Design of magnetic coupling mechanism for wireless power transmission system based on magnetic flux analysis

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Abstract: Aiming at the wireless charging system that can dynamically change arbitrarily in a three-dimensional space such as a smart robot, this paper proposes a new type of magnetic coupling mechanism that combines a disc coil and a spiral coil. It can not only avoid frequency splitting in the short-distance range, but also effectively enhance the coupling strength in the long-distance range. In addition, it can also effectively improve the position robustness and anti-offset ability of the robot's wireless charging system. In this paper, the geometric framework of the new magnetic coupling mechanism is first given. Based on the analysis of magnetic flux, it is theoretically confirmed that the magnetic coupling mechanism can reduce the coupling strength in the near range, avoid the frequency splitting phenomenon, and improve the coupling strength of the system and the energy efficiency of the system in the long range. Finally, based on the finite element simulation software COMSOL, it is proved that the proposed magnetic coupling mechanism can achieve high energy efficiency output in a large range, and has strong position robustness and anti-deviation.

1. Introduction
At present, as the world's advanced intelligent machinery and equipment, robots are widely used in manufacturing, surveying, rescue and life. With the improvement of science and technology, the research and development of robot technology in developed countries has become more and more active. In the process of operation and use of robots, the frequent insertion and extraction of charging increases the labor cost of use, and the endurance as the key to its long-term stable operation is also concerned by scholars.

Wireless Power Transfer (WPT) is a new charging technology developed by researchers in recent years. It is also an advanced technology full of future prospects and widely concerned by researchers at home and abroad\textsuperscript{1-4}. Magnetically coupled wireless power transfer (MC-WPT) technology is widely used because of its long transmission distance and large transmission power. At present, the domestic exploration of it mainly stays in the stage of theoretical research and laboratory, and the research mainly relies on universities and research institutes. However, the research on this technology abroad is more extensive, and it has penetrated into the application scenarios such as electric vehicles and mobile devices.

The application of wireless power transmission technology to the charging and endurance of robots can realize the electrical isolation between robots and charging systems, as shown in Fig. 1. Wireless
charging technology does not require additional cable plug and pull, overcomes the shortcomings of the traditional contact charging method for robots, reduces the corresponding human cost, and improves the complexity of the robot that needs to return to be charged by human, further improving the automation of the charging process. Therefore, more and more researchers apply WPT technology to the charging system of UAV and robot, which has bright application prospects.\(^\text{[5,7]}\). 

Many literatures focus on the design and optimization of magnetic coupling mechanism in wireless power transmission system. A simple circular coil symmetrical magnetic coupling mechanism is analyzed in the literature. The application background of circular coil is given. The influence of transmission distance on mutual inductance and transmission efficiency of circular coil is analyzed. However, the literature is relatively early and there is no further optimization\(^\text{[6,7]}\). There is a literature on the design of spiral coil for power transmission, and a three-dimensional magnetic coupling mechanism is designed. However, it is not suitable, complex and inefficient for robot systems\(^\text{[8,9]}\). Some scholars have analyzed the characteristics of the square coil magnetic coupling mechanism, and compared it with the circular coil using the control variable method. However, the two magnetic coupling mechanisms have little difference in transmission efficiency and offset resistance, and have no prominence\(^\text{[10,11]}\). Some literature introduced a method to increase the magnetic core of the original vice-side single coil to improve the coupling strength and the anti-deviation characteristics of the magnetic coupling mechanism. However, the mutual inductance is difficult to calculate, and the current of the vice-side coil cannot be accurately obtained. The safety of charging cannot be guaranteed, and the volume of the increased magnetic core is large is not desirable for such small mobile devices as home robots\(^\text{[3,12]}\).

To sum up, based on the above problems, this paper uses the magnetic flux theory to analyze the coupling relationship between the coils and the electromagnetic induction effect, and studies and designs a new magnetic coupling mechanism suitable for mobile devices such as robots. The coil is composed of the traditional disc coil and the traditional spiral coil, and becomes a new type of magnetic coupling mechanism: when the connection switch between the spiral coil and the disc coil is closed, it becomes a new type of magnetic coupling mechanism; when the connection switch between the spiral coil and the disc coil is disconnected, it becomes two traditional magnetic coupling mechanisms.

The new magnetic coupling mechanism is connected by two traditional magnetic coupling mechanisms, which has greater self-inductance. Under the same distance condition, the mutual inductance between the secondary coil and the primary coil will also be greatly increased, which can better improve the charging efficiency and anti-offset ability of the robot wireless charging. When transmitting in a short distance, in order to prevent the decrease of transmission power caused by frequency splitting, the switch is opened and the single magnetic coupling mechanism is used to work, which can maintain high-level transmission power.

