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Research on Metal and Living Foreign Object Detection Method for Electric Vehicle Wireless Charging System

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Abstract: In the electric vehicle wireless power transmission system, the high-frequency alternating magnetic field between the transmitter and receiver can have a certain impact on the health of living organisms and may even lead to lesions. In addition, metal foreign objects in an alternating magnetic field can cause their own heating or even cause fires due to the eddy current effect, so foreign object detection is an essential function in the wireless power transmission system of electric vehicles. In order to prevent metals and living organisms from entering the charging area and causing harm to the charging system and living organisms, this paper proposes a method for detecting living organisms and metal foreign objects. Firstly, the equivalent circuits for the detection systems of the living organism foreign objects and metal foreign objects are established, respectively, and the working theory of the detection system is analyzed by deriving equations. Secondly, the comb capacitor simulation model was constructed, and the comb capacitor electrode spacing, wire thickness, and capacitor spacing were designed based on the scale factor γ to explore the effects of the height and bottom area of the living organism's foreign object on the comb capacitor. We constructed a simulation model of the detection coil and designed the inner diameter D, the number of turns N, and the wire spacing S of the detection coil according to the scale factor β. An arrayed detection coil and comb capacitor combination mode is proposed to realize the function of the simultaneous detection of metal and living organism foreign objects, and a compensation capacitor is introduced to keep the detection system in a resonant state. Lastly, a platform for foreign object detection experiments was set up to detect metal screws and beef chunks compared to the detection area without foreign objects. Metal screws entering the detection area cause a 20% voltage drop in the detection circuit resistor, and beef chunks entering the detection area cause a 30% voltage drop in the detection circuit resistor, so the detection method is effective in detecting both metals and living organisms. The feasibility of the combined mode of arrayed detection coils and comb capacitors was verified.

Keywords: comb capacitors; detection coils; compensation capacitors; electric vehicles; wireless power transmission; foreign object detection

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1. Introduction

Wireless power transmission systems can transmit power from the grid to electrical loads without cable connections. Over the past few decades [1], the research on wireless energy transmission technology has never stopped [2,3]. Wireless power transmission technology is widely used in railway transport, medical equipment, and electric vehicles due to its convenience and low equipment loss rate [4–7]. During the wireless charging process of electric vehicles, the energy coupling region of the system may be mixed with certain metal or living organism foreign objects, and the presence of these foreign objects can affect the system transmission efficiency and power. More seriously, the eddy current effect of the metal can cause the temperature of the metal itself to rise and, in severe cases, even cause a fire. Electromagnetic radiation generated by coils causes damage to the reproductive, nervous, and immune systems of living organisms. Therefore, research on foreign body detection is particularly important. Current foreign body detection techniques include two main categories: metal foreign object detection and living organism foreign object detection [8–12]. Research on foreign object detection technology for living organisms is still in its infancy [13]. Most studies have also focused on the use of auxiliary sensors, such as thermal cameras, X-rays, pressure sensors, radars, and heat sensors [14–16]. However, these methods are difficult to integrate with magnetic couplers and are susceptible to environmental influences that can lead to false positives. In contrast, a structurally simple and cost-effective method for the foreign body detection of living organisms using comb capacitors has been proposed. In high-power wireless power transmission system applications, similar to detection coil arrays, literature [17] and literature [18] introduced a comb capacitor-based living organism detection device and analyzed and designed the comb capacitor structural parameters, capacitance spacing, and so on. According to the effect of living organisms on comb capacitors, corresponding parallel resonant circuits and integral circuits are designed for the detection of living organisms. For metal foreign object detection, detector coil arrays have received much attention due to their low cost and high integration. Most of the research on metal foreign object detection using detector coil arrays has focused on optimizing the coil array layout, eliminating detection blind zones, and improving detection reliability [19–21]. Literature [22] proposes an active metal foreign object detection scheme based on impedance change, which solves the problem of a passive detection scheme that cannot achieve the detection under a power-down situation by applying an excitation source to the detection coil, optimizes the coil structure to solve the problem of detecting the blind area, and selects the frequency that deviates from the resonance point with high sensitivity. In practice, spatial misalignment between electric vehicles and ground-mounted power transmitters is inevitable. In order to eliminate this misalignment effect, literature [23] proposes an FOD method based on passive sensing coils using voltage vector decomposition. A non-cooperative MOD (metal object detection) mechanism is proposed in the literature [24] to support the safe operation of WEVC (wireless electric vehicle charging) systems. We designed a unique array of sensing coils to perfectly adapt to the magnetic field characteristics of DD coils. Size-modulated patch coils were created to eliminate detection blind spots by correct polarity configuration. Due to its asymmetric topology, flexible size modulation, and proper polarity configuration, it can effectively detect metallic foreign objects anywhere in the charging area. This research paper introduces and analyzes a method for the detection of living organisms and metal foreign objects based on planar comb capacitors and detection coils. Firstly, the fundamentals of the method for detecting living organisms and metal foreign objects are analyzed separately. Secondly, the comb capacitor and detection coil structural parameters are optimized and designed with the help of a finite element simulation software, Ansys Maxwell-2022R1. Finally, a combined model of the comb capacitor and detection coil is proposed. However, considering the fabrication process, it is difficult for the comb capacitor and the detection coil to reach full resonance, so it is necessary to introduce a compensation capacitor to make the detection circuit work in resonance by matching the appropriate compensation capacitor parameters. By introducing the compensation capacitor, the variation in the impedance parameter is extended to the variation in the parameters of the whole resonant circuit, which improves the sensitivity of foreign object detection. The foreign object detection method used in this paper innovatively fuses a detection coil with a comb capacitor to achieve a system for detecting metal foreign objects and living organisms with high detection accuracy.

