Influence of Contamination Between Receiver Coil and Embedded Transmitter Coil for Dynamic Wireless Power Transfer System

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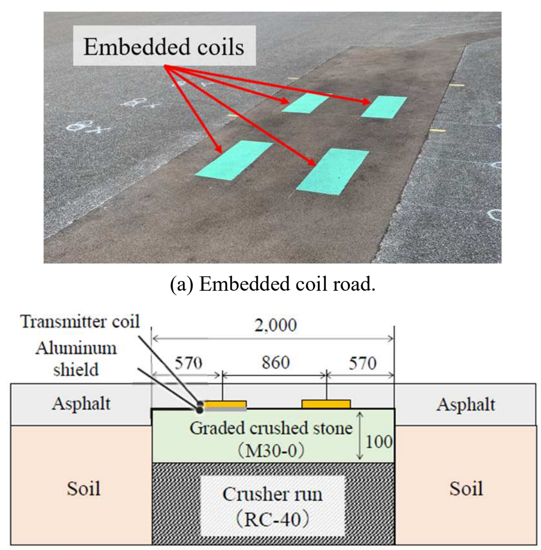
***Abstract*—Embedded coils into road pavement are applied to dynamic wireless power transfer (DWPT) that coil arrangement is different from static WPT system. Contamination easily enters the road pavement between the coils. Therefore, it is necessary to clarify the effect of contamination on the efficiency of DWPT. Coil parameters and theoretical efficiency have been evaluated by an LCR meter. Furthermore, WPT system efficiency has been evaluated by a power transmission experiment. Iron sand, which is the effective contamination in road construction, affects coil parameters causing a 0.14% reduction of maximum efficiency. Moreover, remained seawater and rainwater decrease the AC-to-AC efficiency by 0.93% and 0.6%, respectively. In addition, remained waters change the resonance frequency of the system.**

Keywords—Electric vehicle, Dynamic wireless power transfer, Embedded coils, Contamination.

I. 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 (EV), which can contribute to reducing greenhouse gases including carbon dioxide, are attracting a lot of attention [1][2]. 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 cruising distance and long charging time[3]. As a solution to this problem, an increase in the capacity of the battery is mainly considered, however, there are problems such as a reduction in consumption and an increase in cost due to an increase in weight. Therefore, dynamic wireless power transfer (DWPT) has been proposed [4][5].



(a) Embedded coil road.

(b) Cross section view of road construction.

Fig. 1. Embedded coil road in our lab experiment spot.

Static wireless power transfer has been standardized, as SAE J2954 shows [6], however, there is no clear standardization on the DWPT system. Target frequency, which also means resonant frequency, must remain in the range of 79.00 to 90.00 kHz. This frequency is satisfied with SAE J2954, which designed the target frequency of wireless power transfer for electric vehicles. Besides, from SAE J2954, coil arrangement of static WPT system is placing the transmitter coil on the road pavement or

TABLE I. SPECIFICATIONS OF EXPERIMENT COILS

	Transmitter coil	Receiver coil
Embedded coil length[mm]	868	230
Embedded coil width[mm]	338	230
Bench coil length[mm]	100	100
Bench coil width[mm]	100	100
Sinking coil length[mm]	150	
Sinking coil width[mm]	150	

embedded into road pavement, applying one coil transfer power to one vehicle, such as the parking lot. On the other hand, the transmitter coil in the DWPT system is set in the public road, avoiding collision with the vehicles.

This research focuses on the effect of the surrounding environment of the transmitter coils. Iron sand is one of the most common and effective contaminations for the DWPT system in road construction [7]. Besides, seawater and rainwater are easily flowing through or remained on the road pavement. This work is clarifying the effect of contamination existing in road pavement on the efficiency of the DWPT system.

Dynamic wireless power transfer system with embedded coils is introduced in Section II. Besides, evaluation of contamination with bench test is introduced in Section III. In addition, evaluation of remained rainwater and seawater on the embedded coils is introduced in Section IV.

II. TARGET SYSTEM

In our research group, the coils designed for DWPT have been embedded as shown in Fig. 1. The specifications of embedded coils are shown in TABLE I.

In this paper, the DWPT system using magnetic resonance coupling to EV charging named the third-generation wireless in-wheel motor (WIWM-3) [8] has been considered. Fig. 2 presents the DWPT system for WIWM-3.

