Letters

Metal Object Detection With Detection Coils Perpendicular to Power Coils for Wireless Power Transfer Systems

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***Abstract*—In this letter, a metal object detection (MOD) method with detection coils perpendicular to power coils is proposed. Without a metal object, the induced voltage in the detection coils is ideally zero. When a metal object falls on the top of the Tx pad, an eddy current is induced, and this eddy current in the metal object will induce a voltage in the detection coils. The proposed method can perform well with misalignments between the Tx and Rx pads. No adjustments are required for different winding positions. The concept is well verified with experimental results.**

***Index Terms*—Metal object detection (MOD), wireless power transfer (WPT).**

I. Introduction

Metal object detection (MOD) is now considered a compulsory function for wireless power transfer (WPT) systems. Plenty of research has been carried out in MOD, and many detection methods are provided. Among these methods, the active detection method has a high detecting accuracy since the operating frequency of the detecting system is different from that of the main system [1]. However, this method requires an extra excitation circuit that is complicated and costly. Contrarily, the passive detection method utilizes the field generated by the power coils, which is simpler [2]. To improve the detection accuracy, the induced voltage of the detection coil should be as small as possible when no metal object exists. Thus, detection coils that are decoupled to power coils are commonly adopted [3], [4], such as the ones shown in Fig. 1. One critical issue of this kind of method is there exist blind area between two neighboring coils, and the solution is usually to use double layers for the detection coils [5], as depicted in Fig. 2.

Moreover, most of the field-based detection methods adopt detection coils parallel to the power coils, which are sensitive to the field change perpendicular to the power coils. Both the metal object and the misalignment of the Rx coil will induce field changes in the direction perpendicular to the power coils. Therefore, misalignments might significantly degrade the detection accuracy of the method using parallel detection coils.

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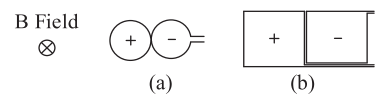

Fig. 1. Decoupled coils. (a) Double loop coils [3]. (b) Nonoverlapped coils [4].

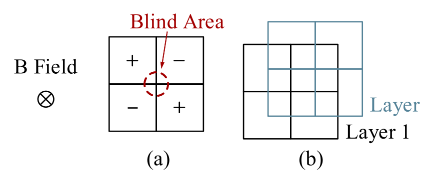

Fig. 2. Eliminate the blind area of decoupled coil sets. (a) Single layer with blind area. (b) Double layers without blind area [5].

In this letter, detection coils perpendicular to power coils are proposed and studied. Compared with parallel detection coils, perpendicular detection coils have two obvious merits. First, they have much fewer blind area and do not need double layers to deal with the blind area. Therefore, the detection circuit could be simpler. Second, the detection accuracy is barely affected by the misalignments between the Tx and Rx pads.

II. Detection Coils Perpendicular to Power Coils

The concept of the proposed detection method is that the detection coils are ideally decoupled to both the power coils and the induced voltages in the detection coils are zero without a metal object nearby. When there is a metal object in the charging zone, the eddy current induced in the metal object will generate nonzero voltages in the detection coils. The detailed design of the proposed detection coils is introduced as follows.

A. Decoupled to Tx Coil

Detection coils perpendicular to the Tx coil is shown in Fig. 3(a). To decouple the detection coil from the Tx coil, two identical detection coils are connected in a counter-series manner so that their induced voltages cancel out each other.

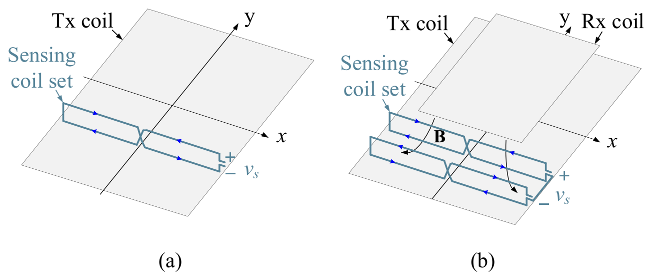

Fig. 3. Sensing coil set perpendicular to Power coils. (a) Decoupled to Tx coil. (b) Decoupled to Rx coil.