Install it at the bottom of the robot, without additional volume, can make greater use of space advantages. The structure of the new magnetic coupling mechanism is compared with that of the two
traditional magnetic coupling mechanisms used in robots, as shown in Fig. 2, where the connection switch is indicated by the solid point.

![Disc magnetic coupling mechanism](image1)
![Spiral magnetic coupling mechanism](image2)
![New Magnetic Coupling Mechanism](image3)

Fig 2. Schematic diagram of magnetic coupling mechanism

2. Theoretical analysis of magnetic flux

At present, the MC-WPT system with dual coil topology is commonly used. Therefore, this paper will use the flux theory to analyze the dual coil wireless charging system, and its equivalent structure is shown in Figure 3.

![Equivalent structure of two coil wireless power transmission system](image4)

Fig 3. Equivalent structure of two coil wireless power transmission system

The two coils in the figure represent the simplified diagram of the primary and secondary side systems respectively. The following coil is marked as coil 1, which is the transmitter of the MC-WPT system. The current flowing through the coil 1 is the equivalent excitation current of the transmitter. The above coil is marked as coil 2, which is the receiving end of MC-WPT system. The current flowing on coil 2 is the current induced by the receiving end.

![Schematic diagram of magnetic flux at receiver](image5)

Fig 4. Schematic diagram of magnetic flux at receiver

In Figure 4, the spherical coordinate system is selected to calculate the excitation magnetic field generated by coil 1 using Biot-Savart’s law is as follows:

\[ A = \frac{\mu I_a}{4\pi r} \int e^{-j\beta r} dl \]  

(1)
\[ H = \frac{1}{\mu} [\nabla \times A] \]  \hspace{1cm} (2)

where \( \beta \) is the wave propagation phase constant, \( \alpha \) is the coil radius, \( r \) is the distance from the field point to the center of the coil, and \( \mu \) is the permeability.

Because this paper is based on the common MC-WPT system to analyze, and is suitable for wireless charging system of high-power mobile devices such as robots, so the dual-coil MC-WPT system belongs to the near-field energy transfer. After simplification, the near-field equivalent expression of the magnetic field is:

\[
H_1 = \begin{bmatrix}
\frac{\omega \mu \alpha \cos \theta I_1}{2\beta r^2} & r \\
\frac{\omega \mu \alpha \sin \theta I_1}{4\beta r^2} & \theta \\
0 & \phi
\end{bmatrix}
\]  \hspace{1cm} (3)

It is well known that the magnetic flux is equal to the product of the magnetic induction intensity and the area perpendicular to it, as shown in Equation (4).

\[
\phi = B \times S = \mu H \times S \]  \hspace{1cm} (4)

The analysis shows that the magnetic field intensity \( H_1 \) generated by the excitation current \( I_1 \) flowing through the coil 1 is not uniformly distributed in the coil 2, which is related to the distance. For the magnetic flux calculation of the coil 2 at this time, the integral calculation is more accurate. At the same time, in order to facilitate the calculation of magnetic flux, this paper uses coordinate transformation to simplify the calculation, the formula is as follows:

\[
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix} = \begin{bmatrix}
\sin \theta \cos \phi & \cos \theta \cos \phi & -\sin \phi \\
\sin \theta \sin \phi & \cos \theta \sin \phi & \cos \phi \\
\cos \theta & -\sin \theta & 0
\end{bmatrix} \begin{bmatrix}
x \\
y \\
z
\end{bmatrix}
\]  \hspace{1cm} (5)

For the two-coil parallel system, the combination (4) shows that only the component of the magnetic field strength in the z-axis can be calculated, that is, \( H_z \) is considered. The \( \cos \theta \) and \( \sin \theta \) expansions from the angle analysis in coordinate transformation are:

\[
\begin{align*}
\cos \theta &= \frac{D}{r_1} \\
\sin \theta &= \frac{\sqrt{r_1^2 - D^2}}{r_1}
\end{align*}
\]  \hspace{1cm} (6)

\( D \) represents the distance between two coils. And see \( H_z \) and \( D \) related.

When analyzing the magnetic flux of coil 2, only \( H_z \) is needed, and the formula is shown in (5):

\[
\phi_z = \int \int \mu H_z ds
\]  \hspace{1cm} (7)

According to the Lenz law, the magnetic flux on coil 2 will produce the electromotive force \( E_2 \) that hinders the change of magnetic flux. Combined with the equivalent impedance of the receiving end, the induced current \( I_2 \) on coil 2 can be obtained. The final induced current amplitude of coil 2 is expressed as:

\[
|I_2| = -\frac{\partial \phi_z}{\partial t} \frac{1}{Z_2} = -\mu S_\text{eq} \frac{\partial H_z}{\partial t} \frac{1}{Z_2}
\]  \hspace{1cm} (8)
Where \( Z_2 \) is the equivalent impedance of coil 2; \( S_{eq} \) is the equivalent area of coil 2.