The maximum efficiency of system η_{max}, and the optimum load resistance R_{Lopt} that maximize η, can be found as follows[9]:

$$\eta_{max} = \frac{(\omega_0 L_m)^2}{\left\{\sqrt{R_1 R_2}+\sqrt{R_1 R_2+(\omega_0 L_m)^2}\right\}^2} \quad (1)$$

$$R_{Lopt} = \sqrt{R_2^2 + \frac{R_2}{R_1}\omega_0^2 L_m^2} \quad (2)$$

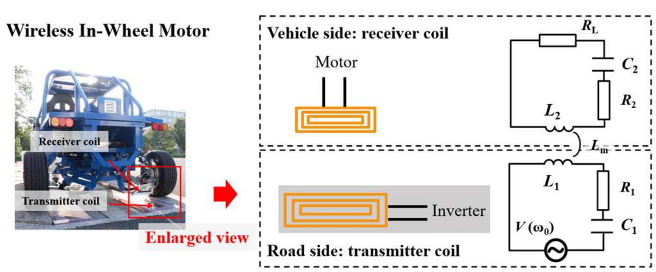


Fig. 2. WPT system applied in wireless in-wheel motor.

Here L_m represents the mutual inductance. ω_0 represents the resonance frequency angle. Besides, The maximum efficiency of system η_{max} can be written as follows:

$$\eta_{max} = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)^2} \quad (3)$$

Here k represents the coupling coefficient, which is affected by the relative position and permeability between the coils. Q represents the strength of resonance and is determined by the equivalent loss of material placed between coils and the coil design, such as the turns and the pitch distance. The equation of k and Q is as follows[10]:

$$k = \frac{L_m}{\sqrt{L_1 L_2}} \quad (4)$$

$$Q_i = \frac{\omega_0 L_i}{R_i} \quad (i = 1 or 2) \quad (5)$$

Resonance frequency mismatch is taken into account when there is contamination between coils. In other words, the imaginary part of impedance on the secondary side is not 0. Power transmission only considers the effective power 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 follows [9]:

$$\eta = \frac{(\omega_0 L_m)^2 R_L}{\left\{(R_2+R_L)^2+\left(\omega_0 L_2-\frac{1}{\omega_0 C_2}\right)^2\right\}R_1+(\omega_0 L_m)^2(R_2+R_L)} \quad (6)$$

Therefore, how will those contaminations affect the DWPT system with embedded coils should be considered.

III. EVALUATION FOR INFLUENCE OF CONTAMINATION IN BENCH TEST

To figure out how will contamination which is easy to enter the road pavement influence the DWPT system, the authors have done the bench test of contamination at first.

A. Evaluated contamination

Lots of road construction materials, such as iron sand and sand, are easy to enter road pavement. Besides, Japan is a rain-rich country, and the rainy season is long. Rainwater that entering the road construction on rainy days impact on the embedded coils has to be considered. Moreover, Japan is a coastal country with many coastal roads. Remained seawater in coastal road effect on the embedded coils also has to be considered. In this work, we use tap water to simulate the rainwater. Seawater has been simulated with marine salt melting in tap water.

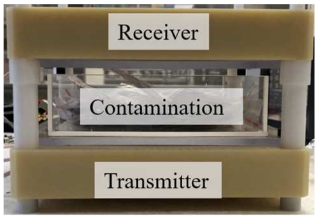


Fig. 3. Contamination evaluation coils.

B. Methodology

Fig. 3 shows coils that are used to evaluate the impact of common contamination which is easy to enter road pavement such as iron sand, sand, water, and seawater. To evaluate the effect of contamination, we put contamination into an acrylic box and the box is inserted between coils, on the surfaces of the transmitter coil. The size of the acrylic box is 155 mm × 155 mm. The specifications of bench test coils are shown in TABLE I.

The nominal air gap is set to 50 mm. Contamination is placed between coils that are connected with the LCR meter, and their inductance, resistance, and mutual inductance L_m are measured at first. Moreover, coupling coefficient k is calculated by measured parameters. Afterward, the efficiency η of the system is calculated, which is an important parameter, to evaluate how will materials affect the WPT system.

