Optimal Design of Wireless Power Transfer System Based on Spherical Motion Device

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Abstract The multi-degree-of-freedom spherical motion device usually requires a built-in data acquisition and processing module and a wireless charging part in its bionic design, while the traditional disc-shaped receiving coil increases with the deflection angle, the system coupling coefficient and mutual inductance will decrease causing the increased power transmission fluctuation and greatly decreased transmission power. In this paper, a tile-shaped receiving coil is designed to ensure the power output when the rotation offset occurs. Then, the formula of radio energy transmission characteristics is derived and verified by finite element simulation. It is proved that the coupling coefficient peak value of the new structure is increased by 12.68% and the variation fluctuation is reduced by 2.26%. The output of the new system at each deflection angle has been improved overall. Finally, an experimental platform is built to verify the accuracy of the simulation analysis and the effectiveness of power transmission.

Index Terms Multi-DOF spherical motion device, Wireless power transmission, Tile-shaped coil, Disc-shaped coil

I. INTRODUCTION

Wireless Power Transfer (WPT) is a non-contact charging method, which avoids the aging problem of wires caused by traditional power transmission, increases the power safety index and the service life of equipment, and reduces the serious safety accidents such as fire caused by power safety. The advent of WPT technology has added convenience and made it possible for electrical equipment to be freed from the bondage of cables [1-3]. Since Nikola Tesla first proposed the concept of WPT at the end of the 19th century, WPT technology has a long history of development so far. Reference [4] proposed a receiving coil (Rx-coil) with a regular tetrahedral structure. By optimizing the winding strategy, the output power at any rotation angle is stabilized above 22W. Reference [5] designed an asymmetric transceiver coil (Tx-coil) structure based on MATLAB, which improved the output power and efficiency. Reference [6] designed the charging coil by using multi-strands parallel serpentine conductor, which reduced the AC resistance of the coil by 13.5%, while the elastic elongation was increased by about one-third. Reference [7] used two decoupled DD coils and resonant capacitors to form an intermediate resonant circuit through the compensation topology of the wireless power transmission system (WPTS), and realizes the switching between constant voltage and constant current charging. Reference [8] designed a butterfly receiver coil structure to improve the transmission efficiency of the receiver in medical wireless devices.

With the continuous innovation of modern industrial technology and the continuous promotion of artificial intelligence, highly integrated and accurate motion devices have received widespread attention. Due to the use of the transmission shaft, the traditional multi-DOF motion device not only increases the floor space and generates more mechanical losses, but also reduces the control accuracy. The generation and development of multi-DOF spherical motion devices are more in line with the requirements of the times [9-11]. For example, reference [12] proposed the liquid-mass suspension hybrid drive multi-DOF motor, the hollow rotor part of the motor can be placed wireless charging device and visual image acquisition device, using multi-dimensional motion actuators and control technology to achieve visual bionics. When the spherical moving device deflects, it will cause deviation between the Rx and Tx-coils, which reduces the transmission efficiency of the system. However, there is still no suitable energy pickup mechanism to improve the transmission efficiency in this case.

In order to fit the WPTS of the spherical moving device, this paper designs a tile-shaped receiving coil. Through the introduction of the spherical moving device, the reason for the power reduction of the WPTS is analyzed, and the transmission characteristics of the system are analyzed. Then,
the traditional disc-shaped receiving coil model was established to compare with the design model, and the finite element analysis software was used to conduct multi-physics simulation calculations on different receiving coils. Finally, experiments have proved the feasibility of the design scheme and the significant improvement of the transmission power by the tile-shaped receiving coil.

II. SYSTEM MODELING AND ANALYSIS

A. STRUCTURE ANALYSIS OF SPHERICAL MOVING EQUIPMENT

Fig. 1 shows the overall structure and section of the multi-DOF spherical motion equipment selected in this paper. Four patch-type permanent magnets are alternately arranged at the center of the rotor equator and connected with a cross-type cross shaft. There are four groups of cylindrical hollow coils on the stator corresponding to the position of the permanent magnets. Each group of cylindrical hollow coils is composed of four small coils. The interaction between the coil and the magnetic field generated by the permanent magnet enables the spherical motor to move in multiple directions. In order to improve the control accuracy, a disk-shaped unipolar permanent magnet is arranged in the opposite direction of the motor shaft, which cooperates with the fine-tuning mechanism composed of five air-core coils at the lower part. By adjusting the magnitude and direction of the stator coil current in different positions, hybrid driving mode is realized [13].

