Wheely Coupler for EV Wireless Charging

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Abstract: Wireless power transfer is a popular charging method for future EVs. However, it is difficult for alignment because receive coil is usually placed at the bottom of vehicles and it is hard to get its exact location when charging. Therefore, to make receive coil visible and convenient for alignment, wheely coil has been proposed that can be embedded in the wheel hub. Half scale model has been analyzed in this paper. Experiment results show that it can achieve transfer efficiency of 85.13% when transfer distance is 50 mm.

1. Introduction

Misalignment is one of major problems for WPT in EV charging because the transmit coil is suited in the ground and receive coil is placed under the car. Therefore, it is difficult for drivers to find the concrete parking position of the highest transfer efficiency.

Many researches had been done about new charging couplers, such as in-wheel WPT system. Power can be transferred through tire and wheel and its mutual inductance model had also been proposed [1]. A non-magnetic non-resonant wireless power transfer scheme to vehicles during in motion had been proposed, which can power EVs even while running [2]. A magnetic coupler structure for an in-wheel WPT system for EV application had been proposed, in which receive coil was fixed in the tire and transmit coil was buried in the road [3]. However, there were only simulation results in these researches, and experiment was not conducted because of its implement hardness.

2. Wheely Coil Formation

To make receive coil visible and convenient for alignment, a wheely coil that can be embedded on the surface layer of wheel hub has been proposed. Like traditional wireless charging coupler, it is also consisted of copper coil, ferrite, as well as shielding material. As shown in Figure.1, the outermost layer is UTZ shell made of insulation material that can fix wheely coil in the hub to prevent it from falling off when rotating. The hub with wheely receive coil is shown in Figure.2.

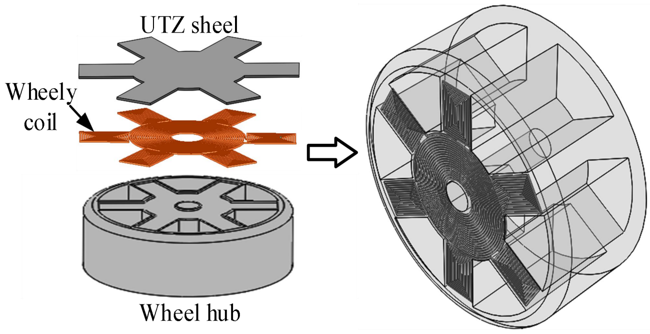


Figure 1: Formation of wheely coupler.

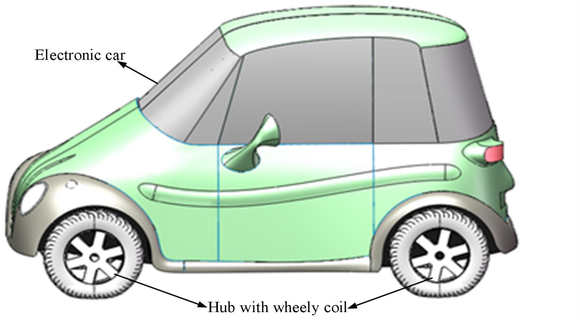
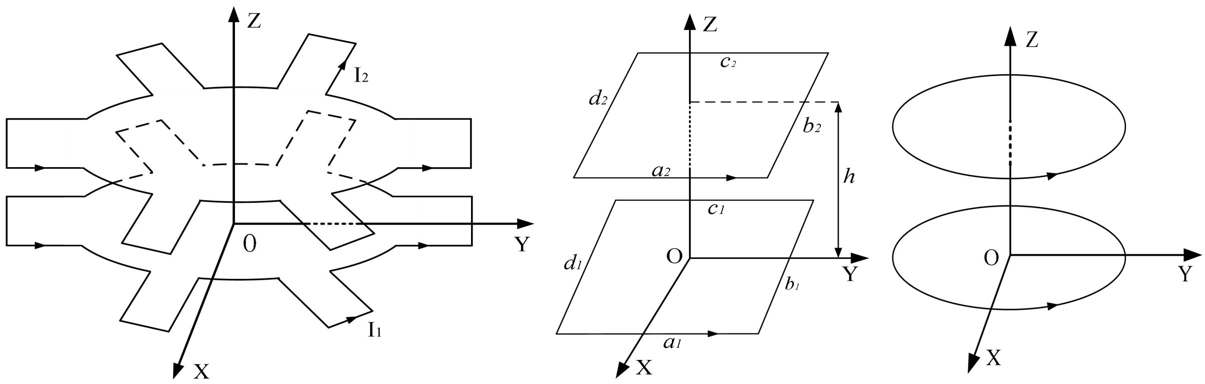