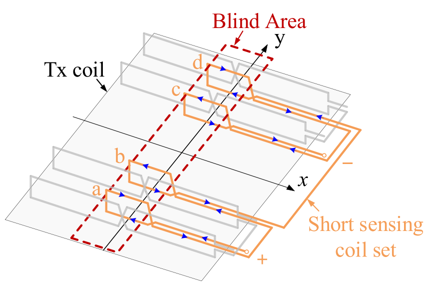

Fig. 4. Eliminating the blind area.

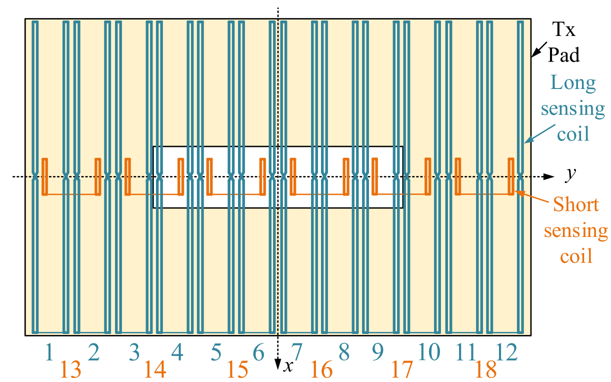

Fig. 5. Complete sensing coil sets.

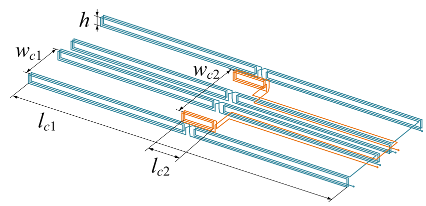

Fig. 6. Parameters of the proposed sensing coil sets.

B. Decoupled to Rx Coil

The coil set in Fig. 3(a) decouples to the Rx coil when Rx has zero misalignments along the x-axis. However, when there is a misalignment along the x-axis, the decoupling is lost. Based on the assumption that the magnetic field on the Tx coil generated by the Rx coil does not vary significantly along directions paralleled to the y-axis. Two neighboring coil sets are connected in a counter-series manner so that the induced voltages from the Rx coil cancel out each other, as shown in Fig. 3(b).

C. Blind Area

When a metal object is symmetrical about the y-axis, the induced voltages in two counter series sensing coils, as shown in Fig. 3(a), are the same, and thereby the total induced voltage is zero. This area, as shown in Fig. 4, is the blind area of using the sensing coil set symmetrical about the y-axis. To eliminate this blind area, extra short sensing coil sets are added on the y-axis, as shown in Fig. 4. To decouple the short sensing coil sets from the Tx coil, two short sensing coil sets that are symmetrical about the x-axis are connected in a counter-series manner so that their induced voltages from the Tx coil cancel out each other. To decouple the short sensing coil sets from the Rx coil, two adjacent short sensing coil sets are connected in a counter-series manner so that their induced voltages from the Rx coil cancel out each other. For example, in Fig. 4, coil a is adjacent to coil b, coil c is adjacent to coil d, coils a and d are symmetrical about the x-axis, and coils b and c are symmetrical about the x-axis. They are connected in series, as shown in Fig. 4, to form a sensing coil set. This coil set is decoupled to both the Tx and Rx coils. In practical implementation, because coils a and b might be far away from coils c and d, it might induce interferences by connecting them with a printed circuit board (PCB) trace. Therefore, the induced voltage of coil sets a and b and that of coil sets c and d could be individually sent to microcontroller unit (MCU) where these two induced voltages are subtracted from one another to produce the final sensing voltage of the whole coil sets of a, b, c, and d.

D. Overall Design

As shown in Fig. 5, the proposed sensing coil sets consists of 18 coil sets: 12 long sensing coil sets and six short sensing coil sets, covering the entire area of the Tx pad. As explained in the last section, the induced voltages of coil sets 13 and 18 are subtracted from one another, similarly for coil sets 14 and 17. For coil sets 15 and 16, if they are subtracted from one another, one blind area is created on the center point of the Tx coil. On the other hand, because coil sets 15 and 16 are located near the center, they are essentially decoupled from the Tx coil. Therefore, they are treated as two independent coil sets to eliminate the center blind area. The dimensional parameters are defined in Fig. 6. h is the height of the sensing coil sets, which equals the thickness of the PCB of the sensing coil sets. N_1 and N_2 are the numbers of turns of the long sensing coil sets and the short sensing coil sets, respectively. Simulations have been carried out to determine the optimal parameter values, which are given in Table I.