B. ANALYSIS OF THE WORKING PRINCIPLE OF THE WPTS

1) Principle of wireless power transmission

When the angular frequency of the Tx and Rx-coils are equal and equal the angular frequency of to the power supply voltage at the same time, the circuit is in a resonance state. At this time, the equation (1) is always established.

\[ \omega_1 = \omega_2 = \omega = \frac{1}{\sqrt{C_1 L_1}} = \frac{1}{\sqrt{C_2 L_2}} \]  

(1)

Define the impedance of the Tx and Rx-coils loop as \( Z_1 \) and \( Z_2 \), respectively. Then its value can be expressed as:

\[
\begin{align*}
Z_1 &= R_1 + j\omega L_1 + \frac{1}{j\omega C_1} \\
Z_2 &= R_2 + R_L + j\omega L_2 + \frac{1}{j\omega C_2}
\end{align*}
\]  

(2)

When the power supply impedance is ignored, knowing from Kirchhoff’s second law (KVL), the loop equation can be expressed as:

\[
\begin{align*}
\omega C_1 I_1 &= \omega C_2 I_2 \\
\omega L_1 I_1 &= \omega L_2 I_2 \\
R_1 I_1 + R_2 I_2 + R_L (I_1 + I_2) &= V_s
\end{align*}
\]
The position of the Tx-coils in the new WPTS in Fig. 4 is modeled mathematically, and the change of the coupling coefficient caused by the angle deviation is analyzed. The angle of lateral deflection is defined as $\alpha$, and the angle of pitch deflection is defined as $\beta$. Select the point on the coil $L_T$ as $m$, then its coordinates can be expressed by equation (6), and its corresponding micro-element $dl_T$ is expressed by equation (7):

$$
\begin{align*}
U_S &= Z_I I_1 - j\omega M I_2 \\
0 &= Z_I I_2 - j\omega M I_1
\end{align*}
$$

In the case of the system in resonance, the currents between the loops of the system are:

$$
\begin{align*}
I_1 &= \frac{(R_2 + R_L) U_S}{\alpha^2 M^2 + R_1 (R_2 + R_L)} \\
I_2 &= \frac{j \omega M U_S}{\alpha^2 M^2 + R_1 (R_2 + R_L)}
\end{align*}
$$

At this time, the input power $P_{in}$, output power $P_{out}$ and efficiency $\eta$ of the WPTS can be expressed as:

$$
\begin{align*}
P_{in} &= \frac{(R_2 + R_L) U_S^2}{\alpha^2 K_{12}^2 L_1 L_2 + R_1 (R_2 + R_L)} \\
P_{out} &= \frac{\omega^2 K_{12}^2 U_S^2 L_1 L_2 R_L}{[\alpha^2 K_{12}^2 L_1 L_2 + R_1 (R_2 + R_L)]^2 (R_2 + R_L)} \\
\eta &= \frac{\omega^2 K_{12}^2 L_1 L_2 R_L}{[\alpha^2 K_{12}^2 L_1 L_2 + R_1 (R_2 + R_L)] (R_2 + R_L)}
\end{align*}
$$

The coupling between the coils can be represented by mutual inductance. From equation (5), it can be seen that when the self-inductance and resonance frequency of the Tx and Rx-coils are known, the performance of the WPTS is mainly affected by the mutual inductance.

Taking the point on the coil $L_R$ as $n$, when it is in the $ac$ segment, the coordinates are equation (8), the coordinates in the $bd$ segment are shown in equation (9), and the corresponding micro-elements are expressed as $dl_R$ and $dl_R'$:

$$
\begin{align*}
x_R &= r \cos \varphi_R \cos \beta \\
y_R &= r \sqrt{r^2 \cos^2 \left(\frac{\pi}{2} - \alpha\right) - r^2 \cos^2 \varphi_R} \\
z_R &= r \sin \varphi_R \cos \alpha \sin \beta
\end{align*}
$$