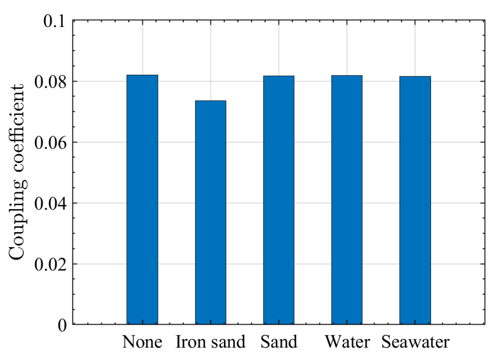
C. Result

Coil's inductance and resistance measurement when different contamination are placed between coils has been operated. Fig. 4 shows the result of parameter measurement of different contamination. In conclusion, contamination such as sand, rainwater, and seawater has less effect on the coupling coefficient of coils and efficiency of the system. However, iron sand decreases the coupling coefficient and efficiency. In addition, the impact of iron sand on coupling coefficient and theoretical transmission efficiency in different airgaps has been evaluated.

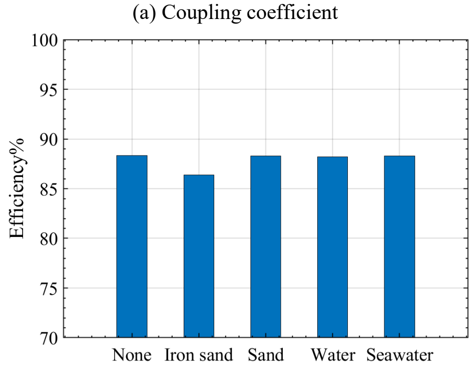
As shown in Fig. 5(a), iron sand affects the coupling coefficient which decreases with contamination, and the difference of k decreased with the increasing airgap. However, it shows that if there is some airgap over 50 mm, there is less effectiveness for the WPT system. Therefore, when performing obstacle detection or maximum efficiency control performed by performing coupling coefficient estimation, it is clear that it is better to maintain a certain distance between coils to eliminate the influence of coupling coefficient caused by air-gap change. Moreover, if the coupling coefficient is bigger than 0.1, the coil efficiency in the full model will get moreover 99%. From Fig. 5(a) we can conclude that despite the presence of iron sand, the condition of coupling coefficient is bigger than 0.1 can also be satisfied below 50 mm air gap.

From Fig. 5(b), we can find that the efficiency decreases when iron sand is placed between coils. Because iron sand. affects the inductance and resistance of coils, it leads to resonance frequency mismatched. Furthermore, the effect is more obvious at long airgaps from the result. It confirms that iron sand does harm to the WPT system, so it is necessary to consider the effect of iron sand when designing the system. Besides, the system efficiency of 95% can be achieved when the coil efficiency exceeds 99% [8][11].

Finally, a power transmission experiment in coil embedded road has been operated to confirm the parameter measurement.

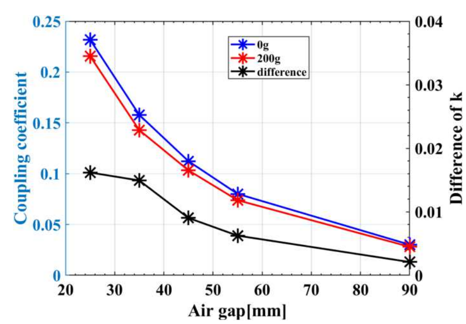


(a) Coupling coefficient

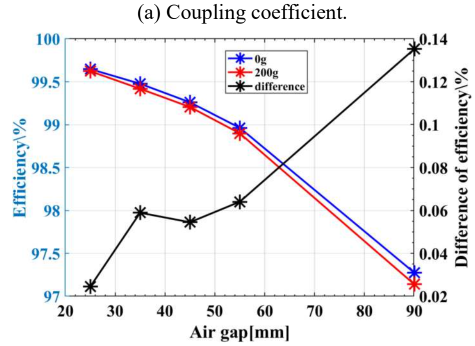


(b) Calculated DC-to-DC efficiency.

Fig. 4. Bench test coil's parameter measurement.

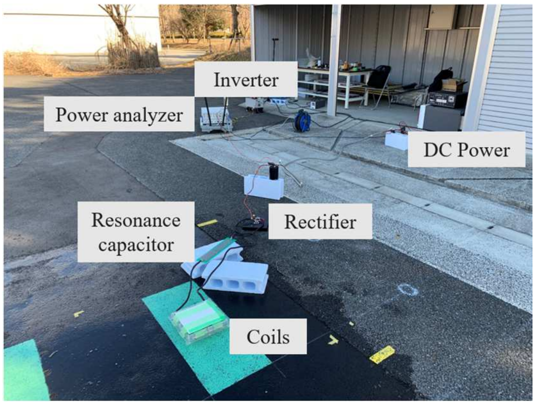


(a) Coupling coefficient.

