Estimation and Positioning Control of Lateral Displacement Using Coil Current in Dynamic Wireless Power Transfer with Rectangular Coil on Dynamic Bench

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***Abstract*—Dynamic wireless power transfer has been studied to extend the cruising distance of the electric vehicles. However, the lateral displacement between coils decreases the efficiency. Previous research has proposed methods to keep the mutual inductance high by estimating the displacement and eliminating it by moving the vehicle sideways to deal with this problem. However, the proposed method in the previous research cannot be applied to dynamic wireless power transfer with rectangular coils. This paper proposes a method to deal with the lateral displacement in the dynamic wireless power transfer system with rectangular coils by estimating the lateral displacement from the receiver side DC current and moving the vehicle toward the center of the transmitter coils. In the experiment on a dynamic bench, nine cases of lateral displacements were all eliminated, and the efficiency was improved up to 12.4 % when the lateral displacement was 75 mm.**

***Index Terms*—wireless power transmission, rectangular coil, displacement control, transmission efficiency**

I. Introduction

Recently, electric vehicles (EVs) have been gaining attention, however the long charging time and the short cruising distance have hindered their proliferation. Dynamic wireless power transfer (DWPT), which is a technology to provide the electric power to running EVs using the magnetic resonance, has been studied to deal with this problem [1]–[4]. Fig. 1 shows the experimental vehicle for the DWPT system.

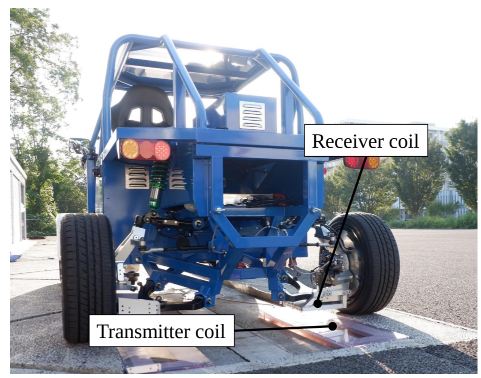


Fig. 1. Experimental vehicle for the DWPT system.

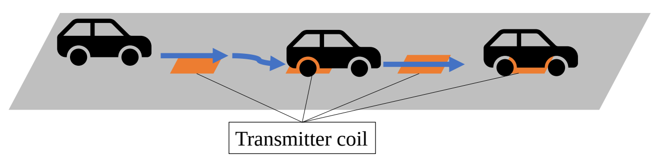


Fig. 2. Lateral position control in the DWPT system.

However, the lateral displacement between the transmitter coil and the receiver coil decreases the efficiency in the DWPT system. Previous research has studied methods to keep the mutual inductance high by estimating the displacement and eliminating it by moving the vehicle sideways, as shown in Fig. 2, to deal with this problem. This method requires estimating the distance to the center line of the transmitter coils.

One method of position estimation is to use the information of the location obtained by GPS or camera [5]–[7]. However, this method simply observes the positon of the vehicle and does not utilize the information of the received power or the efficiency. Therefore, if a marker indicating the location of the transmitter coil is misaligned, it will affect the position estimation result.

In contrast, a new estimation method using the electrical information obtained in the DWPT system has been proposed in previous research [8]–[11]. Sukprasert *et al.* proposed a method to estimate and control the lateral displacement using the received voltage [8]. The research targets the DWPT system with circular coils and a purely resistive load. The distance from the center of the coil is estimated from the received AC voltage, as the mutual inductance of the circular coil is isotropic. Then the lateral displacement is calculated from the kinematics of the vehicle and the distance from the center of the coil.

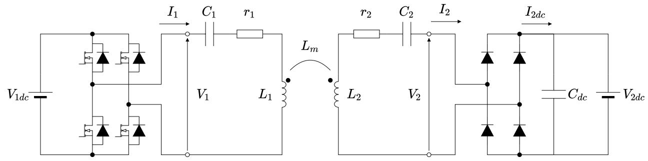


Fig. 3. Circuit diagram of WPT.

