Basic Experimental Study on Helical Antennas of Wireless Power Transfer for Electric Vehicles by using Magnetic Resonant Couplings

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***Abstract*—Wireless power transfer is required for the diffusion of Electric Vehicles (EVs) because it makes possible the process of automatically charging EVs. The technology of wireless power transfer requires three main elements: large air gaps, high efficiency and a large amount of power. Though, there has been no such technology, recently, the technology of electromagnetic resonant couplings was proposed and named WiTricity. With this technology there are large air gaps, high efficiency and large amounts of power. In this paper, the feasibility of wireless power transfer for EVs by electromagnetic resonance coupling is studied. We studied small sized antennas that can be equipped on the bottom of a vehicle and we studied the electrical characteristics of the antenna with equivalent circuits, electromagnetic analysis and experimentation. The length of the air gaps between a transmitting antenna and a receiving antenna affect resonance frequencies. The resonance frequency changes from two to one depending on the length of the air gap. Until a certain distance, maximum efficiencies are not changed. Large air gaps are weak couplings. In a weak coupling at resonance, magnetic resonance couplings can transfer energy with high efficiency. The specification results at high power are proposed. In this paper, the feasibility of wireless power transfer with large air gaps and high efficiency by small sized antennas that can be equipped on the bottom of EVs is proposed.**

***Keywords* - Contactless power transfer, Wireless, Resonance, Coupling, Magnetic**

I. INTRODUCTION

Wireless power transfer is required for the diffusion of Electric Vehicles (EVs) because it makes possible a convenient charging system for EVs. This system can be used in automatic charging systems for the consumer market. When one parks the car, the system charges power to the EV automatically by wireless power transfer. EV needs to be charged once a day. Typically, one would use a cord and plug in one EV at home, but it is not necessary if wireless power transfer technology is used.

The technology of wireless power transfer, electromagnetic induction and microwave power transfer are famous, however, electromagnetic resonance couplings have only been proposed recently [1][5]. The technology of wireless power transfer requires three main elements: large air gaps, high efficiency and a large amount of power. The electromagnetic resonance coupling is the only technology that deals with these three elements. Until now, this phenomenon was explained by the Mode Coupling theory; however, the sizes of antennas were too big to be equipped on the bottom of EVs. The characteristics of antennas and the relation between power and efficiency are not proposed in this theory.

In this paper, however, we consider the antenna size for EVs. We use small antennas that can be equipped on the bottom of EVs. The characteristics of antennas, relation of air gaps, frequency and relation of power and efficiency are shown.

II. SYSTEM OF WIRELESS POWER TRANSFER AND CONFIGRATION OF EXPERIMENT

The entire system of wireless power transfer for EVs is shown in Fig. 1. A high frequency power source distributes power through the transmitting antenna. The transmitting antenna sends energy to a receiving antenna using electromagnetic resonance coupling wirelessly. The energy with high frequency is rectified and charged by batteries or electric double layer capacitors (EDLCs) which are the energy storage mediums.

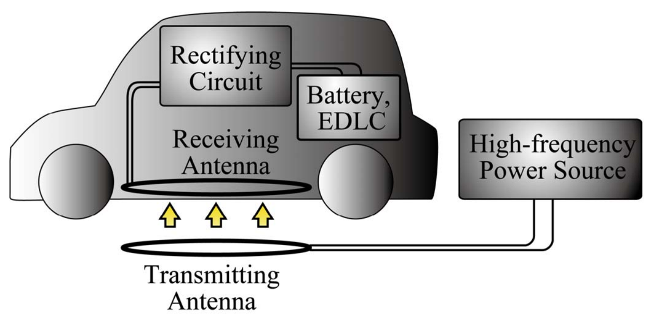


Fig. 1 Concept of contactless power transfer system for EV

Fig. 2 Transmitting antenna and Receiving antenna

Fig. 3 Shielded room

In this paper we will study the antenna- which is very important in wireless power transfer because it decides how large the air gaps and efficiencies are. We will only consider antennas with a 150mm radius since this size is able to be equipped to the bottom of EVs (Fig. 2). The transmitting and receiving antennas are same. Electromagnetic resonance couplings cannot radiate like microwave power transfer. Electromagnetic resonance couplings transfer power by connecting the electromagnetic fields of the two antennas to form a link that does not allow power to radiate outward, and thus conserves energy. The experiment was held in a shielded room at the University of Tokyo (Fig. 3).

The Parameters of the antenna are shown in Fig. 4 and table 1. Through a coaxial cable, the bottom transmitting antenna is fed power. The power is transferred to the top receiving antenna via a wireless magnetic resonance coupling.

