A New Magnetic Coupling Mechanism for Patrol Robot Wireless Charging System

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Abstract. In this paper, a new magnetic coupling mechanism with Double-Layer-Double-D (DLDD) coil and nanocrystalline magnetic core is proposed for patrol robot wireless charging system. In comparison with the traditional magnetic coupling mechanism, the magnetic coupling mechanism proposed in this paper has higher magnetic induction intensity, lower magnetic leakage, higher coupling coefficient and better anti-offset ability. Hence, the efficiency of the wireless charging system can be improved. The organization of this paper is as follows. Firstly, the topological structure of the coil and magnetic core of the new magnetic coupling mechanism are introduced. Then, based on the working principle of the wireless charging system, the influence of the new magnetic coupling mechanism parameters on the transmitted power and efficiency of the wireless charging system is analysed. Moreover, in comparison with the conventional magnetic coupling mechanism, the electromagnetic properties of the two kinds of magnetic coupling mechanism are analysed and compared, including magnetic induction intensity, coupling coefficient and anti-offset ability, etc.

1. Introduction

Recently, for reducing the manpower and improving the patrol reliability, intelligent patrol robots have been widely used in many industries, such as chemical plant, transformer substation and coal mine [1-2]. As an indispensable part of the intelligent patrol robot, the charging systems of the intelligent patrol robots have attracted more and more attentions. Generally, the charging systems of the intelligent patrol robots can be divided into two categories, i.e. wired charging and wireless charging. For wired charging method, it has been popular used in the intelligent intelligent patrol robots due to the merits of simple structure and low cost. However, the potential hazards of the electric spark and inaccuracy docking inevitable exist in the wired charging systems [3-4]. Therefore, the wireless charging technology has been a hot research topic. Wireless charging technology reduces the line aging loss, electric spark and has the characteristics of flexible charging[5], especially suitable for the patrol robot. The structure diagram is shown in Figure 1. Robot wireless charging system mainly includes AC power supply, conversion module, magnetic coupling mechanism and rectifier filter circuit. Magnetic coupling mechanism includes coil and magnetic core, which is the core part of wireless charging system. The coil topology and magnetic core material determine the coupling coefficient and magnetic induction intensity of the magnetic coupling mechanism, thus affecting the efficiency and output power of the wireless charging system. In this paper, a new magnetic coupling mechanism is proposed which contains Double-Layer-Double-D(DLDD) coils and nanocrystalline magnetic core. The electromagnetic properties of the new magnetic coupling mechanism are analysed and compared by the use of Maxwell...
and Simpler, including magnetic induction intensity, coupling coefficient, anti-offset ability, and output characteristics.

Figure 1. The structure diagram of wireless charging system for patrol robot.

2. Analysis of Magnetic Coupling Mechanism

As shown in Figure 2, this paper proposes a new type of magnetic coupling mechanism which is composed of DLDD coils and nanocrystalline magnetic core. The structure of magnetic coupling mechanism is shown in Figure 2(a), and the explosion diagram is shown in Figure 2(b). The size of the magnetic core is 405*405mm and its thickness is 0.1mm. The number of coil turns is 20. The outer size of the transmitting coil and receiving coil is 400*400mm and the inner rectangle is 240*40mm. The transmission distance is designed as 150mm.

Figure 2. (a) Model diagram of magnetic coupling mechanism. (b) Magnetic coupling mechanism explosion diagram.

2.1. Double-Layer-Double-D(DLDD) Coils

DLDD coils has double layers and each layer is composed of two D type coils. In each layer, two D-shaped coils are connected in series, but in opposite directions. Because this connection creates two opposite poles on the surface of the coil, the coil becomes polarized. Due to the polarization phenomenon, compared with traditional circular and rectangular coils, DLDD coils have higher coupling coefficient and lower magnetic leakage[6-7]. DLDD coils combine the features of planar coils and helical coils. Since the current flow in each coil is the same, the mutual inductance of each coil is the same. The self-inductance and mutual inductance calculations of n-layer coils are shown in (1) and (2).

