Study of Electric Aircraft Charged by Beamed Microwave Power

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The ability to wirelessly transmit power over long distances is one of the strengths of a microwave power transmission system. In this study, we applied microwave power transmission technology to the power supply system of an electric aircraft in order to extend the flight time. A partial prototype based on the concept of this system and its design conditions was manufactured. A rectenna that had a center frequency of 5.8 GHz achieved the world's smallest weight to power output ratio. On the basis of the trial results and further study, we confirmed the feasibility of this system. These efforts and our future plans are described in this paper.

1. Introduction

Research on microwave power transmission technology has been advanced in recent years with a focus on the establishment of long-distance wireless power transmission technology to realize a Space Solar Power System (SSPS) in the future. On the other hand, with regard to short-distance non-contact power supply technology using electromagnetic induction and magnetic resonance, the development of products for supplying power to more familiar electronic devices and automobiles is being actively promoted these days. In line with this trend, products employing microwave power transmission technology are gradually beginning to appear. However, there are still few products that take advantage of the strengths of microwaves.

The greatest advantage of microwave power transmission technology is the capability for long-distance non-contact power transmission. In order to fully utilize this advantage, this study focuses on its application for transmitting power to an electric aircraft flying at a distance. Electric aircraft have the potential for various applications, such as observation and monitoring, from the perspective of quietness, safety, and maintainability. However, when an electric aircraft runs only on the power in its batteries, it has a much shorter flight time than that of a gasoline-powered aircraft, thus the utilization range of an electric aircraft is limited. But, by supplying power from an external power source during flight, electric aircraft would be able to extend their flight times and expand their utilization range.

Basic experiments on the application of microwave power transmission technology to an electric aircraft were conducted more than 20 years ago. In those experiments, power was supplied with microwaves in the 2.4 GHz band to an aircraft during flight.[(1), (2)] The experiments demonstrated that the received power was usable as such. However, the entire systems were rather basic having only the structures required for flight and a system for receiving power attached to the underside of the aircraft, and the power transmitting device on the ground moved tracking the bottom of the aircraft. No application to a practical system or product development followed the experiments.

Based on these past studies and the latest technology trends, the authors have begun studying the application of microwave power transmission to an electric aircraft to realize a more practical system that is capable of carrying observation or monitoring devices.

2. Study concept

The usefulness of unmanned aircraft has already been recognized. They are used in fields such as disaster monitoring, monitoring for crime prevention, meteorological observation, radiation observation, and so on. However, the flight time of those aircraft is limited, though it varies from one aircraft to another. This means that aircraft need to land for refueling, which requires additional work and limits the length of a single mission. Based on the above facts, the authors have made "24 h 365 d continuous aerial observation and monitoring" the system design concept of this study. **Figure 1** shows a diagram of the system concept.

The aircraft flies in a circular pattern within the charging area over the ground station while receiving power in the form of microwaves from the ground and charging the battery mounted in the aircraft. The aircraft then flies to the observation or monitoring area using the power it has received to accomplish the mission. When the aircraft needs power supply, it returns to the charging area. When necessary, more than one aircraft can be used to create a continuous monitoring system with minimum takeoffs and landings.

3. Configuration and design conditions

3.1 Configuration

The power supply system is the key to realizing this concept. **Figure 2** shows the configuration of the power supply system.

This system mainly consists of a power-transmitting device installed on the ground, a power-receiving device mounted in an aircraft, and the aircraft itself. Microwaves generated by