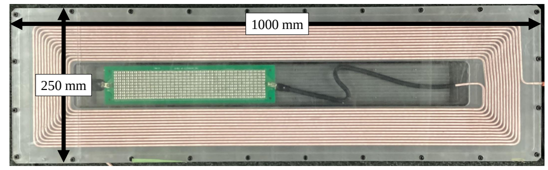


Fig. 4. Transmitter coil used in this study.

TABLE I
EXPERIMENTAL CONDITION

Parameter	Value	Parameter	Value
L_1	251 μH	V_{2dc}	25 V
L_2	96.6 μH	f_0	84 kHz
r_1	245 mΩ	v_x	5 km/h
r_2	263 mΩ	z	50 mm
V_{1dc}	25 V		

Hwang *et al.* also proposed a method to estimate and control the lateral displacement using the received voltage [9], [10]. The research targets the DWPT system with a long charging lane and a purely resistive load. The lateral displacement is estimated from the received AC voltage, as the mutual inductance is constant in the longitudinal direction.

In the DWPT system, the rectangular coil has been used frequently due to its advantages [12]–[15]. However, the mutual inductance of the rectangular coil is not isotropic, nor constant in the longitudinal direction. Thus, the proposed methods in the previous research cannot be applied to the DWPT system with rectangular coils.

Sithinamsuwan *et al.* proposed a method to estimate the longitudinal position in the DWPT system with the rectangular coil and the constant voltage load by using the received current [11].

This paper proposes a method to estimate the lateral displacement using the received current and eliminate the displacement, targetting the DWPT system with rectangular coils and a constant voltage load.

II. CIRCUIT ANALYSIS

A. Efficiency

The circuit diagram of a WPT system is shown in Fig. 3. A full-bridge inverter is used on the transmitter side, and a full-bridge diode rectifier is used on the receiver side. A constant voltage load is used to imitate a battery. $V, I, r, L,$ and C denote the voltage, the current, the resistance, the self-inductance, and the capacitance, respectively. The subscripts '1', '2', and 'dc' indicate the transmitter side, the receiver side, and the rectified components, respectively.

The angular frequency of the supplied voltage ω_0 is set to satisfy the resonance conditions of both the transmitter and receiver sides.

The output voltage of the inverter V_1 is a square wave. However, the high order harmonics are neglected in the following analysis since the WPT circuit functions as a bandpass filter. Since V_1 and V_2 are the RMS values, the following relationship can be derived from the Fourier series expansion:

$$V_1 = \frac{2\sqrt{2}}{\pi} V_{1dc},\ V_2 = \frac{2\sqrt{2}}{\pi} V_{2dc}. \tag{1}$$

Thus, the efficiency can be written as follows:

$$\eta = \frac{V_{2dc}(\omega_0 L_m V_{1dc} - r_1 V_{2dc})}{V_{1dc}(\omega_0 L_m V_{2dc} + r_2 V_{1dc})} \tag{2}$$

where L_m denotes the mutual inductance between the transmitter coil and the receiver coil.

Therefore, if the mutual inductance is positive, the mutual inductance and the efficiency have a positive correlation.

B. Receiver side DC current

From (1), the receiver side DC current I_{2dc} can be approximated as follows:

$$I_{2\mathrm{dc}} \simeq \frac{2\sqrt{2}}{\pi} I_2 = \frac{8}{\pi^2} \frac{\omega_0 L_m V_{1dc} - r_1 V_{2dc}}{\omega_0^2 L_m^2 + r_1 r_2}. \tag{3}$$

Therefore, if the DC link voltage of the transmitter and receiver sides are both constant, I_{2dc} depends only on the mutual inductance. Therefore, the mutual inductance can be obtained from I_{2dc}. This indicates that the lateral displacement can be estimated from I_{2dc} since the mutual inductance depends on the lateral displacement.

