LETTER

Wireless power transmission for multi-degree-of-freedom motor applications based on magnetic field coupling

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Abstract This paper proposes a wireless power transmission scheme for three-degree-of-freedom motors' applications in the field of bionics. In order to overcome the inconvenience of the rotating device with its charged wires, the wireless power transmission of the internal image visual acquisition device is realized. A three-coil receive structure suitable for motion device is designed. Using multi-physical simulation method, the parameters, magnetic flux and received power of single-coil receive structure and three-coil receive structure for wireless power transmission are calculated. The advantages of the three-coil receive structure are obtained. Finally, the accuracy and validity of the simulation are verified by experiments.

Keywords: wireless power transmission, three-coil, rotating device, motor

Classification: Energy harvesting devices, circuits and modules

1. Introduction

Wireless Power Transfer began research in the 19th century. Recently, more and more attention has been paid to wireless power transfer technology [1, 2]. There are two types of wireless charging, one is stationary WPT (SWPT) and another is In Motion WPT (IM-WPT) [3, 4]. Wireless Power Transfer charges mobile robots and electric vehicles for its safety and convenience [5, 6, 7, 8], medical aspects [9, 10, 11]. Such areas have received extensive attention. Omnidirectional wireless power systems with planar receivers have been suggested in [12]. Several wireless charging platforms for multi-receiver applications were proposed [13]. In this paper [14], the WPT system has more than 85% efficiency regardless of the number of receivers. The proposed method eliminated the cross-coupling effect and unbalanced power division problem across the receivers. With multiple TXs or RXs in a limited space, couplings occur between TXs or between RXs. The frequency conditions for maximum efficiency and power transfer under such couplings are proposed [15, 16]. The interesting considerations based on kQ and Q are also given to the magnetic coupled resonance WPT system [17, 18, 19]. This paper presents a detailed circuit analysis of a two-coil inductively coupled WPT model in different compensating topologies to accomplish efficient energy transfer [20]. Grabham found that the circular coil trans-

ferred more energy than the square coil, and the power transfer was not affected by the rotation alignment [21]. This paper [22] introduces that the new coil receiver receives energy at any location near the transmitter. The majority of practical implementations of wireless power systems involve “directional” power flow [23]. Chiuk Song *et al.*, proposed a new type of charger for drones with low electromagnetic interference [24]. The main uses of multi-freedom motors include bionic eyes, robots, aerospace flight instruments, and so on [25]. iCAT robot adopted flexible wire transmission and tension-driven Bionic eye MAC-EYE system [26]. The motor from the use of multiple one-dimensional drive elements to achieve multi-degree-of-freedom motion [27].

2. Establishment and analysis of system model

2.1 Structure and principle of wireless power transmission for multi degree of freedom motor

As shown in Fig. 1, four N and S poles of permanent magnets are fixed by cylindrical rotating shafts in the form of cross. Two pairs of hollow coils are placed in the upper, lower, left and right directions of the outer periphery of the permanent magnet. A cylindrical hollow coil contains four small coils. The interaction between the N and S poles of permanent magnet and the magnetic field produced by the coil realizes the multi-degree-of-freedom motion of the motor. In order to adjust the tail of permanent magnet, the disc-shaped unipolar permanent magnet and a coil group consisting of five hollow coils are placed at the tail of permanent magnet [28]. The spherical stator and rotor of multi-degree-of-freedom motor can be made of non-magnetic shielding material. This design guarantees the feasibility.

Fig. 1. Three coil wireless power transmission model for multi-freedom permanent magnet motor

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DOI: 10.1587/ele.16.20190330

Received May 21, 2019

Accepted May 28, 2019

Publicized June 11, 2019

Copyedited July 10, 2019

2.2 S_{21} parameters for three-coil transmission structure and single-coil structure transmission

In order to study the effect of the coil angle offset on the transmission characteristics of the system, as in Fig. 2, the center position of the coil is not changed, the transmit coil is fixed, and the receive coil deflects θ angle.

