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Influence of Road Material and Contamination with Dynamic Wireless Power Transfer to In-wheel Coil

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Abstract Wireless power transfer (WPT) for Electric Vehicles (EV) becomes a popular topic nowadays. Dynamic wireless power transfer (DWPT) is proposed because it could charging through running, solving the inconvenience that long charging time for EV. There is a new method for DWPT has been proposed in our lab, which making wireless power transfer through the tire. Besides, embedded coils in road also be paid attention in WPT system. It is necessary to evaluate the influence of embedded materials and coils in WPT system.

Key words Electric vehicles, wireless power transfer, road material, wireless in-wheel motor

1 Introduction

In recent years, each country has become more interested in environmental issues including global warming, and various policies have been implemented. Among them, electric vehicles (EVs), which are said to contribute to the reduction of greenhouse gases including carbon dioxide (CO_2), are attracting a lot of attention [1]. However, electric vehicles that have merits such as being eco-friendly and having high controllability have not been spread as much as expected. The major factors are short cruse distance and long charging time [2]. As a solution to this problem, an increase in the capacity of the battery is mainly considered, but there are problems such as a reduction in fuel consumption and an increase in cost due to an increase in weight. Therefore, the idea of the Dynamic wireless power transfer(DWPT) has been attracting attention [3].

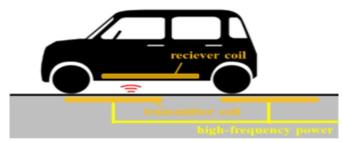
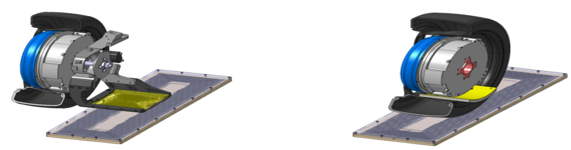


Figure 1: Conventional body side receiver coil.



(a) Out-wheel coil (b) In-wheel coil

Figure 2: Image of wheel-side coil.

2 Target System

Conventional body side receiver coil is shown in Fig. 1. It has the demerit that long air gap will cause loss of efficiency. Because the air gap will change by the body weight or road unevenness, and that will cause non-robustness in the system [4]. In our lab, wireless power transfer through tire to the 3rd In-Wheel Motor(IWM-3) was proposed as can be seen in Fig. 2 [5].

Conventional way for array of transmitter coils on the road is to put the coils on the surface with covers. Although, it will cause the problem that coils will stick out from ground making it dangerous. Moreover, the pad is exposed in air, so it will be damaged easily [6]. There proposed the embedded coils in road with cheap material, such as the asphalt and concrete pavement. However, how will these materials affect WPT system is uncertain. Therefore, it is necessary to evaluate the influence of road materials in WPT system.

3 Principle

WPT system conducts the power transmission using electromagnetic induction. Magnetic field is generated when AC voltage is applied to the transmitter coil. It passes through the receiver coil and induced current is generated. In this research, we use magnetic resonance coupling that is efficient and robust against misalignment of coils because of the LC resonance. Fig. 3 presents the Series-Series circuit topology of magnetic resonance coupling.

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{1}$$

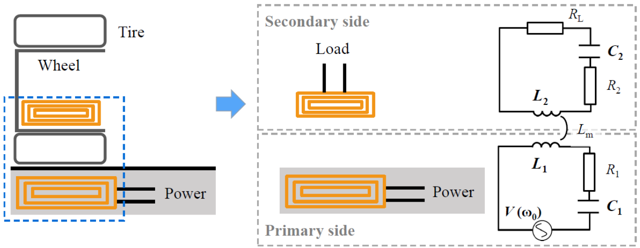


Figure 3: S-S circuit topology in magnetic resonance coupling.(The tire and wheel rotates, but the coil doesn't rotate.)

Here ω_0 is the resonance angular frequency, L is the self-inductance, and C is the capacitance. The subscripts 1 and 2 mean the primary (transmitter coil) and secondary sides (receiver coil), respectively. Target frequency, which also means resonant frequency, is set at 85 kHz. This frequency is satisfied with SAE J2954, which designed the target frequency of stationary wireless power transfer for electric vehicles.

$$\eta_{\max} = \frac{(\omega_0 L_m)^2}{\{\sqrt{R_1 R_2} + \sqrt{R_1 R_2 + (\omega_0 L_m)^2}\}^2} \tag{2}$$

This equation explain the maximum transmission efficiency when the topology is totally resonance. Here R represents internal resistance of the coils. Besides, L_m is the mutual inductance, which represents strength of magnetic coupling. When there are eddy current loss between two coils, it will reflect in $R_{1/2}$ that it will increase. Furthermore, when coupling between coils change, L_m will change. As a result, L_m and $R_{1/2}$ are important parameters to evaluate WPT system.