2. Principle Analysis of Living Organisms and Metal Foreign Object Detection Technology

2.1. Principle Analysis of Comb Capacitor-Based Foreign Object Detection Technology for Living Organisms

When a living organism approaches the comb capacitor, the dielectric between the two pole plates of the comb capacitor as well as the capacitance to ground changes and the capacitance value changes accordingly. Thus, the presence of an organism can be demonstrated by comparing the change in the resistance voltage of the detection circuit before and after the living organism enters the detection area. Unlike the capacitors used in the literature, this paper will investigate planar comb capacitors.

The live foreign object detection circuit is shown in Figure 1, where C_{Di} denotes the comb capacitance, ΔC_{Di} denotes the amount of change in the comb capacitance during the invasion of the living organism foreign object, the input voltage is U_{in}, the external resistor is R_D, and the resonance angular frequency is ω. The control switches Q_i are connected to the corresponding comb capacitors, respectively. When the system charging area is free of living organisms and foreign objects, each comb capacitor C_{Di} resonates in parallel with the inductor L_D, respectively, to satisfy the parallel resonance condition shown in Equation (1). By operating the control switch Q_i to ensure that only one comb capacitor is connected to the circuit at the same time, it is possible to realize the function of detecting organisms over the entire charging area when the comb capacitor is sufficient to cover the charging area.

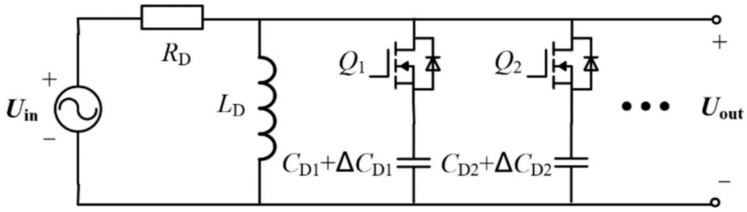


Figure 1. Live foreign object detection circuit.

When there is a living organism foreign object in the detection region, the equivalent resistance expression of the parallel branch composed of inductance and comb capacitance is shown in Equation (2). At this time, the output voltage is shown in Equation (3). A scaling factor γ is introduced, which is defined as the ratio of the output voltage in the presence or absence of the living organism foreign object, as shown in Equation (4). From Equation (4), the scaling factor γ is only related to the amount of change in comb capacitance ΔC_{Di}, which is independent of the comb capacitance C_{Di}. However, there are also live-to-ground capacitance, comb capacitance-to-ground capacitance, and the effect of energy transmitting and receiving coils and cores on comb capacitance in wireless power transmission systems. So, when designing the comb capacitor, C_{Di} should be made as large as possible. When there is no living organism in the charging area, the inductor L_D resonates in parallel with the comb capacitor C_{Di}, and the output voltage U_{out} is equal to the input voltage U_{in}. Therefore, the scaling factor γ is proportional to the system output voltage U'_{out} during foreign object intrusion of living organisms. The larger the change in comb capacitance ΔC_{Di} and the smaller the scaling factor γ, the smaller the U'_{out}, the larger the change in system output voltage, and the more sensitive the detection of living organisms.

$$\omega^2 L_D C_{Di} = 1 \tag{1}$$

$$Z_{(s)} = \frac{j\omega L_D}{1 - \omega^2 L_D (C_{Di} + \Delta C_{Di})} \tag{2}$$

$$U'_{out} = \frac{U_{in}}{1 + J\omega \Delta C_{Di} R_D} \tag{3}$$

$$\gamma = \left| \frac{U'_{out}}{U_{out}} \right| = \frac{1}{\sqrt{1 + \omega^2 R_D^2 \Delta C_{Di}^2}} \tag{4}$$

2.2. Principle Analysis of Metal Foreign Object Detection Technology Based on Detection Coil

In the alternating magnetic field, the magnetic effect or eddy current effect caused by the metal substance mistakenly entering the magnetic field will produce an additional field, this additional field will, in turn, affect the detection coil and change the impedance of the detection coil so that the detection coil voltage changes by comparing the detection coil voltage before and after the detection of metal foreign objects in the detection area to determine whether the metal foreign objects exist.