Fig. 2. Transmitting and receiving coils with deflected angles

The component of the magnetic field strength on the Z axis through the center of the receive coil when the coil is offset at an angle when $H_{Z\Delta} = \mu H_Z$, $\mu = [0; \sin \theta; \cos \theta]$ is a unit vector. When a deflection angle occurs, S_{21} can be expressed as [29]:

$$S_{21} = \frac{j\omega\mu_0\pi N_1 N_2 r_1^2 r_2^2 I_1 \sqrt{R_L R_S} \cos \theta}{U_S (R_L + R_2)(r_1^2 + d^2)^{\frac{3}{2}}} \quad (1)$$

By equation (1), when the transceiver coil is placed in parallel, the effective coupling area of the coil is the largest and the coupling degree is the highest, as the angle increases, $\cos \theta$ decreases and the coupling path decreases. When the transceiver coil is placed vertically, the magnetic field coupling is weak.

Modeling and analysis are carried out on the basis of finite element method. All the geometrical parameters of the coil are shown in Table I. The resonant frequency is set to $f = 200$ MHz, setting the boundary, selecting the aggregate port and the aggregate element.

The transmission performance changes with the rotation angle as shown in Fig. 3. Wireless transmission takes place inside the fixed rotor spherical shell, the launch coil remains in a fixed position, and the receive coil rotates inside the rotor. The XY plane section represents the distribution map of the electric field strength, and the arrow represents the flux density between the two loops. The transmit coil is kept in a fixed position, and the motor rotor belt receives the coil from 0° to 120° .

The single coil receive device gradually increases at the deflection angle, and the electric field passing through the receive coil becomes smaller and smaller. When the rotation angle of the receive coil is greater than 90° , the electric field passing through the receive coil is very small. At this time, there is almost no coupling and the transmission efficiency is low. The transmission efficiency of the three-coil structure is not affected by the rotation angle. Fig. 4 shows the trend of the S_{21} parameter with the deflection angle.

2.3 Analysis of transmission characteristics

In order to study the advantages of the three-coil in space rotating motor compared to the single-coil, the simulation of the design and application circuit confirms the above

Table I. Size parameters of coils

	Launch single coil	Receive single coil
Internal diameter	6 mm	6 mm
External diameter	40 mm	40 mm
Line Path	0.25 mm	0.25 mm
layer	1	1
Number of turns	8	8
material	copper	copper

Fig. 3. Comparison of S_{21} parameters at different angles of single and three coils

Fig. 4. S_{21} parameter change with angle

theoretical analysis. The circuit is transmitted to the coil by AC through the compensation network, and the coil coupling is transmitted to the receive coil to generate a signal. This paper compares the waveform of transmission and reception coil under the traditional single coil structure, and the waveform of transmission and reception coil of the new three-coil circuit structure.

From Figs. 5 and 6 above, it can be seen that in the new three-coil structure circuit, the transmission voltage efficiency of the three-coil coupling coil is higher than that of the traditional circuit single-loop structure. This result verifies the correctness of the above theory. This paper lays the groundwork for the simulation of the following multi-physical field.

2.4 Characteristic analysis of three-coil transmission structure

The three receive coils are evenly placed inside the spherical rotor. The simplified illustration of the three-coil re-

Fig. 5. Wavelet of transmission and receive coil of traditional circuit single loop structure

Fig. 6. Wavelet of emission and receive coil generated by three-coil circuit structure

ceive system is shown in Fig. 7, where d_{s1} is the distance between the center of the transmit coil and the center of the receive coil numbered 1. d_{si} is the distance between the center of the receive coil number i and the center of the transmit coil, and θ_{si} is the deviation angle between the S coil and the i coil. θ_{im} is the deviation angle between i coil and m coil ($i, m = 1, 2, 3, i \neq m, i$ and m are the number of receivers).

Fig. 7. Simplified diagram of the three-coil wireless transmission system

As the number of receive coils increases, define α_i as the amplitude of the first receive coil resonance. γ_{i1} is defined as the intrinsic loss rates of the i th receive coil. ω_i is defined as the intrinsic angular frequency of the i th receive coil.

The following is an explanation of the relevant expressions and parameters in the formula. Because the sum of the inner angles of the triangle is π , the expressions of $k_{3,si}\theta_{si}$ and $k_{3,im}\theta_{im}$ are shown in equation (2) and (3), where L_i and L_m are self-inductances of the i th and m th receive coils. $M_{3si,max}$ is the maximum mutual inductance between the transmit coil and the i th receive coil. $M_{3im,max}$ is the maximum mutual inductance between the i th and the m th receive coils.

$$k_{3,si}\theta_{si} = \frac{\omega_i}{2} \frac{M_{3si,max}|\cos \theta_{si}|}{\sqrt{L_s L_i}} \theta_{si} = \pi(i-1)/3 \quad (2)$$

$$k_{3,im}\theta_{im} = \frac{\omega_i}{2} \frac{M_{3im,max}|\cos \theta_{im}|}{\sqrt{L_i L_m}} \theta_{im} = \pi(i-m)/3 \quad (3)$$

