Sensorless Drone Detection for In-Flight Inductive Power Transfer Using Transmitter-Side Voltage Pulses

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***Abstract*—In-flight inductive wireless power transfer technique is a solution to extend the flight duration and reduce the battery capacity and charging time for drones. Before the power transmission, the drone detection method on a transmitter side is necessary for the reduction of magnetic field emission and power loss. A sensorless receiver coil detection using transmitter-side voltage pulses has been proposed for electric vehicles (EVs). This paper proposes the sensorless receiver coil detection for drones using the same technique. The main difference between the EVs and drones is the change of the attitude of the receiver coil such as altitude, pitch angle, and roll angle. The threshold of the receiver side current during short mode can be decided based on the coupling coefficient, therefore, the attitude difference does not affect the detection accuracy. The effectiveness of the proposal is experimentally validated using a drone test bench with changes of the altitude and pitch angle.**

***Index Terms*—sensorless detection, in-flight inductive power transfer, drones**

I. Introduction

Dynamic wireless power transfer (WPT) technique is an effective way to extend the cruising distance and reduce the battery capacity and charging time for electric mobility such as electric vehicles (EVs) and drones [1]–[8]. In [9], a dynamic WPT for battery-powered railway vehicle systems for non-electrified section is studied. The consumed driving energy is directly charged from ground equipment to the mobility without a stop and wire-connection. The battery capacity reduction is preferable especially for drones because they always output the thrust force, which is more than their gravity force, to keep the flight. The main configurations of in-flight WPT are divided into three: inductive method [2]–[5], laser method [6], and microwave method [7]. The inductive method can transfer much energy with high efficiency. However, the transferred distance is short. On the other hand, the laser method and microwave method can transfer the energy even if the drones are flight at high altitude. However, the amount of energy and efficiency are still low.

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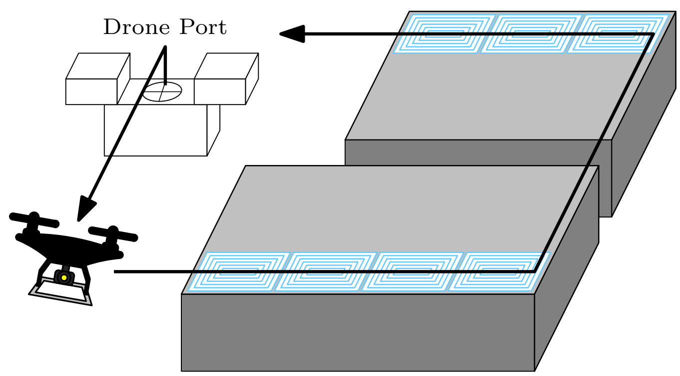


Fig. 1: Scene of in-flight inductive WPT.

This paper focuses on the inductive power transfer for drones. This method is effective for drones whose flight path is fixed as shown in Fig. 1 like a patrol monitoring task, transportation task in a factory, and so on.

The receiver coil detection on the transmitter side is necessary for the safe and efficient WPT [8], [10], [11]. If the detection is not properly done, some problems occur, such as wasted power loss, dangerous electromagnetic emission, and lack of power supply. Detection using a position sensor is a easy way to find the receiver coil. In the case of the in-flight WPT, the misalignment occurs not only in a horizontal plane but also in altitude, pitch, yaw, and roll. Especially, the altitude, the pitch, and roll changes the coupling coefficient between the transmitter coil and receiver coil. Adding the communication device on the drone increases the drone weight, which leads to the reduction of the flight duration. Hence, the sensorless detection is important for the in-flight WPT.

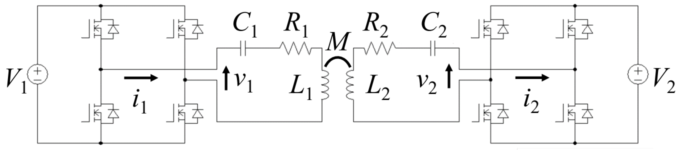


Fig. 2: Series-series type WPT circuit diagram.

The authors' research group has been proposed a sensorless detection for DWPT system of EVs [10], [11]. This method uses the transmitter-side voltage pulses and current response which is changed by the coupling coefficient. The detection based on the coupling coefficient is effective for the in-flight WPT even if the altitude, pitch, yaw, and roll change. This paper shows the measurement results of the coupling coefficient and evaluates the difference of the detection accuracy between the position sensor based detection and the proposed method.