According to Faraday's law of electromagnetic induction, the metal foreign object can be equivalently modeled as a series connection of resistance and inductance. When the detection area is free of metal foreign objects, the equivalent circuit is shown in Figure 2. U_{in} is the input voltage, I_D is the current flowing through the sampling resistor when there are no metal foreign objects, R_D is the testing resistor, L_D is the measuring coil's corresponding inductance, and C_D is the parallel resonant capacitance. Since the detection coil is in resonance with the matched capacitor, the detection coil voltage is the input voltage U_{in}. When the detection area is mixed with metal foreign objects, the equivalent circuit diagram shown in Figure 3a,b is a simplified equivalent circuit diagram. I'_D is the current flowing through the sampling resistor in the presence of metal foreign objects. I' is the current flowing through the detection coil in the presence of metallic foreign matter. L_x is the foreign object equivalent inductance, R_x is the foreign object equivalent resistance, M is the mutual inductance between L_D and L_x, and Z is the reflected impedance.

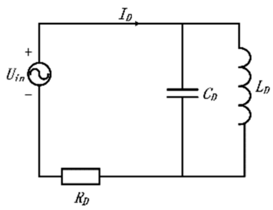


Figure 2. Foreign object detection circuit in the absence of foreign objects.

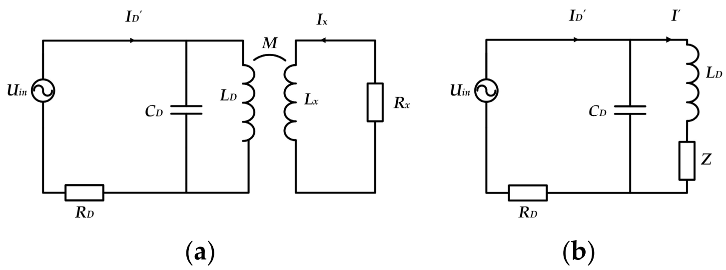


Figure 3. Equivalent circuit model of metal foreign object and detection coil. (**a**) Coupling model for metal foreign object and detection circuits. (**b**) Coupled model simplified circuit.

According to Kirchhoff's voltage law, the following equation is obtained:

$$\begin{cases} U_{in} = I'_D R_D + (I'_D - I')\frac{1}{J\omega C_D} \\ 0 = I'(Z + j\omega L_D) + (I' - I'_D)\frac{1}{J\omega C_D} \end{cases} \tag{5}$$

where $Z = \frac{(\omega M)^2}{R_x^2 + (\omega L_x)^2}(R_x - J\omega L_x)$.

The calculation gives the detection coil voltage as follows:

$$U'_{out} = \frac{j\omega L_D}{J(\omega Z C_D R_D - \omega L_D) + Z} U_{in} \tag{6}$$

$$\beta = \left|\frac{U'_{out}}{U_{out}}\right| = \left|\frac{j\omega L_D}{J(\omega Z C_D R_D - \omega L_D) + Z}\right| \tag{7}$$

The circuit resonance condition is

$$\omega^2 L_D C_D = 1 \tag{8}$$

From Equation (6), it can be seen that when the metal foreign object enters the detection area, the voltage of the detection coil decreases, according to which it can judge whether there is a metal foreign object mixed in. As shown in Equation (7), the scale factor β is set as the ratio of the voltage of the detection coil with and without foreign objects to characterize the detection effect of the system. The smaller β indicates that the greater the change in detection coil voltage, the more effective the system detection.

3. Foreign Object Detection System Parameter Design

3.1. Parameter Design and Simulation Analysis of Comb Capacitor

In wireless power transmission systems, comb capacitors are generally placed on top of the energy-transmitting coils. Figure 4 shows a top view of the basic structure of a comb capacitor. A single comb capacitor consists of two comb electrodes, A_{i} and B_{i}, with the "teeth" of the comb electrodes arranged in a staggered pattern to form a local capacitance cell, where the relevant parameters are defined as length l, width w, electrode spacing d, and electrode thickness r. In this paper, the variation in comb capacitance ΔC_i is taken as the reference standard, and the structural parameters of comb capacitance are optimized and designed with the help of the simulation software Ansys Maxwell-2022R1. The comb capacitance simulation model containing the living organism foreign object is shown in Figure 5, where the red part indicates the living organism foreign object, and the yellow part is the comb capacitance simulation model.