$$
\begin{align*}
x_R' &= r \cos \left(\frac{\pi}{3} - \beta\right) \\
y_R' &= \sqrt{3} r \tan \varphi_R \cos \alpha + r \sin \left(\frac{\pi}{3} - \beta\right) \sin \alpha \\
z_R' &= r \sin \left(\frac{\pi}{3} - \beta\right) \cos \alpha - \sqrt{3} r \tan \varphi_R \sin \alpha
\end{align*}
$$

$$
\left\{\begin{array}{l}
dl_R = (- \sin \varphi_R \cos \beta + \cos \varphi_R \cos \alpha \sin \beta) \\
rd\varphi_R + \frac{\sin (2\varphi_R)}{2} r d\varphi_R \\
\sqrt{\cos^2 \left(\frac{\pi}{2} - \alpha\right) - \cos^2 \varphi_R}
\end{array}\right.
$$

$$
\left\{\begin{array}{l}
dl_R' = \sqrt{3} \sec^2 \varphi_R \left(\cos \alpha - \sin \alpha\right) r d\varphi_R
\end{array}\right.
$$

$r$ is the length of the chord corresponding to the arc of the selected tile-shaped coil, which is also equal to the diameter of the outermost circle of the disc-shaped coil, that is, $r = 2L_T$, and $d$ is the distance from the center point of the disc-shaped coil to the origin. At this time, the mutual inductance $M$ is expressed as:

$$
M = 2 \times \int_{\frac{\pi}{2}}^{\frac{2\pi}{3}} 2 \frac{2\pi}{3} \frac{dl_T}{l_{mn}} d\varphi_T d\varphi_R + 2 \times \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} 2 \frac{2\pi}{3} \frac{dl_R}{l_{mn}} d\varphi_T d\varphi_R
$$

Among them, $l_{mn}$ is the distance between the two points of the coil, which can be calculated by the coordinate formula between the two points.
Fig. 5 shows a cross-sectional view of the new WPTS transmission coil. The wire diameter and wire distance of the disc-shaped coil are represented by $r_T$ and $S_T$, the number of coil turns is $N_i$, the horizontal and longitudinal wire distances of the tile-shaped coil are represented as $S_R$ and $S_H$, and the wire diameter and the number of coil turns are represented by $r_R$ and $n_j$. When the selected point changes in the number of turns of the coil, the amount of change at this time is expressed as:

$$
x'_R = r \cos\left(\frac{\pi}{3} - \beta\right) - (n_i - 1)(S_R + r_R)
$$

$$
L'_T = L_T - (n_i - 1)(S_T + r_T)
$$

$$
A_j = \frac{\pi}{3} + (n_i - 1)\frac{r_R + \sqrt{S_R^2 + S_H^2}}{r}
$$

$$
B_j = \frac{\pi}{3} - (n_i - 1)\frac{r_R + \sqrt{S_R^2 + S_H^2}}{r}
$$

(12)

In equation (12), $A_j$ and $B_j$ are the upper and lower limits of the integral. At this time, the overall mutual inductance $M_S$ and coupling coefficient $K$ of WPTS can be expressed as:

$$
M_S = \sum_{i=1}^{N_i} \sum_{j=1}^{n_j} M(L_T, A_j, B_j, \alpha, \beta)
$$

(13)

III. NEW WPTS DESIGN AND SIMULATION ANALYSIS

A. NEW DESIGN OF RECEIVING COIL

The Rx-coil installed in the spherical motion device will deviate from the transmitting coil with the deflection of the motion device, so that the coupling coefficient of the WPTS designed by the traditional disk-shaped coil will decrease, which will not only reduce the efficiency, but also the generated transmission energy fluctuations will interfere with the stable operation of the WPTS. Therefore, inspired by the idea of patch-shaped permanent magnets [16], a tile-shaped receiving coil was designed. The structure diagram of the Rx-coil of the WPTS is shown in Fig. 6.

The joint system formed by combining the wireless charging system with the selected multi-DOF spherical motion device is shown in Fig. 7.