II. WPT Circuit

This section describes the circuit configurations. A series-series (SS) type WPT circuit whose circuit diagram is shown in Fig. 2 is used in this paper. This circuit is a simple structure, which is suitable for in-flight WPT. v, i, L, C, and R denote voltage, current, inductance, capacitance, and resistance, respectively. The subscript 1 and 2 mean the transmitter side and receiver side. M is the mutual inductance which is changed by the receiver coil attitude. The circuit equation is described as

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} Z_1 & -j\omega M \\ j\omega M & -Z_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{1}$$

where ω is the angular resonant frequency and the following equation is satisfied:

$$\omega = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}}. \tag{2}$$

Z_i is the impedance of the resonant circuit which is expressed as

$$Z_i = R_i + j\omega L_i + \frac{1}{j\omega C_i}. \tag{3}$$

III. Sensorless Detection

This section describes the sensorless receiver coil detection [10], [11]. The flowchart is illustrated in Fig. 3. The left and right figures show the flowchart of the transmitter side and receiver side, respectively. The detection is done using the transmitter coil current i_1 when the rectifier is in short mode. By turning on the lower arm switches of the rectifier, the receiver circuit is shorted. In this mode, the transmitter current $i_{1\mathrm{s}}$ can be calculated from (1) and (2) as

$$i_{1\mathrm{s}} = \frac{R_2}{R_1 R_2 + \omega^2 M^2} v_1. \tag{4}$$

Therefore, $i_{1\mathrm{s}}$ is inversely proportional to the square of the mutual inductance. If the receiver coil couples with the transmitter coil, the mutual inductance increases and $i_{1\mathrm{s}}$ decreases. Therefore, by setting the threshold value $i_{1\mathrm{sth}}$ and comparing the maximum value of i_{1s} with it, the sensorless detection can be conducted. In order to reduce the power during the detection, the inverter periodically output the voltage pulses with small rms value of v_1 for the detection time t_{d} and wait for the waiting time t_{w}.

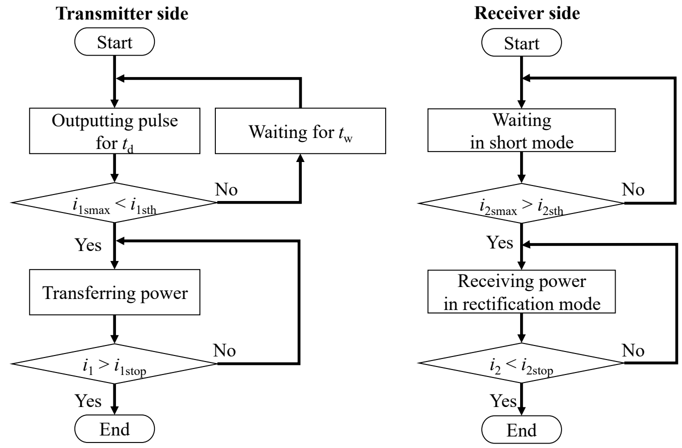


Fig. 3: Flowchart of sensorless receiver coil detection.

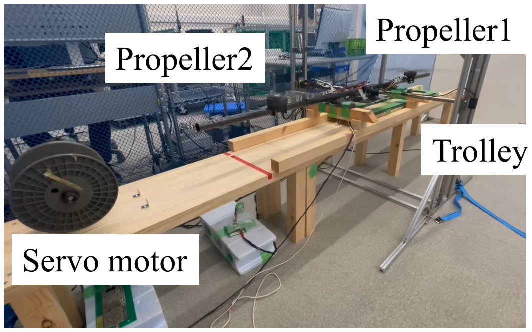
On the receiver side, the rectifier is in the short mode until the start of the WPT. When the WPT starts, the receiver coil current $i_{2\mathrm{s}}$ increases because v_1 increases. Therefore, the receiver side can know the start timing by setting the threshold value $i_{2\mathrm{sth}}$. When i_2 is greater than $i_{2\mathrm{sth}}$, the mode of the receiver side switches to the rectification mode by turning off the lower arm switches of the rectifier. In this mode, the rectifier works as a full bridge diode rectifier.