III. Simulation Study With Misalignment

Based on finite-element simulations, a comparison study between the proposed MOD method and the MOD method in [6] with planar sensing coils is presented as follows. The planar sensing coils are shown in Fig. 7. Two sensing coils that are symmetrical with the x-axis are connected in a counter-series manner to form a sensing coil set decoupled with Tx. In this

TABLE I
PARAMETERS OF WPT AND MOD SYSTEM

Parameters	*Value*
Tx pad size	200 mm × 125 mm
Rx pad size	170 mm × 110 mm
Air gap between Tx and Rx coils	50 mm
Operating frequency	200 kHz
Tx coil current	2 A
Long sensing coil set size($l_{c1}\times\ w_{c1}$)	125 mm × 12 mm
Short sensing coil set size($l_{c1}\times\ w_{c1}$)	20 mm × 18 mm
PCB thickness	2 mm
N_1, N_2	8
Metal object size	30 mm × 30 mm × 0.5 mm

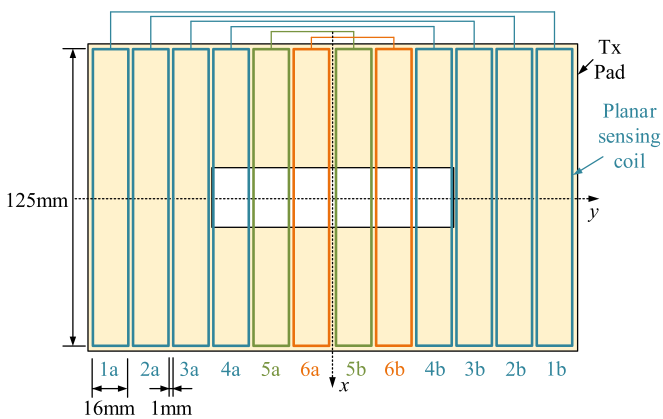

Fig. 7. Planar sensing coil sets proposed in [6].

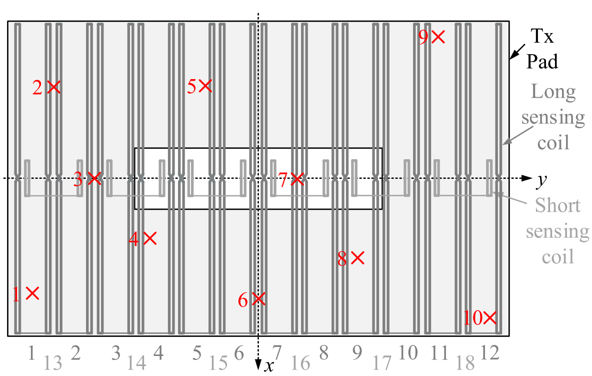

Fig. 8. Map of ten random positions.

study, the width of the sensing coil sets and also the distance between two neighboring sensing coils are the same as those in [6]. The number of turns of each sensing coil set is 8.

Tx coil, Rx coil, and the metal object used in the simulations are the same as the ones described in Fig. 12 and Table I. Fig. 8 shows ten random testing positions. In this study, Rx is placed at a misaligned position ($x = 30$ mm, $y = 30$ mm). Figs. 9 and 10 show the simulated sensing voltages of the planar sensing coil sets and the proposed coil sets, respectively, without the metal object and with the metal object in the ten random positions. It is obvious that the sensing voltages of the planar sensing coil sets without a metal object are close to those with a metal object in most of the positions. On contrary, the proposed coil sets are

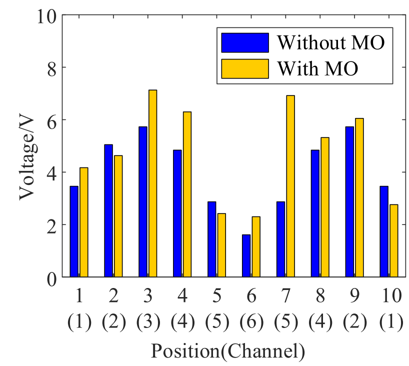

Fig. 9. Simulated sensing voltage of the planar sensing coil sets.