The inductance $L$ is:

$$L = L_1 + M_{12} + \cdots + M_{1n} + \cdots + L_n + M_{n1} + \cdots + M_{n(n-1)}$$

$$= L_1 + L_2 + \cdots + L_n + 2(M_{12} + \cdots + M_{1n} + M_{23} + \cdots + M_{2n} + \cdots + M_{n(n-1)})$$

(1)

The mutual inductance $M$ is:

$$M = M_{11} + \cdots + M_{1n} + M_{21} + \cdots + M_{2n} + \cdots + M_{nn}$$

(2)

2.2. Nanocrystalline Magnetic Core

In this paper, a new type of nanocrystalline material is used to replace the traditional Mn-Zn ferrite material as the magnetic core material. The performance comparison of the two magnetic materials is
shown in Table 1.

| Material name                          | nanocrystalline | Mn-Zn ferrite |
|----------------------------------------|-----------------|--------------|
| Magnetic permeability(μ)               | 16000±30%       | 2300         |
| Saturation magnetic induction intensity(T) | 1.35            | 0.51         |
| Residual magnetic induction intensity(T) | 0.81            | 0.306        |
| Coercive force (A/m)                   | 1.3             | 8.0          |
| Power consumption(W/kg)                | 3               | 17           |
| Density(g/cm³)                         | 7.4             | 4.9          |

Compared with the traditional Mn-Zn ferrite materials, nanocrystalline materials have extremely high magnetic permeability. The permeability is positively correlated with the coupling coefficient and transmission efficiency[8]. Therefore, using nanocrystalline material as the magnetic coupling mechanism of the magnetic core has higher magnetic induction intensity and larger coil coupling coefficient in the magnetic field generated by the coil, resulting in higher energy transmission efficiency. In addition, nanocrystalline materials have higher saturation magnetic induction intensity and lower residual magnetic induction intensity, which can effectively reduce the system operating frequency. Compared with Mn-Zn ferrite materials, nanocrystals have lower coercive force, so the hysteresis loss in the magnetic core is lower. Therefore, nanocrystalline material is used as the core material of magnetic coupling mechanism in this paper.

2.3. Theoretical Analysis of Wireless Charging

In this paper, mutual inductance model is adopt for modeling analysis, which avoids the complexity of analysis and is closer to the physical structure of coupler. In order to generate high frequency resonance, we choose SS compensation structure. The equivalent circuit diagram is shown in Figure 3.

The internal resistances of the primary and secondary coils are \( R_T \) and \( R_r \), the load impedance is \( R_L \), the compensating capacitances of the primary coil and secondary coil are \( C_1 \) and \( C_2 \), the self-inductances of the primary coil and secondary coil are \( L_T \) and \( L_r \) respectively, and the mutual inductance between the coils is \( M \). The current flowing through the primary and secondary coils are \( I_1 \) and \( I_2 \) respectively. \( U_1 \) represents AC power supply and \( R_1 \) represents internal resistance of power supply.

![Figure 3. The circuit diagram of wireless charging system for patrol robot.](image)

When the frequency of AC power supply is \( f = \omega / 2\pi \), the circuit voltage equation can be listed by Kirchhoff's Law:

\[
\dot{U}_1 = \left( R_t + j \omega L_t - j \frac{1}{\omega C_1} \right) \dot{I}_1 + j \omega M \dot{I}_2 \tag{3}
\]

\[
0 = \left( R_r + j \omega L_r - j \frac{1}{\omega C_2} \right) \dot{I}_2 + j \omega M \dot{I}_1 \tag{4}
\]

From (3) and (4):
The load power can be obtained as follows:

\[
P_L = \left| I_2 \right|^2 R_L = \frac{U_1^2}{R_L + R_r} \cdot R_L \frac{R_L}{R_L + R_s} \frac{k^2 Q_1 Q_2}{1 + \frac{k^2 Q_1 Q_2}{Q_2}}.
\]

(6)

Where, \( k \) is the coupling coefficient, \( k = \frac{M}{\sqrt{L_1 L_2}} \); \( Q_1 \) and \( Q_2 \) are quality factors for primary and secondary coils, \( Q_1 = \omega L_1 / (R_s + R_r) \), \( Q_2 = \omega L_2 / (R_s + R_r) \).