At the end time, i_1 increases because of the decrease of the mutual inductance. Therefore, the end time can be decided by the threshold value $i_{1\mathrm{stop}}$. After the end of the WPT, i_2 decreases and finally become zero. Therefore, the receiver side can know the end timing by the threshold value $i_{2\mathrm{stop}}$. As explained above, the sensorless drone detection can be done without any communication devices between the transmitter side and rectifier side.

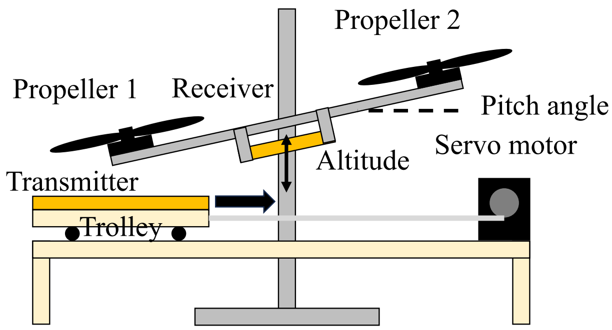
IV. Experiments

This section describes the experimental setup. Fig. 4 shows the drone test bench. The drone part consists of two propellers, a body shaft, an altitude sensor, and a rotary sensor. The altitude and pitch are controlled by the thrust of two propellers. The receiver coil is attached to the drone part. The transmitter coil is put on a trolley which is pulled by a wire connected to a servo motor. By using this test bench, experiments of the in-flight WPT can be conducted with high repeatability.

Table I shows the parameters of the WPT circuit. In the case of the in-flight WPT, the air gap and the attitude of the receiver coil changes. Fig. 5 shows the measurement results of the mutual inductance with the change of the receiver coil attitude. When the pitch angle is zero, the mutual inductance becomes symmetric with respect to the center of the transmitter coil. In the in-flight condition, the drone tilts and the pitch angle becomes a certain value. From Fig. 5, at the beginning of the coupling, the mutual inductance becomes slightly smaller



(a) Photograph.



(b) Illustration.

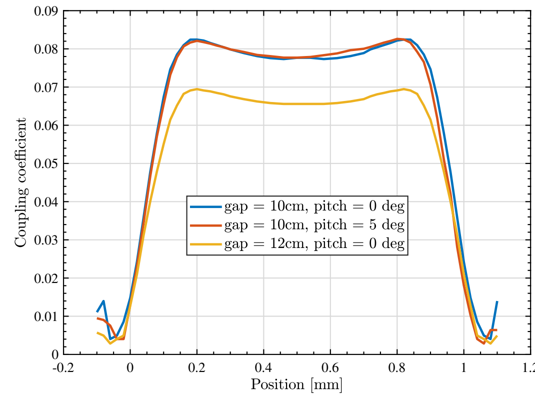
Fig. 4: Drone test bench.

TABLE I: Circuit parameters.

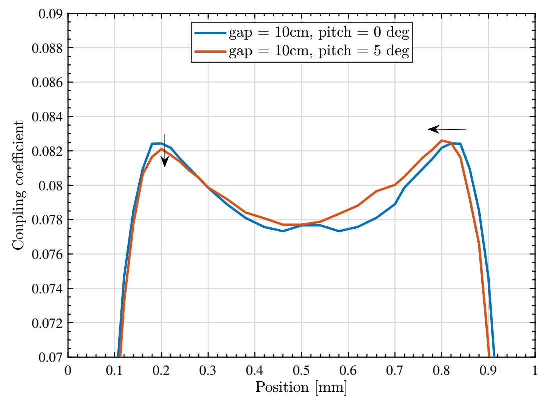
Self inductance of transmitter coil L_1	123.0 μH
Internal resistance of transmitter coil R_1	200 mΩ
Capacitance in transmitter side C_1	29.5 nF
DC voltage in transmitter side V_1	70 V
Self inductance of receiver coil L_2	25.50 μH
Internal resistance of receiver coil R_2	153 mΩ
Capacitance in receiver side C_2	142 nF
DC voltage in transmitter side V_1	50 V
Operating frequency	83.5 kHz

than one without the pitch tilt. On the other hand, at the end of the coupling, the mutual inductance becomes larger than one without the pitch tilt. In other words, when the receiver coil is detected using a position sensor, the power transmission starts while weak coupling, which causes high electromagnetic emission and power loss, and ends even if the mutual inductance is high, which causes the lack of the power transmission. In addition, when the drone attitude is high and the coil is detected using a position sensor, the power transmission starts and ends while weak coupling.