Formula (8) is the expression of induced current on the single-turn receiving coil. Combined with formula (6), it can be seen that the size of induced current is related to the equivalent area of the receiving coil and the magnetic field component \( H_z \) in the receiving coil.

When the secondary coil is a multi-turn coil, the secondary induced current of the multi-turn coil can be obtained by using Equation (8):

\[
\left| I_{2all} \right| = -\mu N_{eq} S_{eq} \frac{\partial H_z}{\partial t} \frac{1}{Z_2}
\]

(9)

Where \( N_{eq} \) is the equivalent number of turns. When the magnetic coupling mechanism is disc structure, the equivalent turns are \( N_{eq1} \); when the magnetic coupling mechanism is a spiral structure, the equivalent turns are \( N_{eq2} \).

The disk magnetic coupling mechanism and spiral magnetic coupling mechanism used in the robot are single. The traditional magnetic coupling mechanism does not make good use of space. The equivalent area and equivalent number of turns of the whole magnetic coupling mechanism have room for improvement. When the two coils are connected, the new magnetic coupling mechanism mentioned in this paper is formed.

It can be seen from Formula (9) that the new magnetic coupling mechanism has the advantages of multi-turns and large equivalent area. With the increase of distance, the weakening performance of magnetic field intensity of MC-WPT system is compensated by multi-turns and large equivalent area. In other words, its ability to produce mutual inductance is greater than that of a single structure.

In short-range transmission, the MC-WPT system will have frequency splitting phenomenon. Therefore, in this paper, the new magnetic coupling mechanism is divided into disk magnetic coupling mechanism and spiral magnetic coupling mechanism, and the switching device added in the middle can well improve the induced current caused by frequency splitting phenomenon that may not meet the expected situation, and better improve the transmission power.

The designed new magnetic coupling mechanism is composed of the traditional disk structure and the spiral structure. In the same case, it will have a greater mutual inductance. Therefore, the transmission distance between the coils can also be increased due to the mutual inductance changes of different magnetic coupling mechanisms. Therefore, this wireless charging system can obtain stronger anti-offset ability.

3. Parameter Design

In order to study the energy efficiency and anti-offset characteristics of the new magnetic coupling mechanism, the new magnetic coupling mechanism formed by switch closure is compared with the traditional single disk structure and single spiral structure. The most commonly used disk structure is used in the launch coil. Based on the simulation software COMSOL, the physical models of disk-disk coupling mechanism, disk-helical coupling mechanism and disk-new magnetic coupling mechanism are established and simulated. The coil geometric parameters are set according to the size of the home small robot shown in Figure 1, as shown in Table 1.

The three magnetic coupling mechanisms are applied to the same SS topology circuit analyzed above, and the secondary circuit is set to resonant state. The simulation software Simulink is used to establish the model and simulate. The electrical parameter settings of the circuit are shown in Table 2.

| Type | Parameters | Numerical value |
|------|------------|----------------|
| N    | Number of turns of primary side coil | 13 |
| a    | Inner diameter of primary side coil | 0.01m |
| \( W_{th} \) | Ramp spacing of primary side coil | 0.004m |
| Type          | Parameters                        | Numerical value |
|---------------|-----------------------------------|-----------------|
| $N_1$         | Number of turns of secondary side coil | 13              |
| $a_1$         | Inner diameter of secondary side coil | 0.01m           |
| $W_{th1}$     | Turn spacing of secondary side coil | 0.004m          |
| $N_2$         | Number of turns of secondary spiral coil | 10              |
| $a_2$         | Inner diameter of secondary spiral coil | 0.058m         |
| $W_{th2}$     | Ramp spacing of secondary spiral coil | 0.004m         |
| $r_{\text{wire}}$ | Radius of coil line | 0.00125m          |
| $D$           | Distance between two coils         | 0.03m           |

Tab.2 Electric parameter of the systems

4. Simulation Analysis

The finite element simulation software COMSOL is used to simulate the transmitting coil and the receiving coil according to the coil geometric parameters given in Table 1. The schematic diagram of the three magnetic coupling mechanisms after simulation is shown in Figure 5.

For the three kinds of magnetic coupling mechanisms, the distance $D$ between the receiving coil and the transmitting coil is taken as a variable to analyze the mutual inductance coupling, transmission efficiency and inductive secondary current capability of the receiving coils with different structures. The
different distance D of the two coils is used as the parameter variable, and the parametric scanning is carried out with the step length of 1cm. The law of the ability index of the three structures changing with the distance D is shown in Figure 6-8.