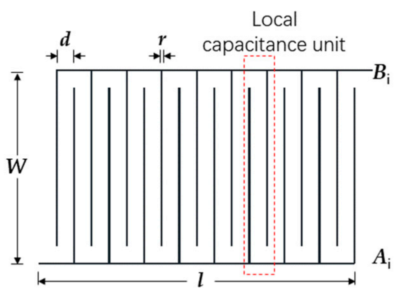


Figure 4. Basic structure of comb capacitor.

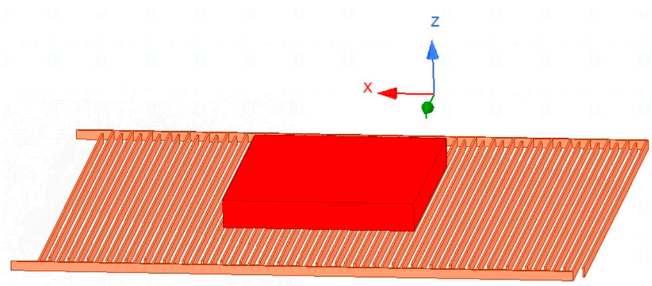
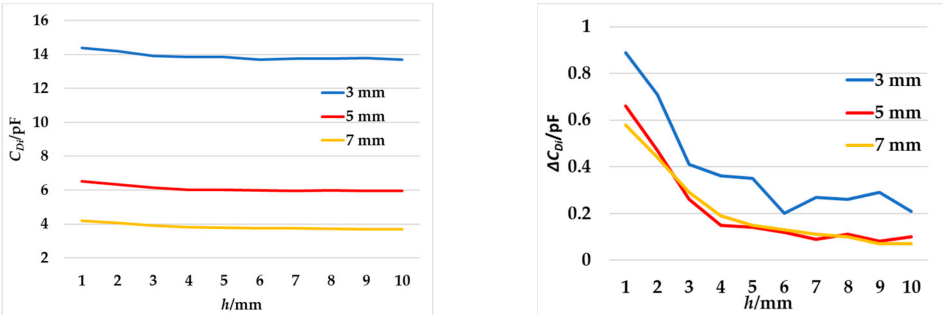


Figure 5. Finite element simulation model of comb capacitor (living foreign object).

A material with a dielectric constant of 400 [25] was used for simulation and analysis in place of the living organism foreign object. The size of the living organism foreign object was chosen to be 50 × 50 × 10 mm^3, and the distance of the living organism foreign object from the center of symmetry of the comb capacitor was denoted by h. The comb capacitor is set to have a length l of 100 mm, a width w of 50 mm, an electrode thickness r of 1 mm, and a wire thickness of 0.035 mm. The relationship between comb capacitance C_{Di}

and its variation ΔC_{Di} with electrode spacing d, living organism foreign object, and comb capacitance distance h is explored, as shown in Figure 6. From Figure 6a, the smaller the electrode spacing d, the larger the comb capacitance C_{Di}. According to Figure 6b, the comb capacitance variation ΔC_{Di} for different electrode spacing d shows an overall decreasing trend with the increase in the distance h between the living organism foreign object and the comb capacitance. The comb capacitance change ΔC_{Di} is significantly larger for a spacing of 3 mm compared to the case where the electrode spacing d is set to 5 mm and 7 mm. Therefore, 3 mm is selected as the comb capacitor electrode spacing in this paper.



(**a**) (**b**)

Figure 6. The variation in C_{Di} and ΔC_{Di} with d and h. (**a**) C_{Di}. (**b**) ΔC_{Di}.

The simulation models of different sizes of living organism foreign objects were established, respectively, to explore the effects of different sizes of living organism foreign objects on comb capacitance, as shown in Figure 7. From Figure 7, the comb capacitance change ΔC_{Di} decreases with the increase in the distance h between the living organism foreign object and the comb capacitance for the same material and thickness. For the same distance h, the relatively large bottom area of the living organism foreign object has a greater effect on the comb capacitance.

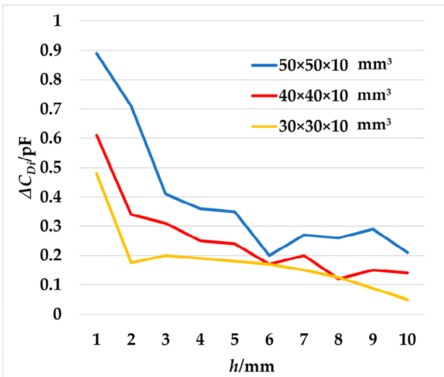


Figure 7. The variation in ΔC_{Di} with h under different living foreign object sizes.