Figure 2: Formation of wheely coupler.

3. Mutual Inductance of Wheely Coupler

The most important consideration of coupler design is how to increase its mutual inductance to assure satisfying charging performance, like transfer high efficiency. The mutual inductance of wheely coupler could be regarded as the combinations of mutual inductance of circle part and rectangular parts. One single turn of wheely coil has been taken as a research object in this paper. Diagram for mutual inductance calculation of wheely coupler is shown in Figure 3.



(a) Wheely coil (b) Rectangular coil (c) Circular coil

Figure 3: Diagram for mutual inductance calculation for wheely coupler.

According to Neumann's formula [4], mutual inductance of circle part could be derived as,

$$M_{\text{Cir}} = \frac{\psi_{21}}{I_1} = \frac{\mu_0}{4\pi}\int_{l_1}\int_{l_2}\frac{\mathrm{d}l_1 \cdot \mathrm{d}l_2}{D}$$
$$= \frac{\mu_0}{4\pi}\int_0^{2\pi}\int_0^{2\pi}\frac{r_1 r_2 \cos(\varphi_1-\varphi_2)\mathrm{d}\varphi_1\mathrm{d}\varphi_2}{D} \tag{1}$$

Mutual inductance of conductor a1 and a2 in Figure.3(b) is,

$$M_{a_1a_2} = \frac{N_1N_2\mu_0}{4\pi}\iint_{a_1a_2}\frac{da_1 \cdot da_2}{|a_1-a_2|}$$
$$= \frac{N_1N_2\mu_0}{4\pi}\int_{-\frac{a_1}{2}}^{\frac{a_1}{2}}\int_{-\frac{a_2}{2}}^{\frac{a_2}{2}}\frac{dxdy}{\sqrt{(x_2-x_1)^2+(y_2-y_1)^2+h^2}} \tag{2}$$

Furthermore, the mutual inductance of rectangular part could be derived as,

$$M_{\text{Rec}} = N_{\text{Rec}}(M_{a_1a_2} + M_{a_1c_2} + \ldots + M_{d_1d_2} + M_{d_1b_2}) \tag{3}$$

N_{Rec} represents the number of turns of rectangular part. Therefore, mutual inductance of wheely coupler is,

$$M = M_{\text{Cir}} + M_{\text{Rec}} \tag{4}$$

4. Wheely Coil Design

Wheely coil is embedded in the surface layer of wheel hub, so its parameter should be basically decided according to the parameters of aluminum alloy hub, especially the diameter of wheel hub. Usually, there are several kinds of wheel hubs used in vehicles, and their diameters have been listed in Table 1.

Table 1: Diameters of common wheel hubs.

Inch	14	15	16	17	18
Diameter/mm	355.6	381	406.4	431.8	457.2

In this paper, the wheel hub with diameter of 16 inch has been chosen as a design reference. What's more, half scale model of wheely coil has been shown in Figure 4 and its parameters have been shown in Table 2.

Table 2: Parameters of wheel coil.