In this paper, the proposed method is compared with the conventional method which uses a position sensor. The position sensor is used for the decision of the starting time. The end time is decided using the same algorithm of the proposed method. The position sensor is put where the edges of the transmitter coil and receiver coil are aligned. The threshold values used in the proposed method are experimentally decided so that the transmitter currents at the start and end of the WPT are the same.



(a) Overall view.



(b) Enlarged view.

Fig. 5: Coupling coefficient with change of receiver coil attitude.

Figs. 6 and 7 show the experimental results with the position-sensor-based detection and sensorless detection when the air gap is 8 cm and pitch angle is 0 deg. In each figure, the top figure shows the transferred power and received power, the second and third figures show the voltage and current responses in the transmitter side v_1 and i_1, and the fourth and fifth figures show the voltage and current responses in the receiver side v_2 and i_2, respectively. From the results, the start time of the conventional method is late compared with the proposed method. This causes the lack of the power transmission. In the proposed method, it is confirmed that the voltage pulses is output before the power transmission at about 5 s. Before the receiver coil detection, i_1 can be reduced by the small rms voltage pulses. In addition, from the figure of the DC power, it is confirmed that the output power by the voltage pulses is less than 10 W which is too small compared with the main transferred power of 1 kW. i_1 gradually decreases after 3 s because the mutual inductance increases. After i_1 becomes smaller than $i_{1\mathrm{sth}}$, the transmitter side starts the power transfer and i_1 quickly increases. The mode of the rectifier properly switches to the rectification mode as shown in the v_2 and i_2 response. As a result, it is confirmed that the sensorless receiver coil detection successfully works as

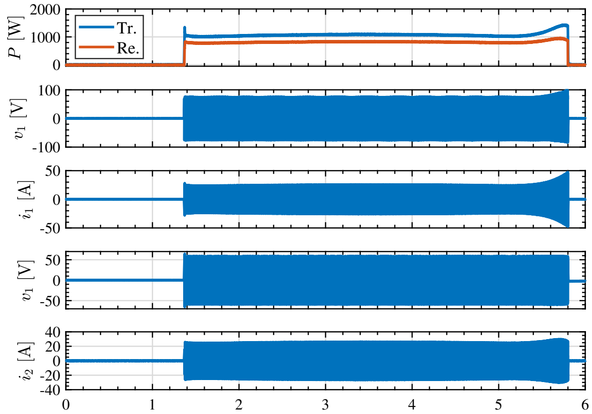


Fig. 6: Experimental results with position-sensor-based detection when gap = 8 cm and pitch = 0 deg.

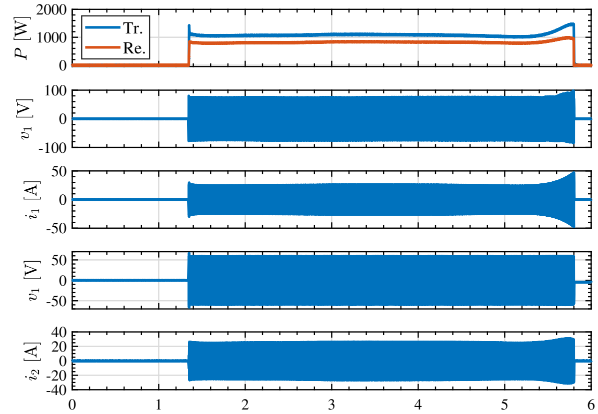


Fig. 8: Experimental results with position-sensor-based detection when gap = 8 cm and pitch = 5 deg.

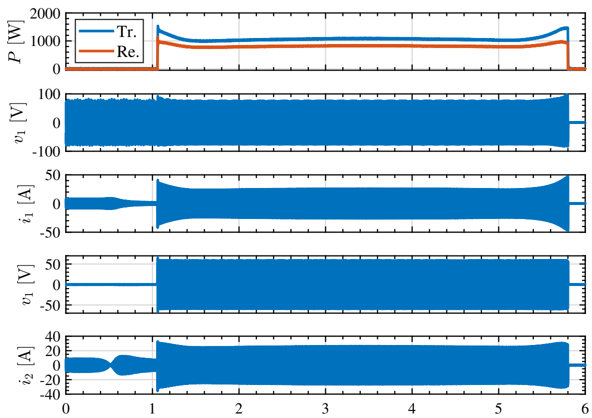


Fig. 7: Experimental results with sensorless detection when gap = 8 cm and pitch = 0 deg.