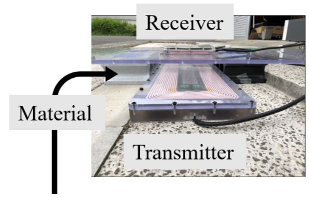
However, resonance frequency mismatch is taken into account when there are contamination between coils. In other words, the imaginary part of impedance in secondary side is not 0. Power transmission only considers the effective power actually consumed. Therefore, when calculating power, only the real part of the complex power is related to efficiency. Above all, we derive the formula for efficiency when resonance does not match as follow: [7]

$$\eta = \frac{(\omega_0 L_m)^2 R_L}{\{(R_2+R_L)^2 + \left(\omega_0 L_2 - \frac{1}{\omega_0 C_2}\right)^2\} R_1 + (\omega_0 L_m)^2 (R_2 + R_L)} \tag{3}$$

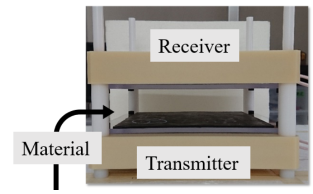
By taking derivatives of Eq.(3) with respect to R_L, the optimum load resistance R_{Lopt} that maximize the efficiency η, can be found as follows:

$$\left.\frac{\partial \eta}{\partial R_L}\right|_{R_L = R_{Lopt}} = 0 \tag{4}$$

$$R_{Lopt} = \sqrt{R_2^2 + \frac{R_2}{R_1}\omega_0^2 L_m^2} \tag{5}$$



(a) Full model



(b) Small model

Figure 4: Images of two experiments.

(a) Asphalt slab

(b) Concrete slab

Figure 5: Model of road pavement materials.

Materials are placed between coils to evaluate the influence on WPT as shown in Fig. 4. Next, we connect coils to LCR Meter, measuring parameters of WPT system. We measure the inductance and resistance of coils, and also the mutual inductance L_m at first. Then using the equation as follow to calculate the coupling coefficient k, which is affected by the relative position and permeability between the coils.

$$k = \left(L_{\mathrm{m}}/\sqrt{L_1 L_2}\right) \tag{6}$$

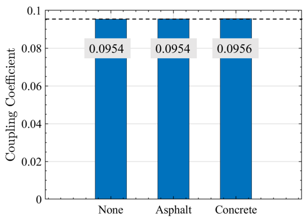
Moreover, there is the quality factor Q, which represents the strength of resonance, and determined by the equivalent loss of material placed between coils and the coil design, such as the turns and the pitch distance.

$$Q_{\mathrm{i}} = \frac{\omega_0 L_{\mathrm{i}}}{R_{\mathrm{i}}} \quad (\mathrm{i} = 1, 2) \tag{7}$$

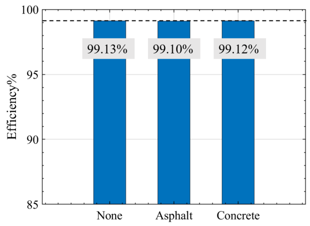
4 Evaluating of Road Material

Fig. 5 shows the model of asphalt pavement and concrete pavement, whose sizes are same with 300 mm×300 mm×50 mm, and we insert them between coils. The size of transmitting coil is 1000 mm×250 mm, and size of receiving coil is 185 mm×185 mm. The inductance of transmitting coil is 233.6 µH, and resistance of it is 62.5 mΩ; the inductance of receiving coil is 97.4 µH, and resistance of it is 18.0 mΩ.

The experiment results at 85 kHz are shown in Fig. 6. According to the Fig. 6, k and η hardly changed with different



(a) Coupling coefficient



(b) Coil efficiency

Figure 6: Calculation result of parameter measurement of road materials in full model.

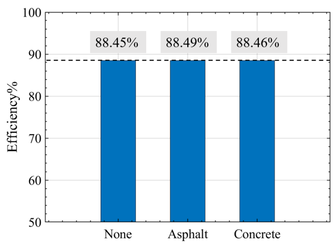


Figure 7: Coil efficiency during actual power transfer in full model.

road materials. Moreover, this is also in line with the design of k to exceed 0.09 requirements. Therefore, considering that the theoretical maximum efficiency is expressed by Eq.(2), the asphalt pavement and concrete pavement does not affect the transmission efficiency in WPT system.

The condition of power transfer experiment is that the input voltage V_{in} is 200 V, and output voltage V_{out} is 140 V. Also air-gap is set to 90 mm, in which the thickness of materials is 50 mm. Moreover, frequency f is set to target frequency, as know as 85 kHz.

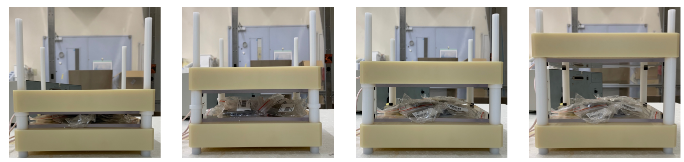
Fig. 7 shows the influence of the road materials on transmission efficiency. It indicates that the η hardly changed with different materials between coils at 85 kHz, which agrees with the result of Fig. 6. In conclusion, contaminants which was worried to affect the system are unlikely to do harm to the system.