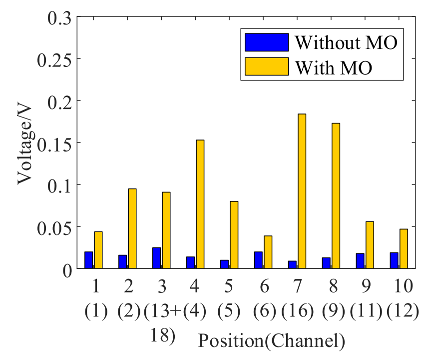

Fig. 10. Simulated sensing voltage of the proposed sensing coil sets.

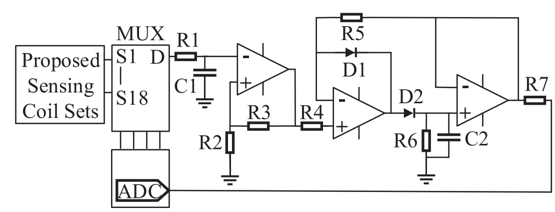

Fig. 11. MOD circuit.

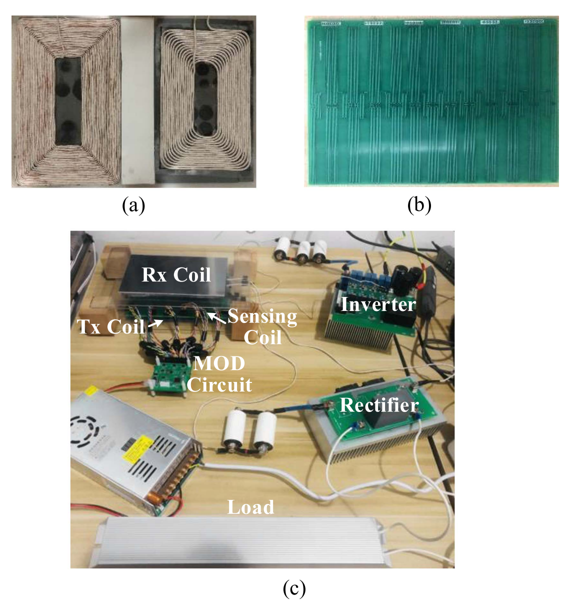

Fig. 12. Prototype system. (a) Tx coil (left); Rx coil (right). (b) Sensing coil sets. (c) Whole system.

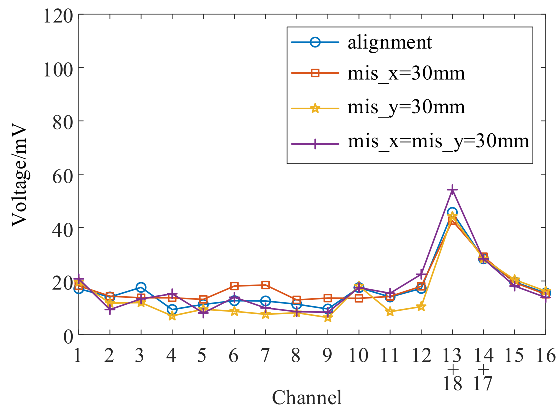

Fig. 13. Sensing voltages of all coil sets with Rx at different positions.