For the purpose of analysis, the dimensions of the living organism foreign object simulation model were determined to be $50 \times 50 \times 10$ mm^3. Since this paper uses the form of PCB planar capacitors, and the common PCB lead thicknesses are 1 oz (0.035 mm) and 2 oz (0.070 mm), the thickness of the capacitor leads is determined by the simulation analysis below. Figure 8 shows the curves of the variation in comb capacitance change ΔC_{Di} with the distance h between the living organism foreign object and the comb capacitance for different wire thicknesses. According to Figure 8, it can be stated that when a foreign object is influenced by the same live organism, the comb capacitance with 1 oz wire thickness has a greater amount of change and more significant living organism detection than the comb capacitance with 2 oz wire thickness. Therefore, in this paper, a 1 oz thickness of wire is selected.

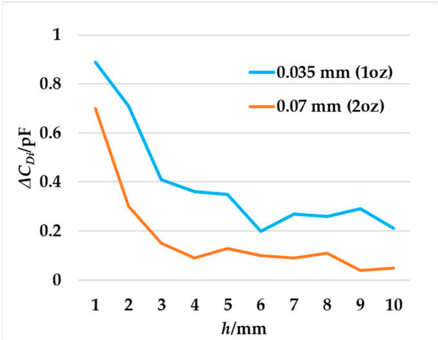


Figure 8. The variation in ΔC_{Di} with h under different wire thicknesses.

Considering the presence of a protective enclosure in practical applications, the distance h between the living organism foreign object and the comb capacitor is set to 3 mm in the following. Since the foreign object detection area is much larger than the detection range of a single comb capacitor, the detection system should use multiple comb capacitors to detect living organisms. In this paper, comb capacitors are arrayed, and the parasitic capacitance C_S between adjacent comb capacitor pole plates derived therefrom affects the normal operation of comb capacitors. Setting the spacing between two neighboring comb capacitors as g, $C_S/\Delta C_{Di}$ is used as a reference basis to explore the variation in this scaling factor with the spacing g, as shown in Figure 9. (C_S is the parasitic capacitance, and ΔC_{Di} is the comb capacitance change when h is 3 mm)

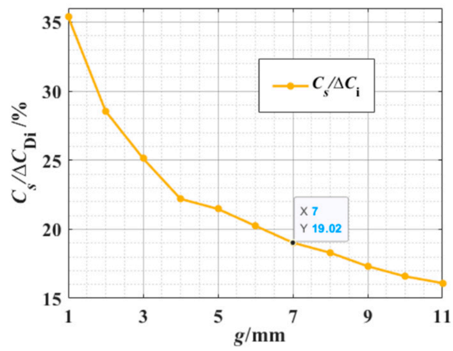


Figure 9. The variation in $C_S/\Delta C_{Di}$ with g.

As can be seen in Figure 9, $C_S/\Delta C_{Di}$ becomes progressively smaller with increasing spacing g, and the rate of decrease is progressively retarded. It can be seen that the larger the capacitor spacing, the smaller the effect between neighboring capacitors, in line with the actual situation. The spacing g should not be too large considering the need for foreign object detection in the area between neighboring comb capacitors. Therefore, in this paper, 7 mm is selected as the spacing between two neighboring comb capacitors, when the parasitic capacitance C_S is less than one-fifth of the comb capacitance variation.

3.2. Detection Coil Parameter Design and Simulation Analysis

The detection coil is a planar square helical coil, and the coil structure is shown in Figure 10. Using Ansys Maxwell to build a simulation model, the optimization objective of the detection coil is the scaling factor β. The relationship between the coil diameter inside D, side length A, and the number of turns N and the scaling factor is investigated to find the optimal detection coil structure parameters. The scale factor β varies with coil diameter inside D, number of turns N, and wire-to-wire spacing S, as shown in Figure 11. Therefore, the selected parameters of the coil structure are coil diameter inside D = 10 mm, number of turns N = 10, and wire-to-wire spacing S = 1 mm.

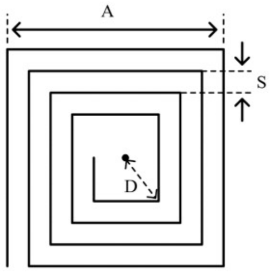
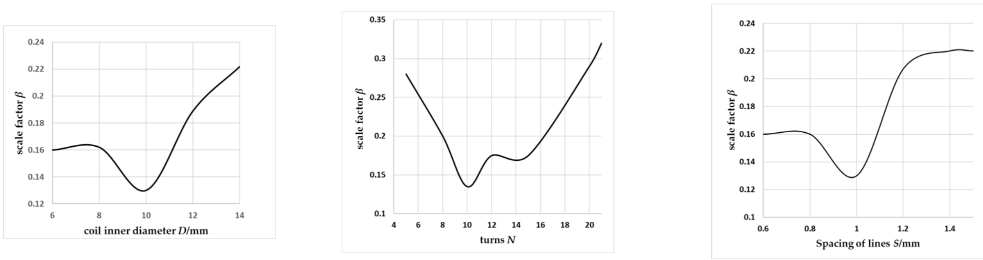


Figure 10. Square detection coil structure.