Symbol	Parameter	Value
r	Inner radius	15 mm
R	External radius	53 mm
NCir	Turns of circle part	20
DL	Longer side	45 mm
DS	Shorter side	32 mm
NRec	Turns of rectangular part	8

In Figure 4, R and r represent the outer diameter and inner diameter of circle part, respectively. DL and DS represent the longer side and shorter side of rectangular part, respectively.

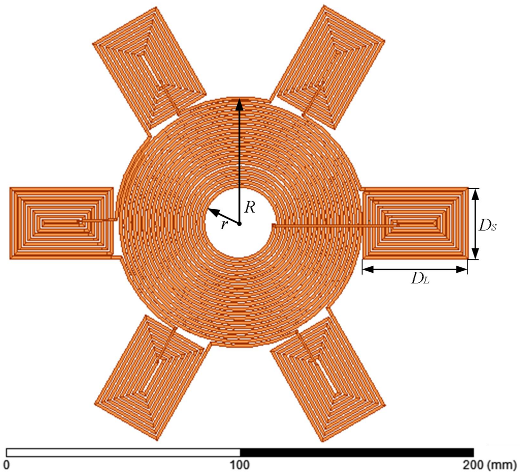


Figure 4: Half scale wheely coil model.

5. Magnetic Core Design

Increasing mutual inductance is of great significance for improving transfer efficiency and adding magnetic ferrite is a suitable choice to some extend. As shown in the Figure 5, coupler without magnetic core has lowest mutual inductance and coupler with double magnetic core on both transmit and receive side has the highest mutual inductance among three situations. Subsequently, four magnetic core types for wheely coupler have been proposed. As shown in Figure 6 (a) is the flat wheely magnetic core, (b) is the flat wheely magnetic core with a central hole, (c) is the stripe and rectangular shape combination magnetic core, (d) is the stripe shape magnetic core. Anti-offset ability in these four situations has been analyzed by using finite software. Their mutual inductance verses offset is shown in Figure 7.

Figure 7 (a) is mutual inductance verses axial offset. It can be found that, mutual inductance has a decreasing tendency as axial offset increase. It declines dramatically when axial offset changes from 20 mm to 40 mm. Figure 7 (b) is mutual inductance verses radial offset. Similarly, it can be seen that mutual inductance has a decreasing tendency as axial offset increase. Coupler with type (a) magnetic has the best anti-offset performance, while type (d) has an unsatisfying anti-offset performance. In this paper, type (c) is chosen for further analysis.

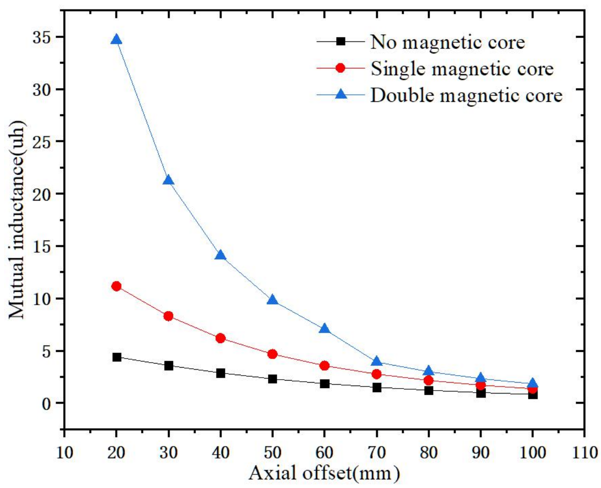
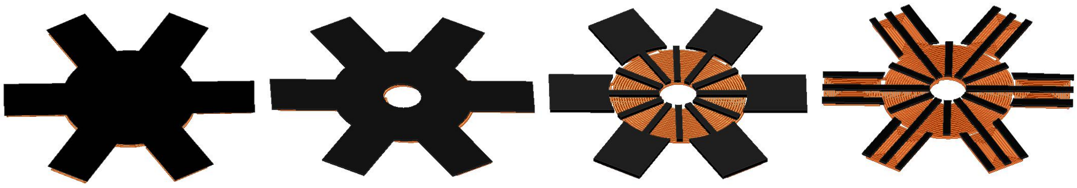
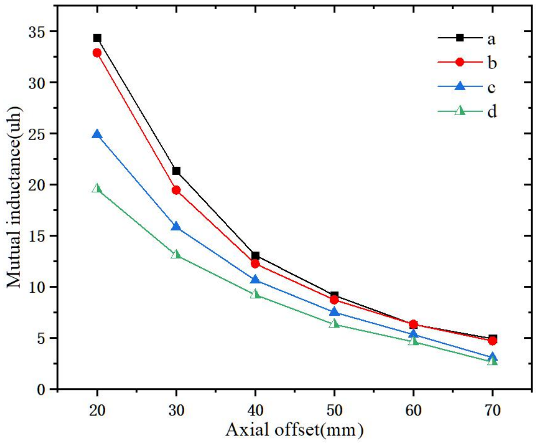