The values of $M_{3si,max}$ and $M_{3im,max}$ can be calculated by formulas 4 and 5, where r_i and N_i are the radius and turns of the i th receive coil, and r_m and N_m are the radius and turns of the m th receive coil respectively.

$$M_{3si,max} = \frac{\pi \mu N_s N_i r_s^2 r_i^2}{2(r_s^2 + d_{si}^2)^{\frac{3}{2}}} \quad (4)$$

$$M_{3im,max} = \frac{\pi \mu N_i N_m r_i^2 r_m^2}{2(r_i^2 + d_{im}^2)^{\frac{3}{2}}} \quad (5)$$

According to the law of cosines, there is a relationship between d_{im} and d_{si} , as shown in the following formula:

$$d_{im} = \sqrt{2d_{si}^2 \left(1 - \cos \frac{|i-m|2\pi}{3}\right)} \quad (6)$$

This shows that once the values of $M_{3si,max}$ and d_{si} are set, the value of $M_{3im,max}$ can be obtained from formulas 5–6. Then the value of γ_i is calculated by formula 7.

$$\gamma_i = \gamma_{Li} + \gamma_{i0} = \frac{RL_i}{2L_i} + \frac{R_i}{2L_i} \quad (7)$$

In the above formula, γ_i consists of γ_{Li} and γ_{i0} , which are the loss rates caused by γ_{Li} and γ_i , γ_{Li} is the resistance of the i th load, R_i is the resistance of the i th receive coil.

The output power P_i and transmission efficiency η_i of the i th receive coil are calculated by (8) and (9).

$$P_i = 2\gamma_{Li}|\alpha_i|^2 \quad (8)$$

$$\eta_i = \frac{\gamma_{Li}|\alpha_i|^2}{(\gamma_s|\alpha_s|^2 + \sum_1^3 \gamma_i|\alpha_i|^2)} \quad (9)$$

Fig. 11 shows that when the three-coil receive system is located around the transmit coil, even if there is no difference between the receive coils, the energy, output power and transmission efficiency of the system are unevenly distributed to each receive coil due to directional problems. This paper [19] showed that the cross-coupling does not affect the maximum efficiency of multiple-transmitter IPT system. the system efficiency can be simply estimated by measuring the kQ -products of individual transmitter-receiver links. When the transmit coil S is coupled with the nearest receive coil 1. Due to the distance, the receive coil 2, 3 will not affect the maximum efficiency of the coil S , 1. Assume that the coupling coefficient of the receive and transmit coil are K , the quality factors are Q_s and Q_1 [30],

The Q factor can be defined as,

$$Q_s = \omega_0 L_s / R_s \quad (10)$$

$$Q_1 = \omega_0 L_1 / R_1 \quad (11)$$

$$\eta_{s1} = k^2 Q_s Q_1 / (1 + \sqrt{1 + k^2 Q_s Q_1})^2 \quad (12)$$

In the same way, we can get the reception efficiency of the transmit coil S to the receive coil 2 or 3,

$$\eta_{s2} = k^2 Q_s Q_2 / (1 + \sqrt{1 + k^2 Q_s Q_2})^2 \quad (13)$$

$$\eta_{s3} = k^2 Q_s Q_3 / (1 + \sqrt{1 + k^2 Q_s Q_3})^2 \quad (14)$$

The optimum efficiency is obtained when the three-coil structure rotates 360 degrees,

$$\eta_{max} = \eta_{s1} + \eta_{s2} + \eta_{s3} \quad (15)$$

After 360 degree rotation in the three-coil structure, the optimal transmission efficiency is obtained several times, which has a great advantage over the single coil structure.

Fig. 8. Simplified multiple-receiver system

In Fig. 8, to neglect the effect of cross-coupling between receivers, when the value of distance increases to 3 cm, $M = 0.13 \mu\text{H}$ and the value of M only accounts for 2.6% there of. Therefore, in the multiple-receiver system designed in this paper, the cross coupling between receivers can be ignored by ensuring that $d > 3 \text{ cm}$ [30]. The schematic diagram of the three-coil system is shown in Fig. 9. The specific parameters of the simulation are shown in Table II.