(**a**) (**b**) (**c**)

Figure 11. Curve of variation in scale factor β with coil diameter inside D and number of turns N, wire-to-wire spacing S. (**a**) The relationship between β and D. (**b**) The relationship between β and N. (**c**) The relationship between β and S.

4. Combined Comb Capacitor and Detection Coil Mode

In fact, the mixing of foreign objects into the coupling region is highly random and fortuitous. In the current exploration process of domestic and international research institutes, metal foreign objects are generally equivalent to RL circuits, ignoring the weak eddy current effect that may be generated by body fluids under alternating magnetic fields, and living organism foreign objects are generally equivalent to RC circuits. However, various types of foreign objects are different in terms of material composition, shape, and structure, which makes it impossible to construct accurate circuit models of foreign objects.

In this paper, by placing arrayed detection coils overlapped with comb capacitors, it is possible to achieve the function of detecting both metal and living organism foreign objects at the same time, as shown in Figure 12. Figure 12a shows a model of the detection coil and comb capacitor combination. The red part of this is the comb capacitor model, as shown in Figure 12b. Figure 12c shows the detection coil set, which is a combination of two detection coils connected in reverse series. Since the comb capacitor detection distance is small, this paper places the comb capacitor on the front side of the PCB and the detection coil on the back side of the PCB. Figure 13 shows the foreign object detection system circuit, where L_D is the array detection coil, and C_{Di} is the comb capacitor. The circuit is compensated in parallel, with the arrayed detection coil and comb capacitor compensating each other, and the compensation capacitor C_{Ki}, which is connected in parallel with the comb capacitor, is added for adjustment so that the detection circuit is in a resonant state. The parameters of the compensation capacitor C_{Ki} are matched according to Equation (9) to ensure that the detection system works in resonance when there is no foreign object in the detection area. The detection system makes up for the previous defects that can only detect a single category of foreign objects of metal or organisms and realizes a set of detection systems that can detect both metal and organism foreign objects.

$$\omega^2 L_{Di}\left(C_{Di} + C_{ki}\right) = 1 \tag{9}$$

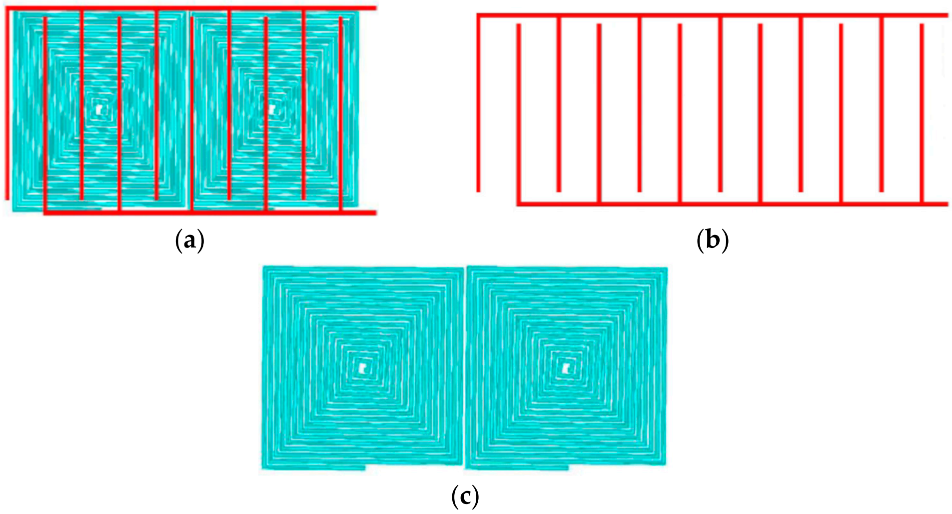


Figure 12. Array detection coil and comb capacitor combination mode. (**a**) Combined array detection coil. (**b**) Comb capacitor model. (**c**) Inverse series rectangular coil model.

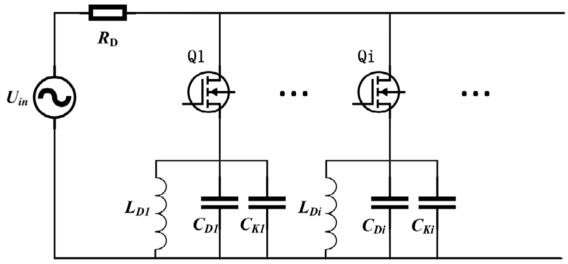


Figure 13. Equivalent circuit diagram of foreign object detection system.

Since the detection area is large, multiple groups of detection devices are required in order to achieve full-area detection. Each group of detection devices is controlled to access the detection circuit in time by switch Qi, and the detection flow is shown in Figure 14.