Figure 5: Mutual inductance verses axial offset.

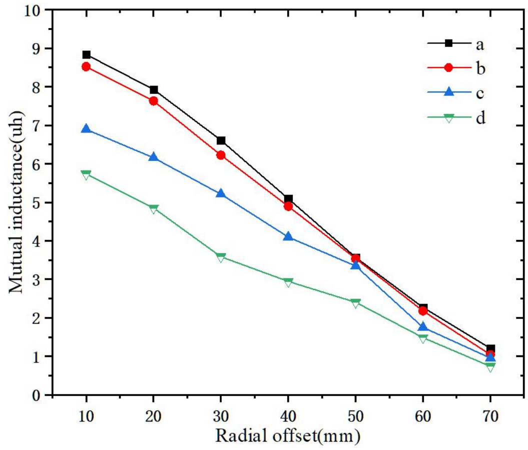


(a) (b) (c) (d)

Figure 6: Four magnetic core types.



(a)



(b)

Figure 7: Comparison of four magnetic core:(a) mutual inductance verses axial offset, (b) mutual inductance verses radial offset.

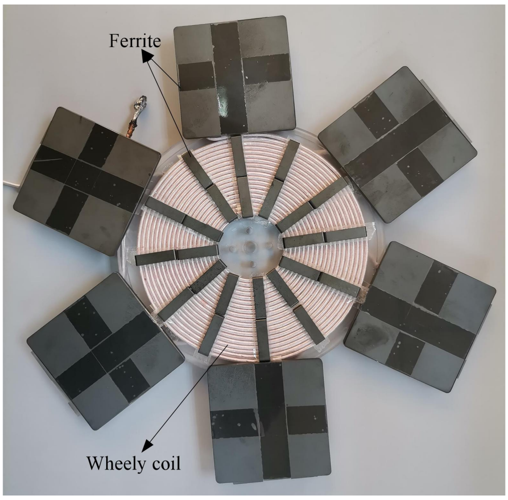


Figure 8: Wheely coil.

6. Experiment Verification

In this paper, a laboratory prototype for wheely coupler WPT system has been fabricated to validate its charging characteristics. Experiment platform is presented in Figure 9, and more details about experimental platform's parameters are presented in Table 3. In the experiment, frequency is set 100 kHz, and self-inductance of transmit and receive coil are 53.67 μh and 52.27 μh, respectively. Figure 10 shows the transfer efficiency versus axial and radial offset. Figure 10(a) shows the transfer efficiency versus axial offset. It can be seen that transfer efficiency increases firstly, reaching highest point at axial offset of 30 mm and 40 mm with efficiency of 88.5%, then it begins to decline from point 40 mm to 70 mm. The transfer efficiency is up to 85% when axial distance is 50 mm. Figure 10(b) represents the transfer efficiency versus radial offset when axial distance is 50 mm. The transfer efficiency has a relative moderate declining trend when radial offset changes from 0 mm to 40 mm, which means wheely coupler has certain anti-offset ability when radial offset happens. Besides, transfer efficiency is over 80% when the radial offset is within 40 mm.