The experimental setups are two types. The lower power setup is shown in Fig. 5. Reflection S_{11} and transmission S_{21} is measured by the vector network analyzer (VNA). The ratio of power reflection is η_{11} and transmission is η_{21} which are defined by equations (1) and (2). The ratio of power transmission means the efficiency of power transfer. When high powers are measured the power meter is used.

$$\eta_{11} = S_{11}^2 \times 100 \qquad [\%] \qquad (1)$$

$$\eta_{21} = S_{21}^2 \times 100 \qquad [\%] \qquad (2)$$

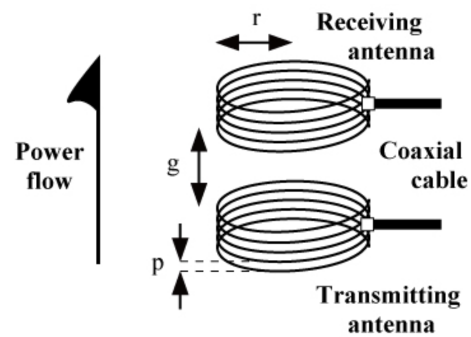


Fig. 4 Parameters of antennas

Table 1 Parameters of antennas

Parameters	Values
radius	r = 150 mm
pitch	p = 3 mm
wire size	w = 2 mm

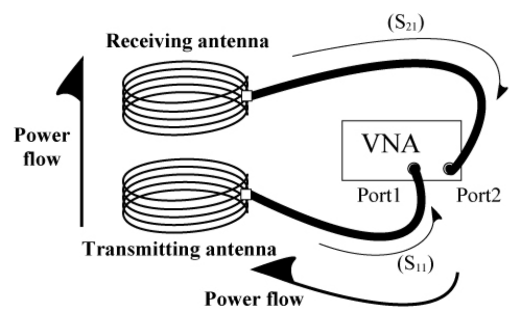
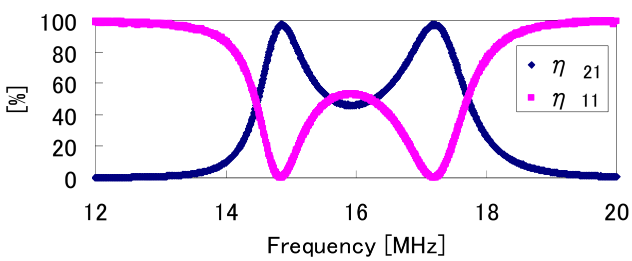


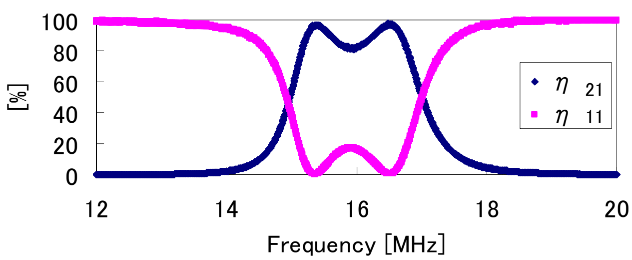
Fig. 5 Experimental setup for low power

III. EXPERIMENTAL RESULT AND REVIEW BY EQUIVALENT CIRCUITS

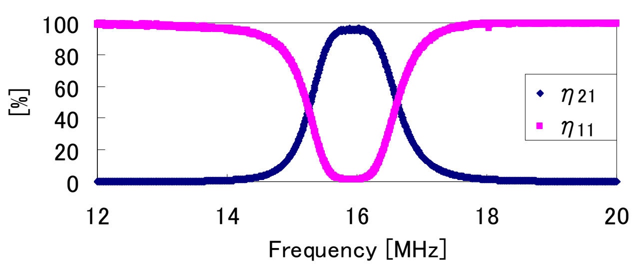
The experiments' results are shown in Fig. 6. In this case, air gaps are short (g = 100mm and g = 150mm). Resonant frequencies divide into two frequencies that are shown in Fig. 6 (a) and (b). In this case, at resonant frequency's efficiency of power transfer is very high and approximately 97% power can be transferred from a transmitting antenna to a receiving antenna. When the air gaps are changed resonant frequencies are changed but maximum efficiency is not changed. In this case, air gaps become long-approximately g ≈ 200mm and two resonant frequencies become one. The maximum efficiency is still the same as two frequencies 97% as is shown in Fig. 6 (c). The longer the air gaps become, the more efficiency is lost. In this case, air gaps are 250mm and the efficiency becomes 80% (Fig. 6 (d)).