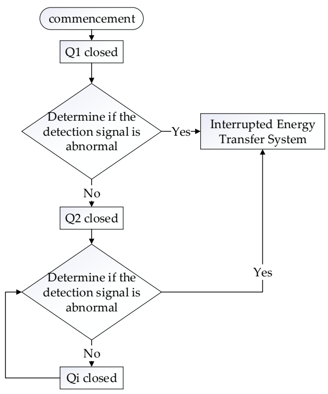
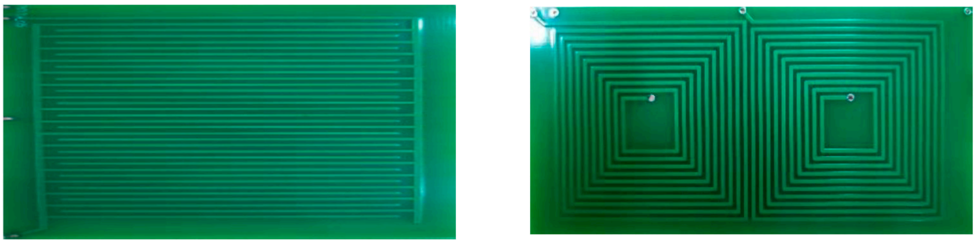


Figure 14. Detection flow chart.

5. Foreign Object Detection System Experiment

In order to improve the sensitivity of the detection of foreign objects in the charging area, this paper adopts the way of mutual compensation between comb capacitors and detection coils and increases the compensation capacitance C_{Ki} for circuit state regulation to ensure that the detection circuit is in a resonant state.

The design of the detection coil and comb capacitor based on the optimized structural parameters described in the previous section is shown in Figure 15, with the comb capacitor on the top layer of the combination and the detection coil on the bottom layer. The structural parameters of the comb capacitor and detection coil used in this paper are shown in Table 1.



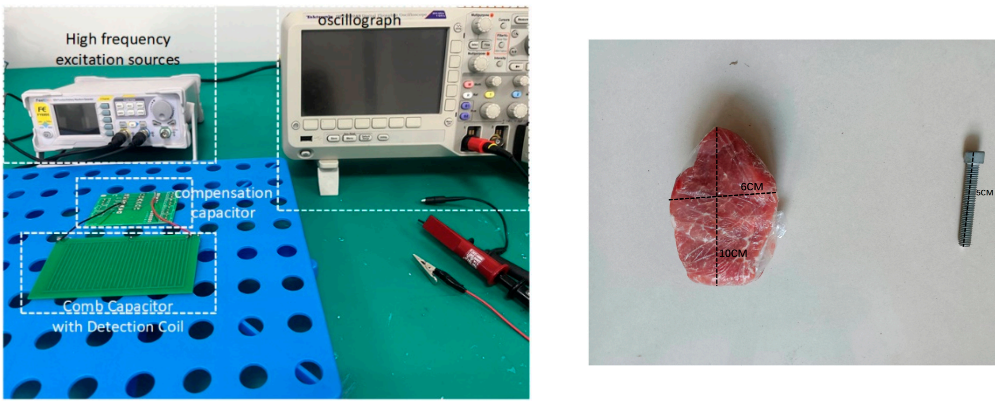
(**a**) (**b**)

Figure 15. Combination of a detection coil and a comb capacitor: (**a**) front side (comb capacitor) and (**b**) reverse side (detection coil).

Table 1. Comb capacitor and detection coil structure parameters.

Comb Capacitor		Detector Coil	
Parametric	**Numerical Value**	**Parametric**	**Numerical Value**
Capacitor length l/mm	100	Inside warp of the coil D/mm	10
Electrode spacing d/mm	3	Number of turns of coil N	10
Capacitance Width w/mm	50	Spacing of lines S/mm	1
Electrode thickness r/mm	1		
Capacitor spacing g/mm	7		

The detection coil inductance L_D was measured as 8.67 µH, and the comb capacitance C_{D1} was 38.87 pF. The external resistor R_D is selected to be 100 kΩ, an AC power signal with a frequency of 3 MHz is applied to the detection circuit, and a compensation capacitor C_{Ki} is added to the circuit to bring the circuit to a resonant state by connecting the resonant conditions in parallel. We constructed a foreign object identification experimental apparatus, as depicted in Figure 16, to confirm the viability of the foreign object detection technique suggested in this work.



(**a**) (**b**)

Figure 16. Experimental platform for foreign body detection. (**a**) Foreign object detection equipment. (**b**) Metal and living organism foreign objects.