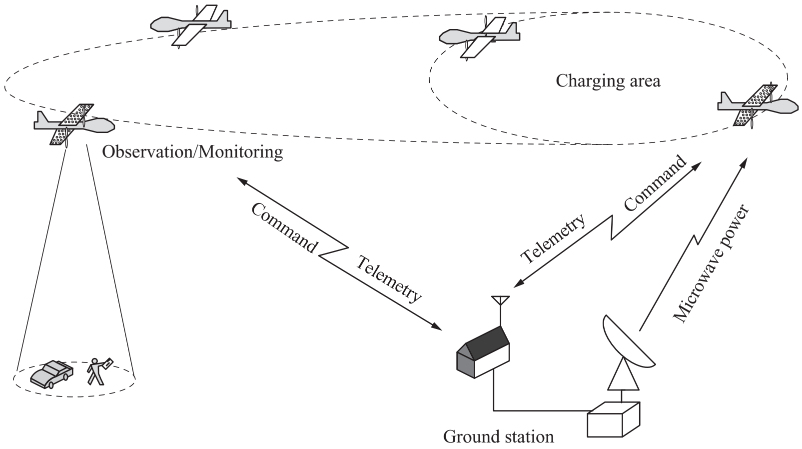

Fig. 1　Picture of concept

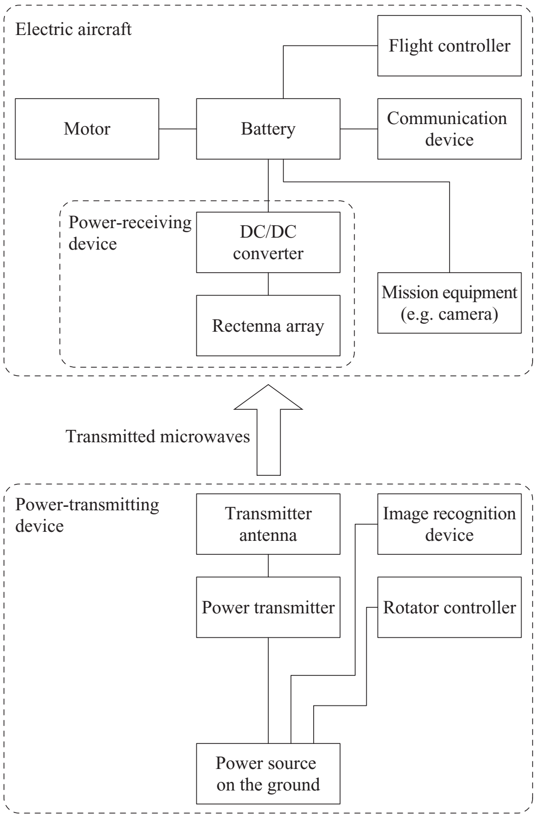

Fig. 2　Configuration of power supply system

the power transmitter are transmitted from the transmitter antenna to a rectenna (an antenna with a rectifier circuit) mounted on the underside of a main wing of the aircraft which is then converted to DC power. The DC power is converted into an appropriate voltage with the DC/DC converter before being used to charge the battery. The electric aircraft is powered by the wirelessly charged battery to drive its propellers and other equipment.

The direction of the microwave beam for power transmission to the aircraft is determined by image recognition. The transmitter antenna is directed by driving the antenna rotation mechanism (rotator). Another method of determining the beam direction is to have the power receiving side transmit a pilot signal for the power transmitting device to detect it. With this method, however, a radio station license would be required for the use of additional radio waves. For this reason, the image-recognition method has been employed for the purpose of establishing a simple system in the future.

3.2　Design requirements

Table 1 shows the design requirements for the sub-systems, which include the power-transmitting device, power-receiving device, and electric aircraft. A frequency of the 5.8 GHz band, or Industry-Science-Medical (ISM) band, which may be employed for a Space Solar Power System (SSPS), is used for the power transmission.

The lightweight power-receiving device and the 0 degrees

Table 1　Design requirement of sub-system

Section	Item	Unit	Design requirement
Power-transmitting device	Microwave frequency	GHz band	5.8
	Transmission power	kW	10
	Transmitter-antenna size	m	ϕ 2 or less
	Antenna pointing accuracy	degree	within ±0.5
Power-receiving device	DC output power	W	160 or more
	Mass	kg	1 or less
Electric aircraft	Turning radius	m	30 (in circular flight while charging)
	Flight level	m	50 (in circular flight while charging)
	Bank angle	degree	0 (in circular flight while charging: calm wind)
	Power consumption	W	160 or less (in circular flight while charging)
	Dimensions	m	3 × 3 (rough value)
	Mass of mounted equipment	kg	1 or more

bank angle (the angle formed by the transverse axis of an aircraft and the ground) when the aircraft makes a circular flight while charging characterize the design requirements of this system. If a power-receiving device includes a rectenna with a fluororesin substrate like those commonly used on the ground, the rectenna itself would be as heavy as around 5 kg/m^2. However, this system requires a lighter power-receiving device because it is mounted in an aircraft. For this reason, as a design condition of this system, 1 kg or less is specified as the total mass of the power-receiving device including the rectenna array, DC/DC converter, and wires.