Fig. 6 shows the relationship between mutual inductance and transmission distance of the three magnetic coupling mechanisms.

Fig 6. Curve diagram of mutual inductance change of magnetic coupling mechanism

From the simulation results, it can be seen that with the increase of transmission distance, the mutual inductance values of the three magnetic coupling mechanisms are decreasing, but the mutual inductance coupling ability of the new magnetic coupling mechanism is always greater than that of the spiral magnetic coupling mechanism and the disk magnetic coupling mechanism. In other words, under the same minimum mutual inductance threshold condition, the offsetable distance of the new magnetic coupling mechanism is the largest, that is, its anti-offset ability is the largest.

Figure 7 shows the relationship between transmission efficiency and transmission distance of three magnetic coupling mechanisms.

Fig 7. Transmission efficiency curve of magnetic coupling mechanism

From the simulation results, it can be seen that with the increase of transmission distance, the transmission efficiency of the three magnetic coupling mechanisms is declining, but the transmission
efficiency of the new magnetic coupling mechanism is always greater than that of the spiral magnetic coupling mechanism and the disk magnetic coupling mechanism. In other words, under the same transmission distance, the transmission efficiency of the new magnetic coupling mechanism is the highest, that is, the charging cost of the new magnetic coupling mechanism is the lowest. When the transmission efficiency is given priority, the switch is closed and the new magnetic coupling mechanism is used for charging, and the effect is the best.

Figure 8 shows the relationship between the side current induced by the side coil of the three magnetic coupling mechanisms and the transmission distance.

Figure 8. Magnetic coupling mechanism secondary side current change curve diagram

It can be seen from the simulation results that due to the frequency splitting phenomenon in the MC-WPT system, there will be a new magnetic coupling mechanism that has the ability to induce the secondary coil current lower than that of the traditional magnetic coupling mechanism in the short-range wireless charging. In other words, the transmission power of the new magnetic coupling mechanism may not reach the expected value in the short-range transmission.

In this case, the switching mentioned in this article highlights its advantages. The switch is used at the intersection of the secondary current curves of the new magnetic coupling mechanism, the spiral magnetic coupling mechanism and the disk magnetic coupling mechanism to switch the selection of the magnetic coupling mechanism and the corresponding compensation capacitor, so that the entire MC-WPT system can achieve the maximum transmission power, and the system is always in the maximum power transmission state.

Figure 9 shows the curve of the switching point and the secondary current optimized by using the switch to switch at the intersection of the secondary current induced by the three magnetic coupling mechanisms to select the appropriate magnetic coupling mechanism for power transmission. The blue point is the switching point, and the yellow curve is the optimized secondary current curve.
Fig 9. Curve of side current variation after optimization of magnetic coupling mechanism

It can be seen from the optimized secondary current curve that the whole MC-WPT system always works in the best working state of the secondary current, and the wireless charging of the robot can be maintained at the maximum power transmission state. It can also be seen that it is feasible to select the appropriate magnetic coupling mechanism and its compensation capacitance by switching at the secondary side current intersection of the three magnetic coupling mechanisms to keep the system in optimal power transmission. When the transmission power is given priority to as the goal, the control switch is used to charge with different magnetic coupling mechanisms under different transmission distances, and the effect is the best.

5. Conclusion
In this paper, through the analysis of the magnetic flux of the robot wireless charging system, the relationship between the equivalent area of the coil, the equivalent turns and the induced current of the secondary coil is obtained. By analyzing the utilization rate of the internal space of the robot, a new magnetic coupling structure is designed, which integrates the traditional disk structure and the traditional spiral structure.

The comsol finite element simulation software is used to model three kinds of magnetic coupling mechanism, and the mutual inductance coupling, transmission efficiency and induction side current ability of each magnetic coupling mechanism are simulated. The relationship curve between the target ability and the transmission distance is obtained. Under different target conditions, for example, the transmission power, transmission efficiency, anti-offset ability and other targets are given priority. According to the required requirements, different magnetic coupling mechanisms and compensation capacitors can be selected for wireless charging by switching under different transmission distances.

The structure size of the magnetic coupling mechanism designed in this paper is based on the size of the selected small home robot, which can be used as a reference for the design of the magnetic coupling mechanism of other types of size robots. The designed new magnetic coupling mechanism can be installed at the bottom of the robot, and does not occupy multiple spaces. The optimized coil can improve the transmission efficiency, transmission power and anti-deviation ability of the robot, which has good promotion effect on the promotion and application of wireless charging for other types of robots, and has good practical application value.

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