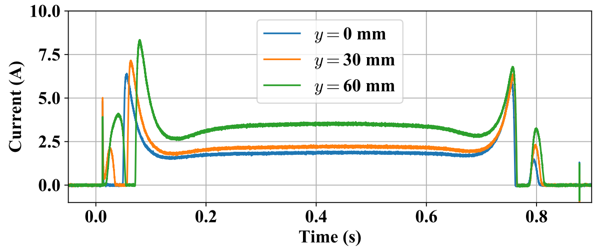
III. ESTIMATION AND POSITION CONTROL OF LATERAL DISPLACEMENT

A. Relationship between lateral displacement and receiver side DC current

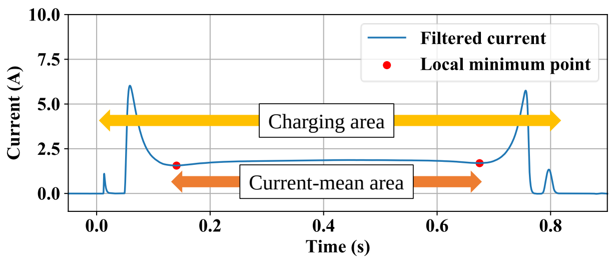
The relationship between the lateral displacement and I_{2dc} is expressed in mathematical equations to obtain the lateral displacement from I_{2dc}. It is assumed that the dimensions of the coils will be normalized for the DWPT system, and the relationship can be obtained beforehand. The rectangular coil used in this study is shown in Fig. 4. Generally, the air gap fluctuates, and influences the mutual inductance and the current. However, this study assumes that the receiver coil is directly connected to the upright of the vehicle. Therefore, the influence is neglected [16].

The longitudinal position of the transmitter coil, the lateral displacement, and the air gap between the coils are defined as x, y, and z. The receiver side DC current I_{2dc} was measured in six different lateral displacements, *i.e.* y = 0, 15, 30, 45, 60, 75 mm to examine the relationship. The experimental condition is shown in Table I.

The measurement result is shown in Fig. 5, in which the current at $y = 0$, 30, 60 mm is shown. It is clear that the larger



(a) Current at $y = 0, 30, 60\,\mathrm{mm}$.



(b) Filtered current and local minimmum point at $y = 0\,\mathrm{mm}$.

Fig. 5. Current with a constant lateral displacement.

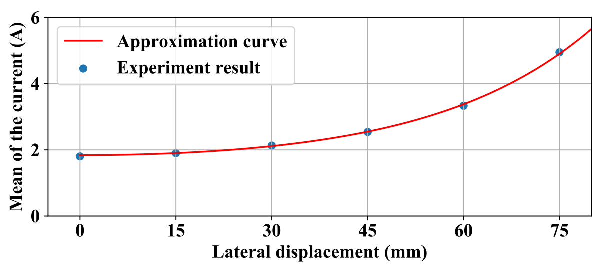


Fig. 6. Relationship between the mean of the receiver side DC current and the lateral displacement. The blue points are the experimental values, and the red curve is the approximation curve. The mean is calculated in the current-mean area.

the lateral displacement is, the higher I_{2dc} is. The longitudinal position where the power transfer starts may not be constant. Therefore, the values such as the current and the efficiency are evaluated only in the area where I_{2dc} is almost constant, called "the current-mean area" in this paper, to eliminate the influence of the low coupling area. The current is filtered to reduce the noise, and the local minimum point of the current is obtained, as shown in Fig. 5(b), to find the current-mean area in the coil used in this study. The area between the two local minimum points is defined as the current-mean area, and the values are evaluaded in this area. It is noted that the current-mean area is shorter than the charging area, as shown in Fig. 5(b).

The receiver side DC current I_{2dc} in the DWPT system with the rectangular coils depends on the longitudinal position. Therefore, the relationship between the lateral displacement and I_{2dc} is expressed by calculating the mean of I_{2dc}, $\overline{I_{2dc}}$. The result of calculating $\overline{I_{2dc}}$ is shown in the blue points in Fig. 6.

The relationship is heuristically expressed as in the following equation using hyperbolic function and constants a, b, c:

$$y^* = \frac{1}{b}\,\mathrm{arccosh}\left(\frac{\overline{I_{2dc}} - c}{a}\right). \tag{4}$$

By fitting (4) to the measurement results of I_{2dc} with the nonlinear least-squares method, the parameters were determined as follows:

$$a = 0.3351,\ b = 0.04009,\ c = 1.506. \tag{5}$$

The approximation curve is shown in the red curve in Fig. 6. All errors at each lateral displacement are less than $1\,\mathrm{mm}$, which is $1.3\,\%$ of the assumed lateral displacement $75\,\mathrm{mm}$. This implies that the approximation curve accurately represents the experimental result.