When an ordinary aircraft makes a circular flight, it generates a horizontal component of lift by keeping a certain bank angle. In this system, however, if the aircraft banks as it flies in a circular pattern while charging, the increased incident angle of the microwaves to the rectenna mounted on the underside of a main wing puts the rectenna out of the high-gain range of the antenna. As a result, the aircraft may become unable to continue flight. For this reason, an aircraft that does not need to bank is specified as a design condition of this system. This study first aimed to create a prototype that allows the aircraft to fly in a circular pattern over the power transmission area.

4. Prototyping and examination of components

Prototyping and examination of components have been carried out for the lightweight rectenna and nonbanking electric aircraft that are needed for the power supply system, which is key to the success of the entire system. As a result, the feasibility of each component has been verified. **Figure 3** shows the appearance of prototypes of the lightweight rectenna and electric aircraft.

4.1 Lightweight rectenna

As a small yet high-gain antenna is needed to efficiently receive the transmitted microwaves, a patch antenna has been employed. The rectenna has an integrated structure in which the rectifier circuit is mounted right behind the rear panel of the antenna. The commercially available aramid-honeycomb has been employed for the substrate and structural members. Consequently, a light weight low-loss rectenna with negligibly small dielectric loss and a mass of 2 g per element has been fabricated. Microwaves at 5.8 GHz have been beamed to a rectenna with this structure and the output power has been measured. The ratio of the mass to the output power obtained from the measurement has been 1 g/W, achieving the world's lightest rectenna among rectennas that operate in the 5.8 GHz band.[3]

Based on this result, the mass of the power-receiving device required to obtain the 160 W of output power specified in the design conditions has been estimated to be 1 kg or less, where the power-receiving device includes and consists of lightweight rectennas placed in consideration of the unevenness of the power density actually formed on the receiving surface by the transmitted microwaves, a DC/DC converter, and wires. The feasibility of a power-receiving device with this lightweight rectenna has thus been verified.

4.2 Electric aircraft

Before examining an electric nonbanking aircraft, the characteristics of a normal banking electric aircraft were investigated. The investigation result demonstrated that a bank angle of 25 to 40 degrees is necessary to fly in a circular pattern with a 40 m turning radius without any difficulty. Therefore, to fly in a circle with a bank angle of 0 degrees, the common way of flying in a circle using a horizontal component of lift generated by the bank angle must be modified fundamentally. Two methods for reducing the bank angle have been examined.

(1) Using the difference in thrust between the propellers mounted on the right and left main wings.
(2) Employing a wing-shaped fuselage and mounting a rudder in the rear of the fuselage to generate lift in the horizontal direction.

First, a flight test of a sub-scale prototype was conducted for the method using the difference in thrust between the right and left propellers. However, the prototype was unable to fly normally because it was extremely difficult to balance the difference in thrust between the right and left propellers.

Second, a circular flight using a wing-shaped fuselage and rudder was examined. **Figure 4** shows the principle of a circular flight without banking. As the figure shows, when an aircraft turns left during flight, for example, it first moves its vertical-tail rudder into the turning direction. The aircraft yaws forming an angle of attack on the wing-shaped fuselage and generating a force in the turning direction. Then, the aircraft moves further the rudder to increase the force in the turning direction. The aircraft can fly in a circle in this manner. An experimental prototype of such an aircraft will be manufactured and flight tests will be conducted.