The presence of foreign matter is determined by comparing the voltage change in the external resistor R_D. Figure 17a shows the change in the voltage waveform of resistor R_D when metals (metal screws) and living organisms (beef blocks) sequentially enter the detection area. Figure 17b–d shows the waveforms of the input voltage U_{in} and resistance voltage U_{RD} of the foreign object detection circuit when there is no foreign object in the detection area, when there is a beef block in the detection area, and when there is a metal screw in the detection area, respectively. It can be observed that when both metal foreign objects and living organism foreign objects enter the detection area, they both cause a change in the circuit parameters, which leads to a change in the U_{RD}. Taking the voltage amplitude change of more than 10% as the criterion for passing the test, upon analyzing Figure 17b–d, it can be found by comparison that the screws lead to an amplitude change of 20% in the resistor voltage of the detection circuit, which is a significant change in amplitude, and it is easy to achieve the effective detection of metals of this size. Testing the beef block as a biosample, as shown in Figure 16b, leads to a 30% amplitude change in the resistance amplitude of the detection circuit. Both methods caused at least a 20% change in amplitude, indicating that the detection method is highly sensitive.

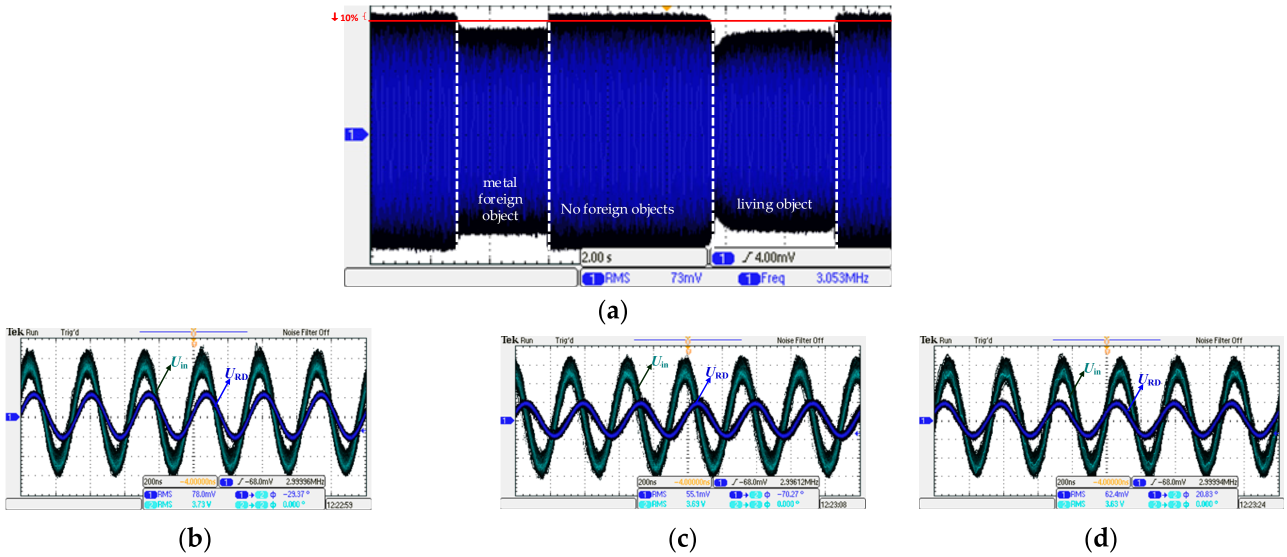


Figure 17. Waveforms of U_{in} and U_{RD} when metal and living organism foreign objects enter the detection region. (**a**) Metal and live foreign objects enter the detection area in sequence. (**b**) No foreign object. (**c**) Living organism foreign object (beef block). (**d**) Metal foreign object (metal screw).

In summary, it is experimentally verified that the foreign object detection method can achieve the detection of metal and living organism foreign objects with high detection sensitivity.

6. Conclusions

First, the circuit models for the detection of metal foreign objects and living organism foreign objects are established in this article. Formulas are derived in order to analyze the design concepts for the structural parameters of the comb capacitor and detection coil. Second, simulation software was used to optimize the comb capacitor's electrode spacing and wire thickness. This study examined the impacts of a biological foreign item's size and distance, as well as the distance between neighboring comb capacitors, on the comb capacitor. Parameters such as inner diameter, number of turns, and wire spacing of the detection coil were optimally designed. Finally, a combination model of arrayed detection coil and comb capacitor that can detect both metal and living organism foreign objects is proposed, and a compensation capacitor is introduced to improve the operation of the detection circuit and increase the sensitivity of the detection system.

The presence of metal screws and beef blocks for the detection of foreign objects in the detection area is caused by the detection circuit resistance voltage amplitude changes reduced by 20% and 30%, respectively, to achieve an effective detection of metal and living organisms foreign objects. The experimental results demonstrate the feasibility of the combined mode of detection coil and comb capacitor, which has the dual functions of metal foreign object detection and living organism foreign object detection with high detection sensitivity. The detection of multiple foreign objects of different classes in the detection area at the same time will be a potential area for future research.

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