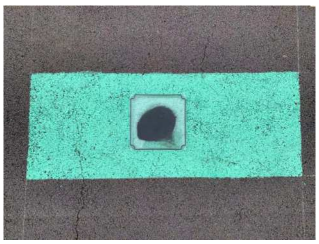


(b) Calculated coil-to-coil efficiency.

Fig. 5. Iron sand evaluation with bench coil's parameters.



(a) Power transmission experiment.



(b) Iron sand between coils (here only transmitter side is shown).

Fig. 6. Iron sand evaluation in power transmission with embedded coils.

Iron sand is placed between the coils in different weights. The evaluated value is DC to DC efficiency including power conversion. DC voltage of transmitter side V_1 and receiver side V_2 is set to 160 V and 120 V, respectively, and operating frequency is set to 85 kHz. About 1.5 kW experiment has been operated. The receiver coil is located in the center of the transmitter coil, and the distance of coils is 80 mm including the thickness of the road pavement. Fig. 6(a) shows the experiment setup and Fig. 6(b) shows the iron sand is placed between coils. Fig. 7 shows the experiment result. From the result, we can conclude that 200 g of iron sand caused a 0.07% power transfer efficiency decreased. In addition, although the power transfer efficiency decreases, the WPT system can keep a good DC-to-DC efficiency when iron sand exists between coils.

IV. Influence of Remained Rainwater and Seawater on The Embedded Coil

In previous studies, seawater is confirmed that will have an effect on coils resistance [12]. Besides, seawater will generate eddy current loss in the WPT system and cause the system to be detuned [13][14]. However, the measurement in small-scale model shows seawater has less effect on coil parameters when placing between coils, which is against previous studies. In order to find the reason, the authors have considered evaluating the impact of rainwater and seawater with embedded coil roads.

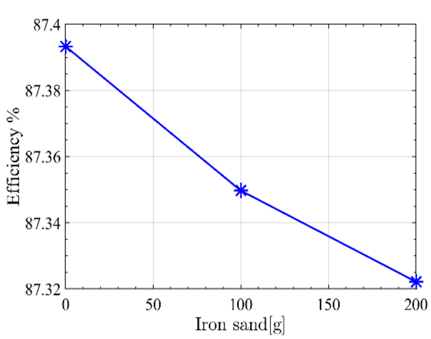
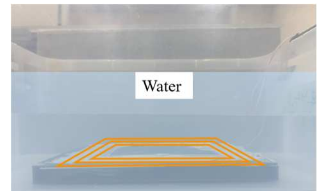


Fig. 7. Power transmission result of mearsured efficiency with iron sand.

(a) The embedded coil for sinking.



(b) Coil sank in waters.

Fig. 8. Sinking the coil into waters test.

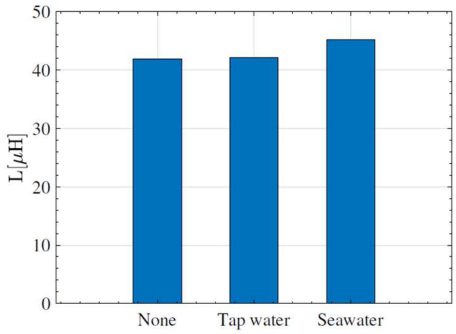
A. Coil parameter measurement

First, the authors have considered sinking the embedded coil into waters which simulates the worst condition of rainwater or seawater existing in road pavement. Fig. 8(a) shows the coil which is used to evaluate the impact of coil sinking. The silicon sealing is spreading on the wire making the water isolated. The size of the coil is shown in Table 1. The image of the experiment is shown in Fig. 8(b) and we confirm that the coil is totally sunk into the waters to simulate when waters remained in road construction. The LCR meter is connected with the sinking coil, measuring the coil parameters.

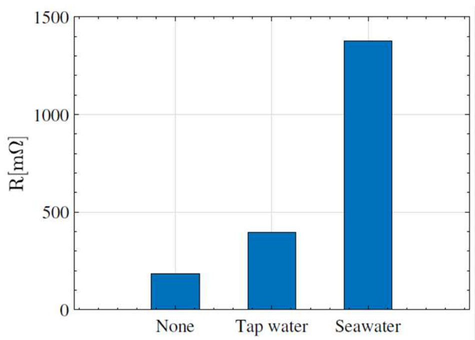
Fig. 9 shows the result of the parameter experiment. The inductance changed less when sinking the embedded coil into tap water, however, it increased when sinking the embedded coil into seawater. Besides, when the embedded coil is sinking in waters, the resistance of the coil increased, which seawater impact is much greater than tap water. Therefore, remained rainwater and seawater in road construction increase embedded coils resistance, causing a loss in the WPT system, which seawater impact is more than rainwater.

