Analysis of Misalignment Effect on Wireless Charging System for Inspection Robots

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Abstract. To solve the issues including the inflexibility, connector wear, and electric shock risk in contact charging system for inspection robots, the wireless charging system for inspection robots is introduced in this paper. The circuit model of this paper is developed based on the mutual inductance theory. The expressions of the receiving power and the efficiency are derived. The coordinate calculation method for mutual inductance between non-coaxial rectangular spiral coils according to the movement characteristics of inspection robot is presented. According to the calculation method, the characteristics of the receiving power and the efficiency varying with the position change of the receiving coil are investigated. The location of the positioning device for starting the wireless charging system can be selected based on the system characteristics. The theoretical analysis is verified by experiments.

1. Introduction
The inspection robots are wildly applied in smart factories and smart substations to replace the manual inspection tasks. At present, the inspection robots are mainly charged with contact through the manual or mechanical plug-in. The manual contact charging method is inflexible and not suitable for the smart unmanned development. Another contact charging method is realized through the automatic mechanical structure, which also causes the connector wear and electric shock risk.
In recent years, the wireless power transfer technology is developed and applied in the fields including electronic devices, medical implants [1-2], electric vehicles [3-7], rail transit, and the drones. In [8], the optimizing compensation topologies for inductive power transfer at different mutual inductances are proposed. The optimizing three-phase three-layer coil array for omnidirectional wireless power transfer is investigated in [9]. The multiphase inductively coupled resonant converter is proposed for wireless electric vehicle charger in [10]. A two-loop control method in wireless power transfer system is studied in [11].
In this paper the wireless power transfer technology is applied in the charging system for inspection robots to solve the issues mentioned before. Firstly the structure of the wireless charging system for the inspection robot is introduced. Secondly the circuit model of this wireless charging system is developed according to the circuit theory of mutual inductance. Then the coordinate calculation method for mutual inductance between non-coaxial rectangular spiral coils with alignment according
to the movement characteristics of inspection robot is investigated. Based on the calculation method, the characteristics of the receiving power and the efficiency varying with the position change of the receiving coil are studied. The location of the positioning device for starting the wireless charging system can be selected according to the obtained system characteristics. The theoretical analysis is verified by experiments and the conclusion is drawn finally.

2. System description
The sketch of the wireless charging system for inspection robot proposed in this paper is shown in Figure 1. The transmitting coil is installed underground. The receiving coil is installed under the chassis of the inspection robot. The robot moves along the fixed line trajectory. Hence the lateral misalignment is ignored in this paper. The positioning device is set to detecting the access of the robot. In order to improve the flexibility of the wireless charging system and reduce the requirement of the stopping location, the location of the positioning device is selected to determine the wider effective charging area where the receiving power and the efficiency are acceptable. During the access process of the robot, the wireless charging system starts when the robot reaches the location of the positioning device.

![Figure 1. The sketch of the wireless charging system for inspection robot.](image1)

The structure of the wireless charging system is shown in Figure 2. The transmitting side includes the high-frequency power source, the transmitting coil, and the LCC compensation circuit. The receiving side includes the receiving coil, the LC compensation circuit, the rectifier, the DC converter and the battery. The energy is transferred wirelessly through the magnetic coupling between the transmitting coil and the receiving coil.

![Figure 2. The structure of the wireless charging system for inspection robot.](image2)

3. Circuit model of system
The circuit model of the wireless charging system for the inspection robot is developed in this paper. The equivalent circuit of this system is shown in Figure 3. $U_i$ represents the high-frequency power source. $L_1$, $C_1$, and $C_t$ are the inductance and capacitors of the compensation circuit in transmitting side. $L_t$ and $R_t$ are the inductance and the resistance of the transmitting coil respectively. $L_r$ and $R_r$ denote the inductance and resistance of the receiving coil respectively. $C_r$ is the compensation capacitor in receiving side. $M$ is the mutual inductance between the transmitting and receiving coils. $R_L$ represents the equivalent AC resistance in the receiving side.
Figure 3. The equivalent circuit of the wireless charging system for the inspection robot.

To maintain the stability of the current through the transmitting coil, the components of compensation circuit in transmitting side should satisfy that 

\[ C_i L_i = \frac{1}{\omega^2} \quad \text{and} \quad C_i (L_i - L_t) = \frac{1}{\omega^2}, \]

where \( \omega = 2\pi f \), and \( f \) is the operating frequency.

