be eliminated. The source of this clutter is not yet clear. The subsequent design should focus on designing a better bandpass filter and consider adding a 600kHz bandstop filter.

Secondly, a set of coils circuits currently contains two outputs. We had to read their average value separately, and manually divide output I by output II . This work was originally planned to be completed by a division loop composed of an analog multiplier, but the waveform obtained by the rectifier loop (output II) is not stable. If the loop is directly divided, this unevenness will be amplified, so that in the end, a DC voltage cannot be obtained but an AC voltage can be obtained. The next work should include how to obtain a stable voltage amplitude signal.

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Appendix A
The Effect of Metal on the Tx and Rx Coil

In chapter two, we derived the voltage function of search coil. In fig.12 we did not consider the mutual inductance between metal and Tx coil and Rx coil. Here, we will discuss whether this mutual inductance will affect the results.

First of all, in the voltage equation of the search coil(2-1), we have considered the influence of metal and Tx coil and Rx coil. So formula 2-1 will not change.

$$U_{s1} = I_1 j\omega M_{1s1} + I_2 j\omega M_{2s1} + I_e j\omega M_{es1} \tag{2-1}$$

The problem is mainly concentrated in formula 2-2. The prerequisite for this formula is that the system is working in resonance. However, the appearance of metal objects may change the equivalent impedance of the secondary side and destroy the resonance state. Therefore, this formula will no longer hold, which may affect the subsequent derivation.

$$I_2 = -\frac{j\omega M_{12}}{r + R} I_1 \tag{2-2}$$

So what needs to be demonstrated here is whether the metal will have a great impact on formula 2. For this, we did some experiments. In the experiment, we first put the system in resonance, and then put paper clips, coins, and cans in the middle of the coil and then observe the current in Tx coil and in Rx coil through an oscilloscope. We found that when putting paper clips and coins, the current changes in phase and amplitude were too small, so that the oscilloscope could not observe this change at all. In other words, the formula is still valid at this time, and the subsequent derivation will not cause problems.

When putting a can into the charging area, the current in Rx coil did not change. The amplitude of I_1(current in Tx coil) changed by 0.8 A(4%), and the phase changed by 0.1 degrees.

From the perspective of formula 2-2, the phase relationships did not change too much, only the multiple relationship of amplitude was changed a lot. In the subsequent derivation, we use this layer of phase relationship to make the parameters of the Rx coil part all be reduced to the real part of the formula, so small changes in the phase will not add the receiving coil factor to the imaginary part, and the amplitude changes will only change the size of the real part. For phase, the impact is limited.

In fact, it was also mentioned in the introduction in Chapter 1 that the electrical parameters of small metals to the transmission and reception coils are limited [24] [23], which is why it is difficult to find small metals in the application of circuit parameters. Therefore, both the experiments and the preliminary research here illustrates the limited influence of metals on circuit parameters. The method proposed in this research uses this point for derivation and then proposes the method of phase-detection for small metals.

Appendix B

Discussion of Different Turns of Search Coil

Another way to increase the sensitivity of the coil to metal is to increase the number of coil turns. Since the mutual inductance is proportional to the number of turns of the coil, this method may affect both the real and imaginary parts in the formula 2-5, so it is hard to judge whether it will increase the sensitivity of the coil to the position at the same time. Fig.45