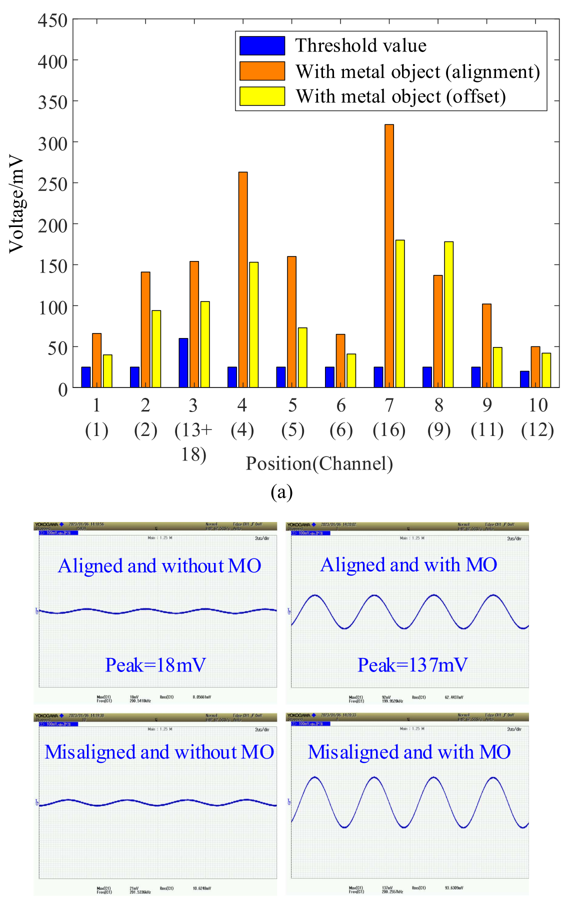

Fig. 14. Experimental results with a copper sheet placed at ten random positions: (a) the sensing voltages and (b) the waveforms of the induced voltages of the sensing coil set 2 (100 mv/div).

able to detect the metal object in all ten positions under the misalignment condition.

IV. Experiment Verification

A. Detection Circuit

The detection circuit includes three eight-channel multiplexers (ADG708), an amplifier, a peak detection circuit, and an MCU, as shown in Fig. 11. With the multiplexers, all 18 coil sets in Fig. 5 are scanned continuously to check the induced voltages. Only one sensing coil set is checked each time.

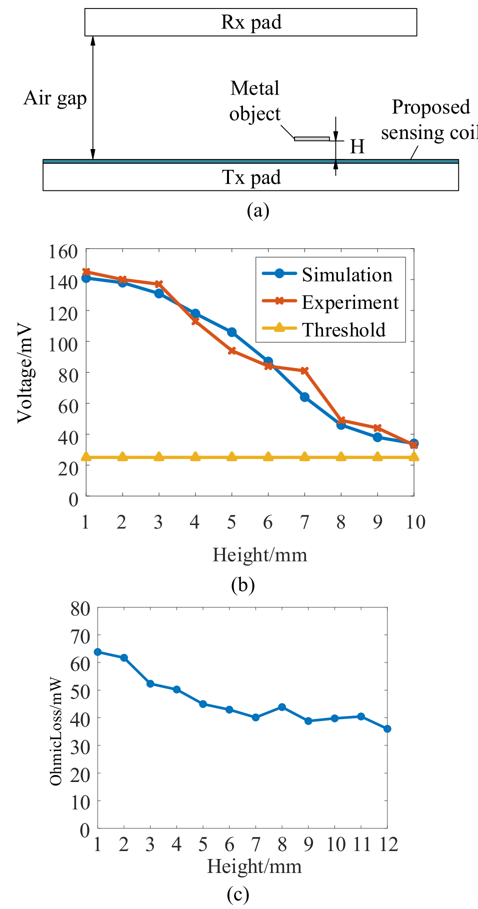

Fig. 15. Experimental results with a metal object at different heights. (a) Metal object with a height h. (b) Sensing voltages at different heights. (c) Ohmic loss when MO at different heights.

B. Experimental Results

A prototype system is constructed for experiments, as shown in Fig. 12. The Tx and Rx pads are small in size because they are designed for light vehicles, such as automatic-guided vehicles. All parameters of the system are given in Table I.

For each coil set, the induced voltages are measured without a metal object when Rx is in different positions in the misalignment range. The highest induced voltage is set as the threshold value for the corresponding coil set. Fig. 13 gives the voltages of all sensing coil sets with Rx at different positions.

A square copper sheet with a size of 30 mm $\times$ 30 mm $\times$ 0.5 mm is used as the metal object. It is placed in ten random positions on the sensing coil pad, as shown in Fig. 8. The induced voltages of the corresponding sensing coil sets are given in Fig. 14, when the Rx coil is aligned with the Tx coil and when it has a 30-mm misalignment in both the x and y directions. With the metal object, the induced voltages are obviously higher than the threshold values.

Furthermore, the metal object is placed at different heights at position eight to test the MOD system, as shown in Fig. 15(a). The experimental results are given in Fig. 15(b), compared with simulation ones. It shows that the metal object can be successfully detected within a 10-mm height.

V. Conclusion

This letter proposes a novel MOD method based on sensing coils perpendicular to power coils. Detailed design of the sensing coil sets is provided to ensure decoupling between the sensing coil sets and Tx or Rx coils. With this design, the detecting accuracy is not affected by the misalignments between Tx and Rx. The proposed sensing coils can be fabricated on a two-layer PCB, and therefore, it is cost effective.

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