Based on the circuit theory, the current through the transmitting coil is deduced as

\[ I_s = \frac{U_s}{j \omega L_t} \]  \hspace{1cm} (1)

The receiving coil is compensated with the capacitor, which satisfies that 

\[ C_r L_r = \frac{1}{\omega^2}. \]

According to the theory of the mutual inductance, the current in receiving coil can be calculated as

\[ I_r = \frac{MU_s}{L_t (R_t + R_r)} \]  \hspace{1cm} (2)

The receiving power is deduced as

\[ P = \frac{M^2 U_s^2 R_t}{L_t^2 (R_t + R_r)^2}. \]  \hspace{1cm} (3)

The efficiency can be expressed as

\[ \eta = \frac{\omega^2 M^2 R_t}{R_t (R_t + R_r)^2 + \omega^2 M^2 (R_t + R_r)}. \]  \hspace{1cm} (4)

According to (3) and (4), the receiving power and the efficiency are influenced by the mutual inductance between the transmitting coil and the receiving coil. During the moving process of the robot, the changing relevant position between the transmitting and receiving coils causes the variation of the mutual inductance. The stopping position of the robot will determine the characteristics of the charging system while the system operation after the robot access is detected by the positioning device. Hence the system characteristics during the moving process of the receiving coil are investigated in this paper. The system characteristics can provide a basis for the selection of the location of the position device to detect the robot access.

4. Mutual inductance calculation and system analysis

The transmitting and receiving coils in wireless charging system for inspection robots are rectangular spiral coils. The schematic diagram of non-coaxial rectangular spiral coils is shown in Figure 4. In the transmitting coil, the maximum length is \( l \) while the maximum width is \( w \). The number of turns of transmitting coil is \( N_1 \). In the receiving coil, the maximum length is \( l \) while the maximum width is \( w \). The number of turns of receiving coil is \( N_2 \). The distance between the adjacent turns of every coil is \( d \). In the Cartesian coordinate system for a three-dimensional space, as shown in Figure 4, coordinate origin \( O \) denotes the center of the transmitting coil and the point \( O' \) is the center of the receiving coil. \( A_i \) is the start point of the \( i^{th} \) turn in the transmitting coil. \( B_i, C_i, D_i, \) and \( E_i \) are the next points of the \( i^{th} \) turn in transmitting coil. \( A_{i+1} \) is the end point of the \( i^{th} \) turn and the start point of the \( (i+1)^{th} \) turn. \( A'_i \) is
the start point of the $j^{th}$ turn in receiving coil. $B'_j$, $C'_j$, $D'_j$, and $E'_j$ are the next points of the $j^{th}$ turn in receiving coil. $A_{j+1}$ is the end point of the $j^{th}$ turn and the start point of the $(j+1)^{th}$ turn.

![Diagram of non-coaxial rectangular spiral coils](image)

**Figure 4.** The schematic diagram of non-coaxial rectangular spiral coils.

The coordinate calculation method for mutual inductance between non-coaxial rectangular spiral coils is studied in this paper. In the Cartesian coordinate system for a three-dimensional space, $O$ is denoted as $O(0,0,0)$ and $O'$ is represented by $O'(O_x, O_y, O_z)$. Hence, the points in transmitting coil are expressed by

$$A_i = \left( \frac{W}{2} - d(i-1), 0, 0 \right), i=1,2,\ldots,N_i$$

$$B_i = \left( \frac{W}{2} - d(i-1) - \frac{L}{2}, -d(i-1), 0 \right)$$

$$C_i = \left( -\frac{W}{2} + d(i-1) + \frac{L}{2} + d(i-1), 0 \right)$$

$$D_i = \left( -\frac{W}{2} + d(i-1) - \frac{L}{2} + d(i-1), 0 \right)$$

$$E_i = \left( -\frac{W}{2} - d(i-1), -\frac{L}{2} + d(i-1), 0 \right)$$

$$A_{i+1} = \left( \frac{W}{2} - d(i-1), 0, 0 \right)$$

(5)

And the points in receiving coil are expressed by

$$A'_i = \left( \frac{w}{2} - d(j-1) + O_x, O_y, O_z \right), j=1,2,\ldots,N_i$$

$$B'_i = \left( \frac{w}{2} - d(j-1) + O_x, \frac{L}{2} - d(j-1) + O_y, O_z \right)$$

$$C'_i = \left( \frac{w}{2} + d(j-1) + O_x, \frac{L}{2} - d(j-1) + O_y, O_z \right)$$

$$D'_i = \left( \frac{w}{2} + d(j-1) - \frac{L}{2} + d(j-1) + O_y, O_z \right)$$

$$E'_i = \left( \frac{w}{2} - d(j-1), -\frac{L}{2} + d(j-1), O_z \right)$$

$$A'_{i+1} = \left( \frac{w}{2} - d(j-1) + O_x, O_y, O_z \right)$$

(6)

In this coordinate system, according to (5) and (6), the $i^{th}$ loop in transmitting coil is written as

$$I_{p(i)} = AB + BC + CD + DE + EA_{i+1}.$$
The $j^{th}$ loop in receiving coil is

$$I_{(j)} = A'_{j}B'_{j} + B'_{j}C'_{j} + C'_{j}D'_{j} + D'_{j}E'_{j} + E'_{j}A'_{j+1}. \tag{8}$$

Hence, the mutual inductance between the $i^{th}$ loop in transmitting coil and the $j^{th}$ loop in receiving coil can be expressed as

$$M_{ij} = \frac{\mu_{i} \mu_{0}}{4\pi} \int_{\gamma_{ij}} \frac{dl_{i}(j)}{R_{ij}} \tag{9}$$

where $\mu_{i}$ is the relative magnetic permeability ($\mu_{i} \approx 1$, in air), $\mu_{0}$ is the magnetic permeability of vacuum ($\mu_{0} = 4\pi \times 10^{-7}$ H/m), and $R_{ij}$ represents the distance between current microelements of the $i^{th}$ loop in primary coil and of the $j^{th}$ loop in secondary coil.