B. SYSTEM MODELING

Since the receiving coil is arranged inside the rotor, as so to describe the influence of the rotor movement on the WPTS, the rotor sphere center is set as the coordinate origin, the output axis is the Z axis direction, and the spatial rectangular coordinate system is established as shown in Fig. 8, which defines the movement of the motor rotor around the X-axis, Y-axis and Z-axis is achieved. When the motor rotor moves around the Y-axis, the relative position of the receiving and sending coils does not change significantly. This article will not discuss such situations. The position deviation caused by the other two cases is shown in Fig. 9. Among them, A, B, C
and a, b, and c are the typical movement positions in two different situations, that is, with the deflection movement of the motor rotor, the position of the Rx-coils pulling WPTS constantly changes, thus affecting the transmission performance of WPTS.

![Simplified schematic diagram of the joint charging system](image)

**FIGURE 8.** Simplified schematic diagram of the joint charging system

![Schematic diagram of the position shift of the WPTS](image)

**FIGURE 9.** Schematic diagram of the position shift of the WPTS

In order to verify the feasibility of the tile-shaped coil designed in this paper, based on the Eddy current platform in the finite element simulation software ANSYS Maxwell, a WPTS simulation platform based on the disk-like receiving coil and the tile-shaped receiving coil is respectively built in this section, in which the disk-like coil is also used in the transmitting coil and the same size and material as the disk-shaped receiving coil. Table 1 shows the parameters set by the system. Among them, the angle of inclination of the tile-shaped receiving coil is 60°, and all coils are made of copper wire of the same specification, all of which are made of 1mm copper wires, and the spacing is selected as 40mm.[17,18]

| Parameter                      | Disc-shaped transmitter coil | Disc-shaped receiving coil | Tile-shaped receiving coil |
|--------------------------------|-------------------------------|---------------------------|----------------------------|
| Turns per coil n               | 10                            | 10                        | 10                         |
| Radius of the first turn r      | 30 mm                         | 30 mm                     | 30 mm                      |
| Wire diameter D                 | 1 mm                          | 1 mm                      | 1 mm                       |
| Radius difference α             | 0.25 mm                       | 0.25 mm                   | 0.25 mm                    |
| Current I                       | 5 A                           | 5 A                       | 5 A                        |

In Table 1, the radius of the first turn of the tile-shaped Rx-coils is half of the chord corresponding to its radian.

**C. ANALYSIS OF SIMULATION RESULTS**

1) Analysis of transmission characteristics

In ANSYS Maxwell, through the parameterized scanning of the rotation angle, the change of the coupling coefficient of two different receiving coils moving around the X-axis and Y-axis is obtained to reflect the transmission performance of the WPTS [19-21], and get the data is imported into Matlab for result analysis.
Fig. 10 shows the coupling coefficients of two WPTS obtained by finite element analysis when the operating frequency of the system is set to 75 kHz, where $K_{RT}$ is the coupling coefficient between the WPTS coils, $\text{rotateX}$ is the rotation angle of the Rx-coil around the X axis, and $\text{rotateY}$ is the receiving angle of rotation of the coil around the Y axis. Fig. 11 shows the percentage of the coupling coefficient difference between the two different WPTSs in Fig. 10, which is shown by $\Delta$ in the figure. It can be seen from the figure that whether it is a traditional disc-shaped receiving coil or an improved tile-shaped receiving coil, as the deflection angle of the Rx-coil increases, the coupling coefficient is continuously reduced. The coupling coefficient when the Rx and Tx-coils are directly aligned maximum. With the increase of the deflection angle, the coupling coefficient of the new tile-shaped receiving coil has been higher than that of the system composed of the traditional disc-shaped receiving coil.

When the WPTS is working, it will inevitably produce leakage magnetic flux, which will not only cause the decline of the system transmission performance, but also cause huge interference to the surrounding organisms [22-26], so we hope that in the system transmission process the smaller the leakage flux, the better.

$$w_K = \frac{K_{max} - K}{K_{max}} \tag{14}$$

$w_K$ is the WPTS coupling coefficient fluctuation, $K_{max}$ is the maximum WPTS coupling coefficient, and $K$ is the coupling coefficient after the Rx-coils is deflected.

In the offset range of 20°, the maximum coupling coefficient of the traditional disc-shaped receiving coil is 0.11024, and the minimum coupling coefficient is 0.01982. The improved tile-shaped receiving coil is adopted, and the variation range of its coupling coefficient is 0.02514-0.12422. The peak value of the coupling coefficient has increased by 12.68%, and its variation fluctuation has been reduced by 2.26%. It shows that the WPTS composed of tile-shaped receiving coils proposed in this paper has better transmission performance and anti-offset performance.