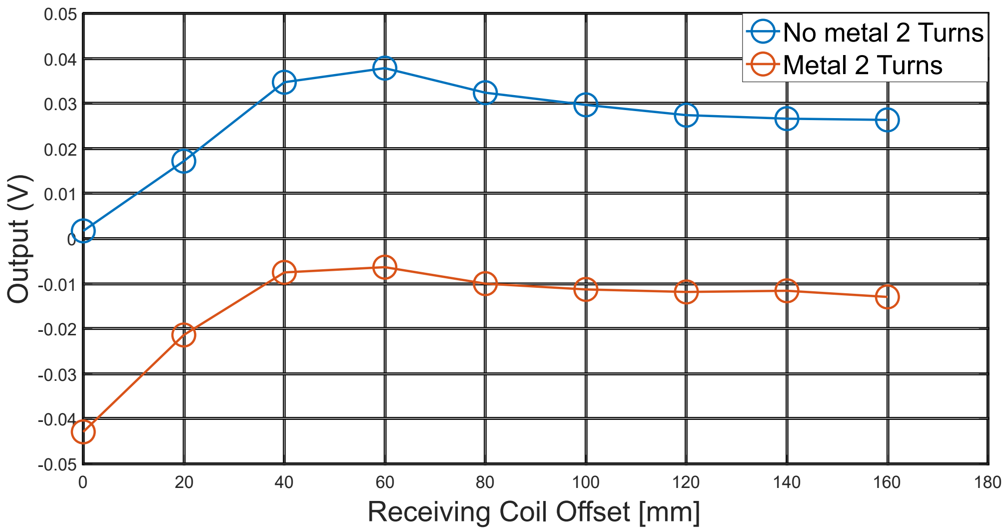

Fig. 45: Experiment Results of Two Turns Search Coil

shows the results of 2 turns search coil experiment. Fig.46 shows the results of 4 turns search coil experiment. It can be seen that increasing the number of turns does increase the range of output change whether it is Rx coil misalignment or metal. This shows that increasing the number of coil turns will increase the system's sensitivity to displacement and metal. And unfortunately when using a 4-turn coil for detection, if the coil displacement exceeds about 30mm, even if there is metal, the output will be the same as the result when the coil is aligned without metal.

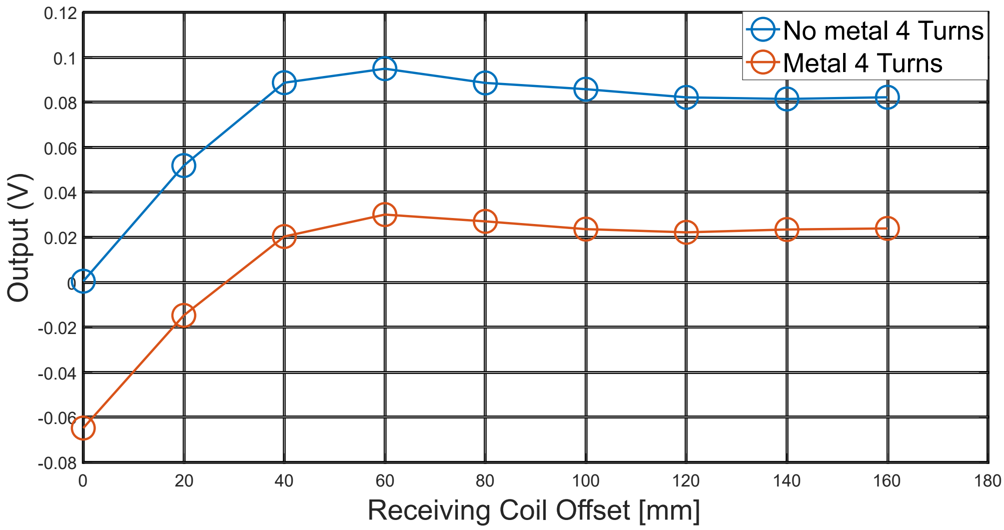

Fig. 46: Experiment Results of Four Turns Search Coil

This indicates that the presence of metal cannot be detected at this time. Therefore, simply increasing the number of detection coil turns does not guarantee that the system can better distinguish between coil misalignment and metal.

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[2] **Han Xu**, Takeda Kodai, Mizoguchi Tomoya,Koseki Takafumi,"Foreign Metal Detection Robust to Coil Misalignment in Wireless Power Transfer System",The Institute of Electronics, Information and Communication Engineers,Wireless Power Transfer (WPT),Jul 3, 2020