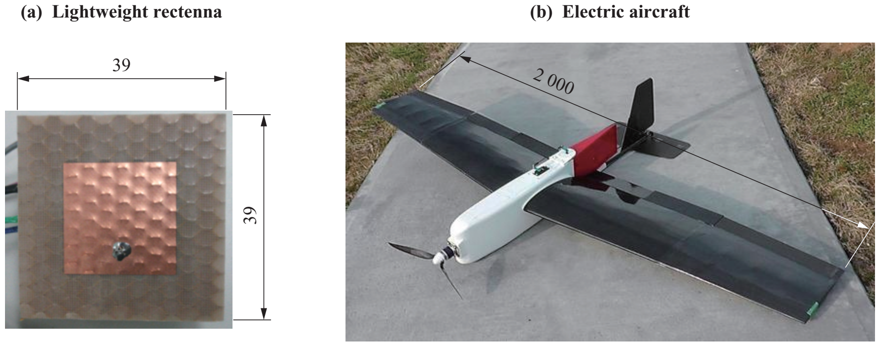

Fig. 3 Appearance of light weight rectenna and electric aircraft (unit:mm)

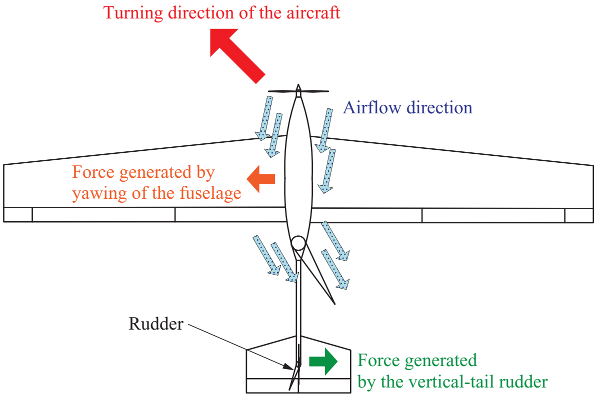

Fig. 4 Principle of circular flight

5. System feasibility

The power supply system, a key for the success of this system, has been examined based on the prototyping of components and the examination results described in **Section 4**. When the altitude is 50 m above the transmitter antenna on the ground and the turning radius is 30 m, the power transmission distance is 58 m. The received power has been calculated by the following Friis transmission equation (1), assuming that the transmitted radio waves are plane waves.

$$P_r = \frac{P_t G_t}{4\pi R^2} A_e \quad \cdots\cdots (1)$$

$$A_e = \frac{\lambda^2}{4\pi} G_r \quad \cdots\cdots (2)$$

P_r : Received power
P_t : Transmitted power
G_t : Transmitter antenna gain
A_e : Effective aperture area
G_r : Receiver antenna gain
R : Power transmission distance
λ : Wavelength of transmitted radio waves

As equation (1) represents the received power of each antenna of the rectenna mounted on the lower surface of the wing, the total DC power output from all the rectennas is represented by equation (3), where the RF-DC conversion efficiency of the rectenna rectifier circuit is taken into account.

$$P_{DC} = \sum_{i=1}^{n} (P_r \cdot \eta_r)_i \quad \cdots\cdots (3)$$

P_{DC} : DC output power
η_r : RF-DC conversion efficiency of the rectifier circuit

The DC power has been calculated by using equation (3) and the receiver antenna gain confirmed in the prototype components. In the calculation, the rectenna structures are assumed to be mounted inside a main wing so as to make the front surfaces of the rectennas face the power transmitting part on the ground. The DC power calculated in consideration of the unevenness of the power density formed on the receiving surface is 166 W, which exceeds the design condition of 160 W. Thus, it has been verified that sufficient power can be supplied for an aircraft in flight.

After examining an angle detection method using image recognition to control the microwave beam direction, flight test of a sub-scale-model electric aircraft, flight test of an actual-size aircraft, power transmitting and receiving tests in a radio-wave dark room, and the acquisition of a radio station license, we plan to conduct an outdoor flight test in which power is actually supplied via microwaves to an aircraft in flight.

6. Conclusion

This paper describes the results of determination of the system concept, prototyping of components, and system feasibility examination in terms of the application of microwave power transmission technology to an electric aircraft. This paper also demonstrates the feasibility of this system through the verification of the feasibility of a lightweight power receiving system and a nonbanking electric aircraft, which are unique to this system.

Currently, a small unmanned aircraft can fly outside regulated areas without infringing on the Civil Aeronautics Act in Japan. The usefulness of unmanned aircraft has been recognized and this has led to their utilization around the globe, but this has also brought various problems with regard to safety and privacy to light. The authors aim to establish this system through a variety of tests, giving due consideration to safety and legislative trends.

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