The total mutual inductance between non-coaxial rectangular spiral coils can be calculated according to

$$M = \sum_{i=1}^{N_{1}} \sum_{j=1}^{N_{2}} M_{ij} = \sum_{i=1}^{N_{1}} \sum_{j=1}^{N_{2}} \frac{\mu_{i} \mu_{0}}{4\pi} \int_{\gamma_{ij}} \frac{dl_{i}(j)}{R_{ij}} \tag{10}$$

According to the coordinate calculation method, the characteristics of the mutual inductance between the transmitting and receiving coils varying with the receiving coil position can be obtained. Combining (10) with (3) and (4), the receiving power and the efficiency of the system can be calculated when the receiving coil is at different positions. The characteristics of the receiving power and the efficiency varying with the position of the receiving coil are shown in Figure 5 and Figure 6.

**Figure 5.** The characteristics of the receiving power varying with the position of the receiving coil.

**Figure 6.** The characteristics of the efficiency varying with the position of the receiving coil.

According to the characteristics shown in Figure 5 and Figure 6, the receiving power and the efficiency change with the misalignment between the transmitting coil and the receiving coil. The receiving power and efficiency increase when the misalignment decreases and reach the maximum
when the misalignment is zero. Hence, the location of the positioning device for detecting the robot access and starting the wireless charging system can be selected according to the characteristics of the receiving power and the efficiency varying with the position of the receiving coil.

5. Experimental verification

To verify the characteristics in the theoretical analysis part, the experiment is carried out in this part. The prototype of the proposed wireless power transfer system is shown in Figure 7. The transmitting side includes the high-frequency inverter, the LCC compensation circuit, and the transmitting coil. The receiving side includes the receiving coil, the LC compensation circuit, and the load. The output voltage of the high-frequency inverter is 20 V. The operation frequency of this system is 85 kHz. The transmitting coil and the receiving coil are identical rectangular spiral coils. The length is 0.30 m. The width is 0.30 m. The number of turns is 7. The vertical height between the primary and secondary coils is 0.10 m. The distance between the adjacent turns of every coil is 0.01 m. \( L_1 = 5.0 \mu H \), \( C_1 = 700.5 \text{nF} \) (the calculated value is 701.2 nF) and \( C_p = 231.7 \text{nF} \) (the calculated value is 232.2 nF). \( C_s = 173.6 \text{nF} \) (the calculated value is 174.4 nF). The load resistance is 4.2 \( \Omega \).

![Figure 7. The prototype of the proposed wireless power transfer system.](image)

Changing the position of the receiving coil, the voltage of the load is measured. The experimental characteristic of the receiving power varying with the position of the receiving coil is obtained as shown in Figure 8.

![Figure 8. The experimental characteristic of the receiving power varying with the position of the receiving coil.](image)

According to the curve of the receiving power varying with the position of the receiving coil, the receiving power and efficiency increase when the misalignment decreases and reach the maximum when the misalignment is zero. The receiving power is low when the positioning device is set too far away from the central position of the transmitting coil and reaches the maximum when the positioning device is set at the central position of the transmitting coil. If the threshold of the receiving power is set as 40 W, the effective wireless charging area can be determined as shown in Figure 8. The waveforms of the output voltage of the inverter and the voltage of the load are shown in Figure 9 and
Figure 10 comparatively when the receiving coil is at the edge position and the central position of the effective wireless charging area. The receiving power is 40.2 W and the efficiency is 81.3 % at the edge position. The receiving power is 60.2 W and the efficiency is 84.6 % at the central position.

![Figure 9. The waveforms of the output voltage of the inverter and the voltage of the load at the edge position.](image)

![Figure 10. The waveforms of the output voltage of the inverter and the voltage of the load at the central position.](image)

6. Conclusions
The wireless charging system for inspection robots is introduced in this paper to solve the issues in contact charging system for inspection robots. The circuit model of this paper is developed and the expressions of the receiving power and the efficiency are derived. The coordinate calculation method for mutual inductance between non-coaxial rectangular spiral coils according to the movement characteristics of inspection robot is studied. According to the calculation method of the mutual inductance, the characteristics of the receiving power and the efficiency varying with the position change of the receiving coil are investigated. The receiving power and efficiency increase when the misalignment decreases and reach the maximum when the misalignment is zero. The location of the positioning device for starting the wireless charging system can be selected according to the system characteristics.

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