Table 3: Parameters of experiment platform.

Symbol	Parameter	Value
f	Frequency	100 kHz
Lp	Self-inductance of transmit coil	53.67 μh
Cp	Tuning capacitor of transmit coil	47.19 nF
Ls	Self-inductance of receive coil	52.27 uh
Cs	Tuning capacitor of receive coil	48.46 nF
M	Mutual inductance	8.62 μh

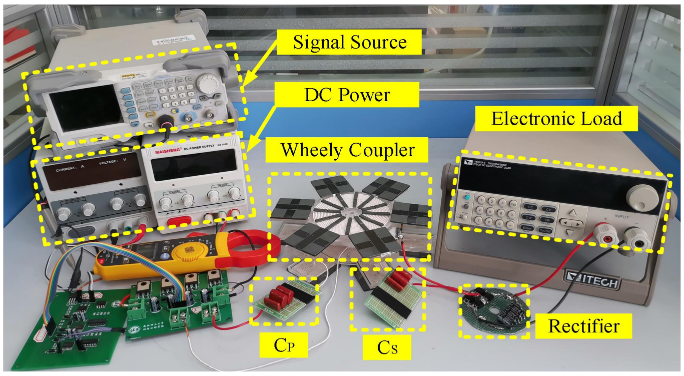
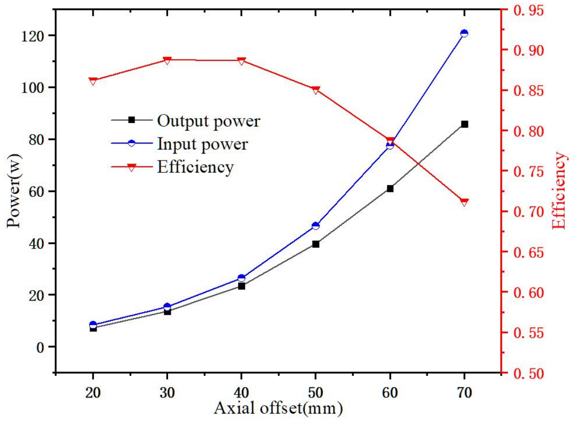
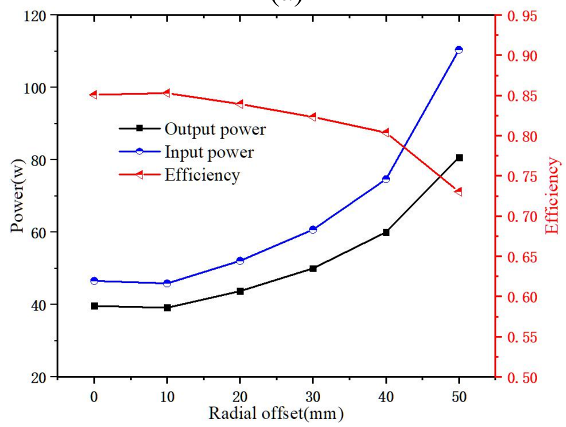


Figure 9: Experiment platform.



(a)



(b)

Figure 10: Transfer efficiency versus offset. (a) axial offset; (b) radial offset.

7. Conclusions

In this paper, a new coil formation, wheely coupler, has been proposed for EV wireless charging to overcome the difficulty for alignment when charging. Mutual inductance of its half scale has been deduced theoretically based on the model of rectangular and circle coupler. Besides, its anti-offset ability on radial, axial direction has also been analyzed. Finally, a corresponding experiment platform has been fabricated to verify its effectiveness. Experiment results show that it can realize transfer efficiency of 85.35% when transfer distance is 50 mm and it has relative stable transfer efficiency when radial offset is within 40 mm..

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