5 Evaluating of Contamination

5.1 Evaluate coils of small model

In order to evaluate the affect of contamination, we put contamination materials into an acrylic box. Then we insert the contamination materials between coils. The size of the acrylic box is 155 mm×155 mm, and the size of transmitting coil and receiving coil are same with 100 mm×100 mm. The inductance of transmitting coil is 18.7 μH, and resistance of it is 36.5 mΩ; the inductance of receiving coil is 19.1 μH, and

Figure 8: Contamination: sand iron.



(a) 25mm air-gap (b) 45mm air-gap (c) 55mm air-gap (d) 90mm air-gap

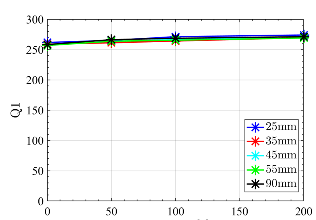
Figure 9: Different air-gaps in the small model.

resistance of it is 40.6 mΩ. Sand iron is the example of contamination materials in road construction, that is shown in Fig. 8.

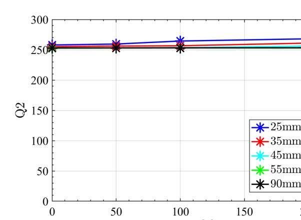
5.2 Test result in various air-gaps

First we measure coil parameters with different air-gaps. As shown in Fig. 9, when the air-gap is getting longer, the distance between material and secondary coil will get longer. According to Eq.(7), we measure inductance and resistance of each coil and the quality factor of them. From Fig. 10, neither various air-gaps nor different amount of contamination could affect Q_1 and Q_2.

Then, we calculate difference of k and η when the contamination is set to 200g with various air-gaps, using measured parameters before. From Eq.(6), we can get the coupling coefficient k. According to Eq.(1) and (5), the nominal secondary side capacitor C_{2nom} and the optimal load resistance, that makes the maximum efficiency, R_{Lopt} can be known. The condition of resonance frequency is used when there are no contamination between coils. On the other hand, we calculate

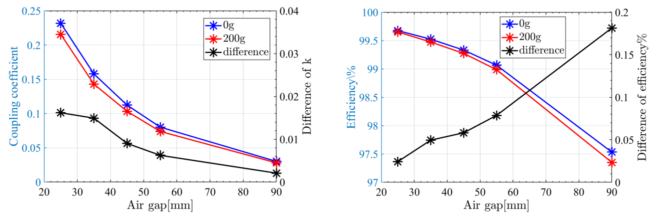


(a) Q_1



(b) Q_2

Figure 10: Quality factor of coils with different air-gap in small model.



(a) k in small model

(b) Estimated coil efficiency with k of small model and coil parameters of full model

Figure 11: Difference of k with different air-gaps in small model and estimation of η with full model.

the efficiency with contamination considering the resonance frequency mismatched condition. Therefore, the efficiency in the condition of various air-gaps and different contamination is able to be calculated. Under each air-gap condition, R_{Lopt} and C_{2nom} at 0g sand iron were calculated, and the efficiency with various conditions is estimated due to the change in sand iron amount.

In Fig. 11, the blue line and red line corresponds to the left axis, the black line which represents the difference corresponds to the right axis.

As shown in Fig. 11(a), sand iron could affect the coupling coefficient which decreases with contamination and difference of k decreased with increasing of air-gap. However, it shows that if there is some air-gap over 50mm, there is no affect for the WPT system. Therefore, when performing obstacle detection or maximum efficiency control performed by performing k estimation, it is clear that it is better to maintain a certain air-gap to eliminate influence of k caused by air-gap change. Moreover, if k is bigger than 0.1, the coil efficiency in the full model will get more over 99%. From Fig. 11(a) we can make a conclusion that despite the presence of sand iron, the condition of k is bigger than 0.1 can also be satisfied below 50mm air-gap.

From Fig. 11(b), we can find that the efficiency will decrease when sand iron is placed between coils. One of the reason is that the contamination leads to resonance frequency mismatched because sand iron affects the inductance and resistance of coils. Furthermore, the effect is more obvious at long air-gaps from the result. It confirms that sand iron will do harm to the WPT system, so it is necessary to consider the effect of sand iron when design the system. Besides, the system efficiency of 95% can be achieved when the coil efficiency exceeds 99%. [8]

6 Conclusion

In this paper, we evaluated how will the road materials and contamination in road construction affect WPT system. In result, asphalt and concrete has no impact with WPT system, those are good material which could be used to coil embedment. Furthermore, we found that sand iron will affect inductance and resistance when it close to the coil. Besides, sand iron could do harm to coupling coefficient and efficiency of the system, because it leads to resonance frequency mismatched. Since it affects the coil parameters and WPT system, it is necessary to consider the effect of sand iron when designing the system.

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