Fig. 9. Structure diagram of the three-coil and single-coil wireless transmission

All the geometrical parameters of the coil are shown in Table II. In the selection of the physical tree, the resonant frequency is set to $f = 200 \text{ KHz}$. The transmission characteristics of the system at different rotation angles are shown in Fig. 10. The transmit coil is kept in a fixed position, and the receive coil rotates around the motor's stator axis. The receive coil rotates from 0 degrees to 120 degrees around the stator axis of the motor. Fig. 11 shows that in a single-coil receive device, the magnetic flux is the largest and the transmission efficiency is higher when the offset angle of the sending and receive coils is 0 degrees. With the increase of the partial angle, the electric field strength decreases and the magnetic flux decreases. The electric field strength of the three-coil receive device is almost independent of the rotation angle, and the magnetic flux through the receive coil is relatively stable.

Table II. Size parameters of coils

	Launch single coil	Receive single coil
Internal diameter	6 mm	6 mm
External diameter	40 mm	40 mm
Line Path	0.25 mm	0.25 mm
layer	1	1
Number of turns	8	8
material	copper	copper
D_{S1}	3 cm	3 cm
D_{12}, D_{13}, D_{23}	3 cm	
R_i	0.1 Ω	0.1 Ω
f	200 KHz	200 KHz

Three-coil wireless receiver with 112.5° deflection

Single coil wireless receiver with 112.5° deflection

Fig. 10. Comparison of magnetic flux parameters at different angles of single and three coils

From Fig. 11, we show that when the S transmit coil and the 1 receive coil deflect from 0 to 120 degrees, 2,3 receive coils rotate at the same angle with the rotation of 1 receive coil. The efficiency effect diagram of 1,2,3 receive coils move at the same time are given.

Fig. 11. Comparison of transmission efficiency between single and three coils at different angles

3. Experimental verification of three-coil receiving structure

From the experimental results, it can be seen that the receiving and transmitting waveforms of the three-coil structure, as shown in Fig. 12, which is the operation platform of the experiment.

The parameters of circuit components for the launch coil and 3 receive coils are shown in Table III. The experimental platform for three-coil wireless power transmission system is shown in Fig. 13.

Table III. Parameters of circuit components

	Launch coil	Receive three coils
$L_i/\mu\text{H}$	5.25	4.12
C_i/nF	0.19	0.24
R_i/Ω	0.2	0.15
f/KHz	200	200

Schematic diagram of transmitting coil waveform

Schematic diagram of receiving coil waveform

Fig. 12. Oscilloscope waveform

Fig. 13. Experimental platform for three-coil wireless power transmission system

It is obvious observed from Fig. 14 that under the three-coil receive structure, the receive efficiency of the multi-degree-of-freedom motor tends to be stable at different angles during the rotating process, and the voltage and current can be uniformly received by the receive coils at different angles, and when the deflection angle is large, the receive efficiency of the single-coil receive structure decreases obviously.

Schematic diagram of transmission efficiency of three-coil wireless charging device at different rotation angles

Schematic diagram of transmission efficiency of single coil wireless charging device at different rotation angles

Fig. 14. Comparison of transmission efficiency between single and three coils at different angles

4. Conclusion

This research provides a three-degree-of-freedom motor with a hollow spherical rotor. Its rotor is a hollow spherical shell. The hollow part can be equipped with wireless transmission device and visual image acquisition device. In order to realize wireless transmission of internal device of motor rotor, a novel three-coil receive coil structure suitable for its motion mode is designed. Compared with the traditional single coil receive structure. Multi-physical simulation is used to simulate the variation of S_{21} parameters of single coil and three-coil receivers for wireless power transmission. Driven by the motor rotor, the new three-coil structure rotates the receive coil from 0 to 120 degrees, and the transmission efficiency is very stable. It solves the disadvantage of angle deviation on efficiency in current research. The changes of magnetic flux, voltage and current of the receive coil when rotated from 0 to 120 degrees driven by the motor rotor are compared. The advantages of three-coil receive structure are obtained. Finally, the accuracy of the simulation and the effectiveness of power transmission are verified by experiments.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (51577048, 51877070, 51637001); Hebei Provincial Natural Science Foundation Project (E2018208155); Hebei Province Higher Education Science and Technology Research Key Project (ZD2018228); High-energy-saving Motor and Control Technology National and Local Joint Engineering Laboratory Open Project (KFKT201804); Hebei Province Graduate Innovation Funding Project (CXZZSS2019084).

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