The system efficiency is:

\[
\eta = \frac{P_L}{P_r} = \left| \frac{I_2}{I_1} \right|^2 \frac{R_L}{R_L + R_s} \frac{k^2 Q_1 Q_2}{1 + \frac{k^2 Q_1 Q_2}{Q_2}}.
\]

(7)

According to (4) and (5), the larger \( k^2 Q_1 Q_2 \) is, the higher the system output power and efficiency will be. Therefore, the coupling coefficient and quality factor of magnetic coupling mechanism have important influence on the output power and efficiency of wireless charging system. According to (1) and (2), due to the use of DLDD coil and nanocrystal material, the magnetic coupling mechanism proposed in this paper has higher self-inductance, stronger magnetic field strength, and higher magnetic coupling coefficient and quality factor than traditional couplers, so it can realize power transmission with higher power and higher efficiency.

3. Analysis and comparison of electromagnetic performance

In this section, the electromagnetic performances of the proposed magnetic coupling mechanism using DLDD coil and nanocrystalline materials are investigated and compared to that of the conventional one in terms of magnetic field distribution, coupling coefficient and output power. In order to have a reasonable performance evaluation, the coil turns, coil spacing, core thickness, Leeds wire diameter and other important parameters of the two electromagnetic couplers are kept the same for the two magnetic coupling mechanisms.

Figure 4 compares the traditional and new magnetic coupling mechanism which is more suitable for the wireless charging. The DLDD coil and SLDD coil with nanocrystalline material as the core are named as magnetic coupling mechanism A and magnetic coupling mechanism B respectively, and the traditional SLDD coil with Mn-Zn ferrite as the core is named as magnetic coupling mechanism C. The structure of each magnetic coupling mechanism and corresponding magnetic field intensity distribution diagrams of the coils are shown as follows.
Figure 4. Magnetic coupling mechanism structure and magnetic field intensity distribution diagram. (a) Structural diagram of magnetic coupling mechanism A. (b) Magnetic field intensity distribution of magnetic coupling mechanism A. (c) Structural diagram of magnetic coupling mechanism B. (d) Magnetic field intensity distribution of magnetic coupling mechanism B. (e) Structural diagram of magnetic coupling mechanism C. (f) Magnetic field intensity distribution of magnetic coupling mechanism C.

According to the simulation results of magnetic coupling mechanism B and C, when the coil type and core thickness are the same, the nanocrystalline material significantly enhances the magnetic induction strength between coils, reduces magnetic leakage, and optimizes the magnetic field distribution. Comparing the distribution of magnetic field intensity between magnetic coupling mechanism A and B, the results show that the magnetic field intensity produced by magnetic coupling mechanism A is much greater than that of magnetic coupling mechanism B because the adoption of DLDD coil improves the mutual inductance and coupling coefficient of coil.

Through the Maxwell parameter scanning, the anti-offset ability of the above three magnetic coupling mechanisms is studied. As shown in the Figure 5, magnetic coupling mechanism A has the best anti-offset ability and the highest coupling coefficient. The coupling coefficient of the magnetic coupling mechanism B is lower than that with the magnetic coupling mechanism A. The magnetic coupling mechanism C has the minimum coupling coefficient and the worst anti-offset ability. Therefore, we can draw the conclusion that the nanocrystalline material can increase the coupling coefficient of the coil more than the Mn-Zn ferrite material, so that the wireless charging coil has a better anti-offset ability.
4. Conclusion

In this paper, a novel magnetic coupling mechanism for patrol robot is proposed. Theoretical analysis shows that the magnetic field strength and coupling coefficient are improved by using DLDD coil and nanocrystalline material. In comparison with the conventional magnetic coupling mechanism, the new magnetic coupling mechanism has higher electromagnetic induction intensity, less magnetic leakage, higher coupling coefficient and stronger anti-offset ability, which is suitable for wireless charging of robot.

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