2) Electromagnetic field analysis

When the WPTS is working, it will inevitably produce leakage magnetic flux, which will not only cause the decline of the system transmission performance, but also cause huge interference to the surrounding organisms [22-26], so we hope that in the system transmission process the smaller the leakage flux, the better.
When the RX-coil is deflected, the Fig. 12 and Fig. 13 show the surrounding magnetic field distribution of the two receiving coils. The magnetic field limit is set to $B \in [0.001, 0.002]$ T. We can know that when the new tile-shaped receiving coil is deflected, the magnetic field of the system is more stable, and the magnetization effect is more significant, which not only improves the transmission characteristics of the system, but also reduces the impact on the surrounding environment. Since the frequency of the magnetic field and the output power of the WPTS are low, the electromagnetic field generated by it will not cause harm to the human body [27, 28].

**IV. EXPERIMENTAL VERIFICATION**

Fig. 14 shows the experimental platform of the WPTS. The DC power supply of the experimental device provides voltage and current for the system. The load is an electronic load. At a resonance frequency of 75 kHz, the WPTS transfers energy to the load through a coupling mechanism, and the system transmission power is obtained by measuring the input/output voltage and current of the system. In addition, an RCD protection circuit is added to the design of the circuit diagram of the coupling mechanism to prevent overvoltage when the thyristor is turned on and off. Table 2 shows the power loss of some devices in the WPTS. By calculating the power of the system in different deflection states, the power loss offset curve is obtained.

**Table 2**

| Device type                        | WPTS based on disc-shaped receiving coil | WPTS based on tile-shaped receiving coil |
|------------------------------------|-----------------------------------------|------------------------------------------|
| Power inverter                     | 3.67 W                                   | 3.65 W                                   |
| Primary compensation network       | 1.82 W                                   | 1.82 W                                   |
| Secondary compensation network     | 1.83 W                                   | 1.84 W                                   |
| Transmit coil                      | 0.26 W                                   | 0.26 W                                   |
| Receiving coil                     | 0.01 W - 0.13 W                          | 0.03 W - 0.19 W                          |

Table 2 shows as the position of the Rx-coils shifts, the overall loss of the system is also changing. Since the output power of the improved WPTS is greater than that of the traditional system, its power loss is also increased accordingly. At the best position of power output, the loss increase is about 16.7%, which is within an acceptable range due to its small magnitude.
When the position of the receiving device changes with the deflection of the spherical motion device, it is output power can be obtained by measuring its input/output voltage and current, as shown in Fig. 15. In Fig. 15, channels 1 and 2 are respectively the measurement of input and output parameters. We can know from Fig. 16 that as the deflection angle of the Rx-coil increases, the output power of the WPTS gradually decreases, and when the deflection angle reaches 60°, its transmission power is small, which cannot guarantee the power requirements. However, the output power of the tile-shaped receiving coil when facing directly reaches 3.5W, which is 9.1% higher than the output power of the traditional disc-shaped receiving coil.

![Graph](image)

**FIGURE 16.** The output power curve when two different receiving coils are deflected

\[
p_w = \frac{P_{\text{max}} - P}{P_{\text{max}}} \quad (15)
\]

\(w_p\) is the WPTS output power fluctuation, \(P_{\text{max}}\) is the maximum WPTS output power, that is, the power output when the Tx and Rx-coils are facing each other, and \(P\) is the power output after the Rx-coils is deflected. In the 20° deflection range, the output power is controlled above 1.4W. It can be seen from the equation (14) that the overall performance of the WPTS based on the new tile-shaped receiving coil is better than the traditional structure, and the output power fluctuation is reduced by about 13%, which fully confirms its superior anti-deflection characteristics.

**V. CONCLUSION**

At present, most researches on the offset of WPTS focus on the lateral offset or the deflection of the Rx-coil around the axis. Based on the exploration of the spherical multi-DOF motion device, this paper proposes a tile-shaped receiving coil to improve the anti-deflection characteristics of the WPTS. The formula of the transmission power and the efficiency change with the coupling coefficient are deduced. The anti-deflection characteristic of the design model is analyzed through the finite element software, and the experimental platform is built to verify the accuracy of the simulation and the effectiveness of the power transmission.

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