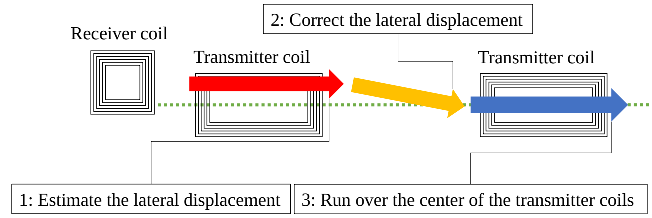


Fig. 7. Assumed situation and flow of the proposed method.

B. Assumed situation

A DWPT system in which multiple transmitter coils are positioned in a straight line, and a receiver coil approaches the transmitter coils in an angle parallel to the longitudinal direction of the coils, as shown in Fig. 7, is assumed. It is assumed that the methods proposed in [9], [10] is used to determine whether the receiver coil is located to the left or to the right of the transmitter coil.

C. Estimation and positioning control of lateral displacement

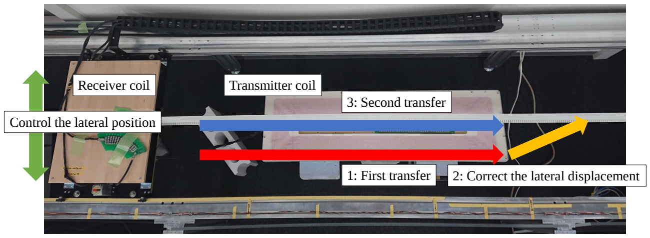
The flow of the proposed method is shown in Fig. 7. Firstly, the receiver coil receives the power from the first transmitter coil. After the receiver coil finishes receiving the power from the first transmitter coil, the lateral displacement is estimated from the receiver side DC current I_{2dc} using (4). Secondly, the receiver coil moves to the center line of the transmitter coils. Thirdly, the receiver coil runs over the center line in the subsequent power transfer.

IV. EXPERIMENT

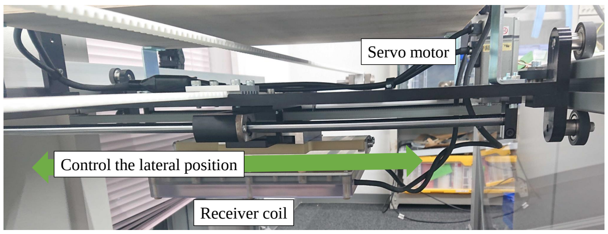
A. Setup

An experimental equipment was set to validate the proposed method, as shown in Fig. 8. The dynamic bench was used to imitate the movement of vehicles. The transmitter coil was placed in the center of the bench, and the receiver coil ran over the transmitter coil. As shown in Fig. 8(b), the lateral position of the receiver coil was controlled by a servo moter. The experimental condition is shown in Table I.

Fig. 8(a) shows the experiment flow. The receiver coil was placed with an initial lateral displacement y_0. Firstly, the receiver coil ran with the constant lateral displacement



(a) Overall view of the dynamic bench and flow of the experiment.



(b) Side view of the receiver coil.

Fig. 8. Dynamic bench used to move the receiver coil.

and received the power from the transmitter coil. The lateral displacement was estimated from I_{2dc} after the receiver coil finished receiving the power. Secondly, the lateral position was controlled to eliminate the initial lateral displacement y_0. Thirdly, the receiver coil ran over the transmitter coil again, then I_{2dc}, the DC-DC energy efficiency, and the corrected lateral displacement were measured to evaluate the effect of the positioning control. The energy efficiency η_e was calculated as $\eta_e = \frac{W_2}{W_1}$, where W_1 is the output energy of the source in the current-mean area, and W_2 is the energy consumption of the load in the current-mean area.