Besides, the mutual inductance of the embedded coil and receiver coil has been considered. Therefore, the theoretical mutual inductance between coils is measured using the LCR meter has been operated.

Fig. 10 shows the theoretical mutual inductance result with different frequencies. We can find when water or seawater has remained in the road pavement, the mutual inductance has decreased. In other words, the coupling coefficient decreased from (4), because the inductance of coils changed less when water and seawater remained in the road pavement. Moreover, because the resistance changed dramatically when water or seawater remained, from (5), we can infer the Q of the embedded coil decrease. As a result, from (3), when the coupling coefficient of coils decreases and Q of the embedded coil decreases, the decline of AC-to-AC efficiency of the system can be expected.



(a) Inductance.



(b) Resistance.

Fig. 9. Coil sank into different waters experiment result.

B. *Power transmission experiment*

To verify the expectation, a power transmission experiment with different frequencies in coil embedded road has been operated to evaluate the effect of the waters entering the road construction. We sprinkle tap water and seawater over an area of 3 m^2 around the upper part of the embedded coil and check the change in power transmission efficiency 2 L by power transmission. Since it takes time for tap water to penetrate the road surface, power is transmitted after five minutes from sprinkling the tap water. The evaluated value is AC-to-AC efficiency. DC voltage of transmitter side V_1 is set to 100 V and receiver side V_2 is set to the optimal efficiency point, and operating frequency is set to 86 kHz to 88 kHz. About 500 W experiment has been operated. The receiver coil is located in the center of the transmitter coil, and the distance of coils is 80mm

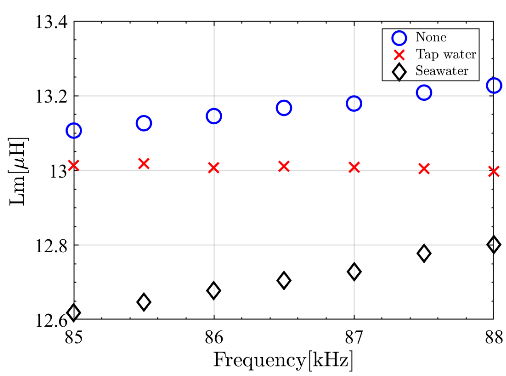


Fig. 10. Calculated mutual inductance result with different resonance frequencies with the embedded coil.

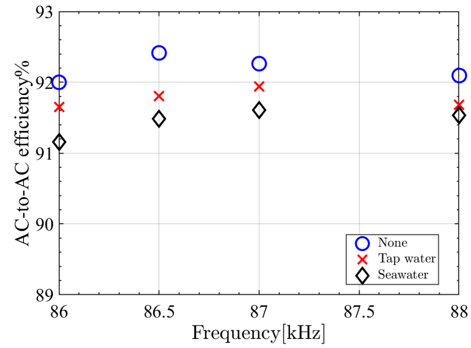


Fig. 11. Power transmission result in different resonance frequencies with the embedded coil.

including the thickness of the road pavement. Fig. 6(a) shows the experiment image.

The result of power transmission is shown in Fig. 11. From the result, remained seawater and rainwater are proved to decrease the power transmission efficiency by 0.93% and 0.6% at the resonance frequency of coils, in which the influence of seawater is worse than rainwater. Moreover, remained rainwater and seawater changes resonance frequency from 86.5 kHz to 87 kHz. It demonstrates that remained waters affect the efficiency of the WPT system, leading to efficiency decline

CONCLUSION

This work proposed the system that applying embedded coils to the DWPT system. Besides, this work evaluated contamination entering road construction's impact on the embedded coil. Although the iron sand affects coil parameters, leading to resonance frequency mismatched, and decreases efficiency, the DWPT system can keep a good efficiency in power transmission. Moreover, rainwater and seawater remained in road construction to increase coil resistance. Remained seawater is considered to generate eddy current loss because it increased coil resistance dramatically. Furthermore, remained seawater and rainwater decrease the AC-to-AC efficiency of power transmission by 0.93% and 0.6%, respectively. In addition, remained seawater and rainwater change the resonance frequency of the system.

Embedded coils parameter measurement in different resonance frequencies with rainwater or seawater remained should be done in order to figure out the influence of contamination on the embedded coil parameters. FEM simulation of eddy current loss should be considered to verify the eddy current loss generated by remained seawater.

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