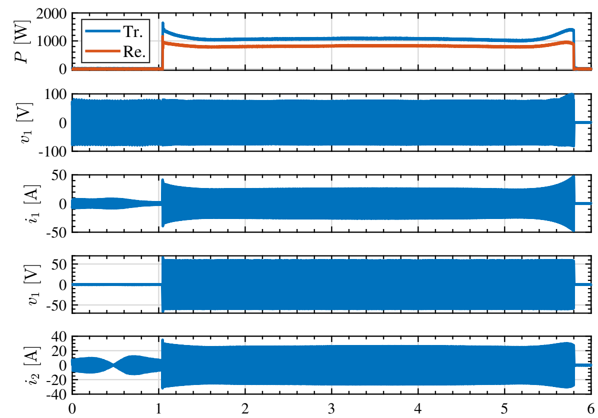


Fig. 9: Experimental results with sensorless detection when gap = 8 cm and pitch = 5 deg.

described in Fig. 3.

Figs. 8 and 9 show the experimental results with the position-sensor-based detection and sensorless detection when the air gap is 8 cm and pitch angle is 5 deg. Figs. 10 and 11 show the experimental results with the position-sensor-based detection and sensorless detection when the air gap is 10 cm and pitch angle is 5 deg. Each figure show the same response described in Figs. 6 and 7. The attitude changes causes the mutual inductance change. However, from Figs. 8 and 10, the start timing of the WPT of the conventional method always the same even if the receiver coil attitude changes. On the other hand, the proposed method regulates the start timing with the change of the mutual inductance as shown in Figs. 9 and 11. Therefore, the proposed method is effective for the in-flight WPT of drones.

V. Conclusions

This paper proposes the sensorless receiver coil detection for the in-flight WPT of drones. The proposed method uses the voltage pulses in the transmitter side whose consumed power is very small. The experimental results validates the effectiveness of the proposed method. The sensorless detection is properly conducted even if the pitch angle and the altitude of the receiver coil change. This proposal is useful since it can be applied to the dynamic WPT systems whose relative position of the transmitter coil and receiver coil changes.

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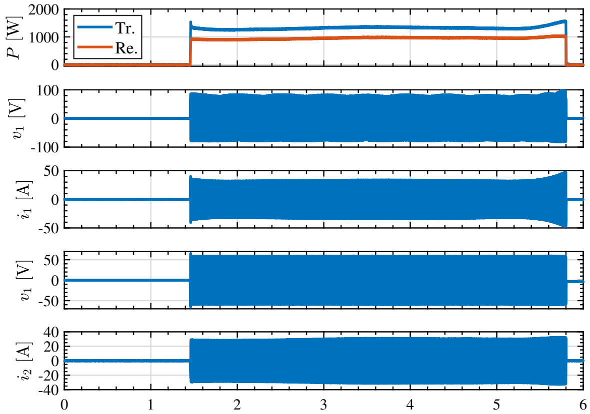

Fig. 10: Experimental results with position-sensor-based detection when gap = 10 cm and pitch = 5 deg.

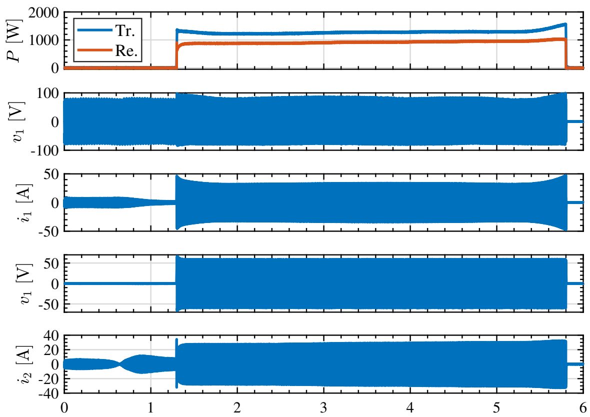

Fig. 11: Experimental results with sensorless detection when gap = 10 cm and pitch = 5 deg.

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