Nine cases of initial lateral displacements, *i.e.* $y_0 = 15$, 22.5, 30, 37.5, 45, 52.5, 60, 67.5, 75 mm, were experimented. The experiment was performed five times for each lateral displacement.

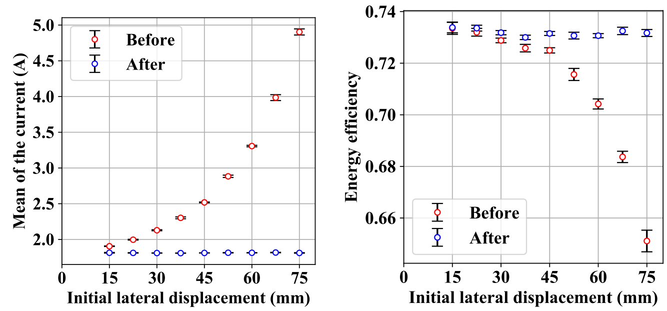
B. Result

The experimental result is shown in Fig. 9. The red circles are the mean values of the first transfer, and the blue circles are those of the second transfer. The error bars express the standard deviations. The values were calculated in the current-mean area, which was defined as the area between the two local minimum points of filtered I_{2dc}.

As shown in Fig. 9, the positioning control decreased the mean of the receiver side DC current and improved the DC-DC energy efficiency. Since the source voltage was set low to prevent the overcurrent, the forward voltage drops of the diodes were relatively high for the received voltage. Thus the DC-DC efficiency was relatively low as the efficiency of the rectifier was low.

Fig. 10 shows an example of the waveform of the efficiency, the receiver side DC current, and the lateral displacement at the initial lateral displacement $y_0 = 75\,\mathrm{mm}$, which shows that the lateral displacement was eliminated.

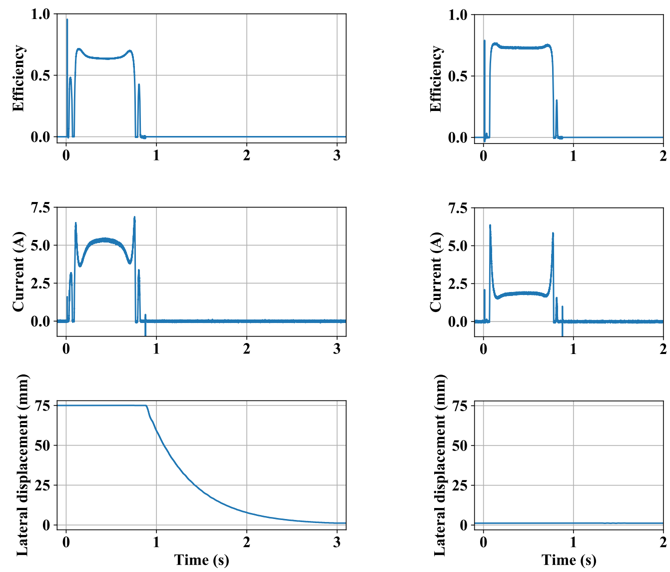
The mean of the corrected lateral displacement was $2.2\,\mathrm{mm}$, and the standard deviation was $0.77\,\mathrm{mm}$. Thus, it is concluded



(a) Mean of the receiver side DC current $\overline{I_{2dc}}$.

(b) DC-DC energy efficiency η_e.

Fig. 9. Experimental result. The red circles are the values of the first transfer, and the blue circles are those of the second transfer. The error bars express the standard deviations. The values were calculated in the current-mean area.



(a) Before the position control.

(b) After the position control.

Fig. 10. Example of the waveform of the efficiency, the receiver side DC current, and the lateral displacement at the initial lateral displacement $y_0 = 75\,\mathrm{mm}$.

that the proposed method eliminates the lateral displacement and improves the efficiency.

V. Conclusion

This paper proposes a method to estimate and control the lateral displacement in the DWPT system with rectangular coils. In the experiment on a dynamic bench, nine cases of lateral displacements were all eliminated, and the efficiency was improved up to $12.4\,\%$ when the lateral displacement was $75\,\mathrm{mm}$.

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