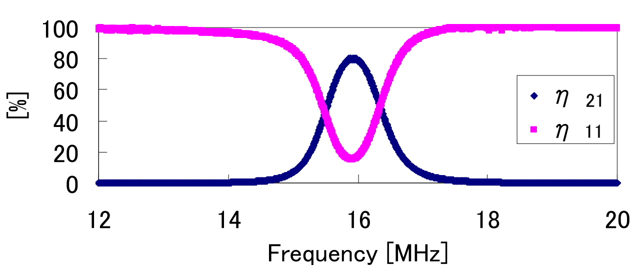
(a) g = 100 mm



(b) g = 150 mm



(c) g = 200 mm



(d) g = 250 mm

Fig. 6 Experimental results of efficiency in each gap

The relation of maximum efficiency to air gaps is shown in Fig. 7. The results of electromagnetic analysis were determined by the Method of Moment (Cal.) and the results (Exp.) are shown. The two resonant frequencies are f_m and f_e ($f_m < f_e$). The efficiency in Fig. 7 is the efficiency at f_m. The relation of resonant frequencies to air gaps is shown in Fig. 8. The relation of coefficient couplings to air gaps is shown in Fig. 9. The coupling coefficients during the experiments had small errors which were caused by characteristic impedance.

When air gaps are large, the coupling coefficients become small. Nevertheless, the efficiency of power transfer is very high. By electromagnetic analysis, when an air gap is g = 200mm, the couplings coefficient is only k=0.057. This means that in wireless power transfers using magnetic resonant couplings, if the coupling is weak, the electromagnetic resonance coupling can still transfer enough power to have a large air gap.

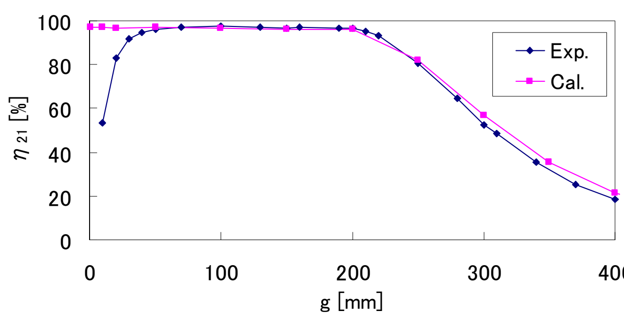


Fig. 7 Air gaps g vs. efficiency of power transfer η_{21}

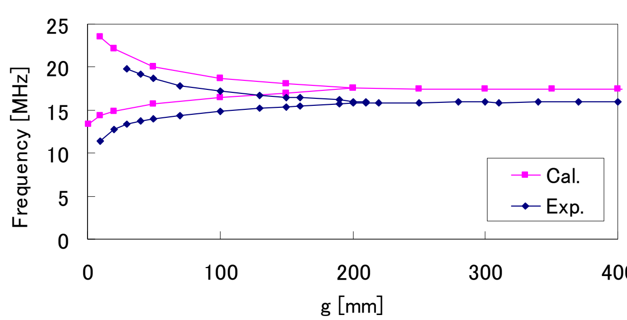


Fig. 8 Air gaps g vs. two resonant frequencies f_m and f_e ($f_m < f_e$)

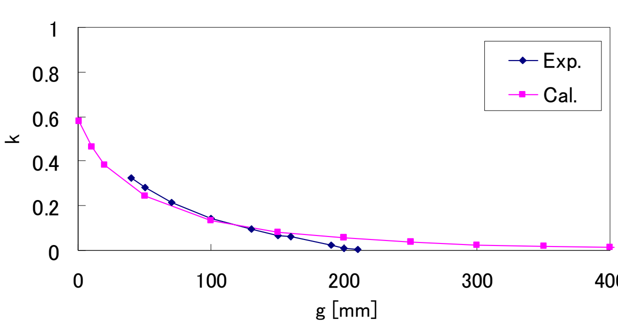


Fig. 9 Air gaps g vs. coupling coefficient k

IV. EXPERIMENTAL RESULT OF RELATION EFFICIENCY TO POWER

The coupling coefficient is set up by two resonant frequencies. The equivalent circuit of the magnetic resonance coupling is shown in Fig. 10. The only loss is copper, and in this case we ignore resistance R in order to prevent the equation from becoming too complicated. As well, the loss is so small that it is insignificant. Therefore, in this equation, $R = 0$. L is self induction and C is capacitance. These are decided by the distribution parameter system. The coupling coefficient is represented by the mutual inductance L_m. The transmission S_{21} is equivalent (3). The efficiency of power transfer is set up by equivalent (3) and (2). Equivalent (4) is delivered by resonant condition that leads to two equivalent frequencies in equivalent (5) and (6). By two resonant frequencies, the coupling coefficient is lead to equation (7). Angular frequency is ω. Z_0 is the characteristic impedance.

$$S_{21}(\omega) = \frac{2jL_m Z_0 \omega}{L_m^2\omega^2 - \left(\omega L - \frac{1}{\omega C}\right)^2 + 2jZ_0\left(\omega L - \frac{1}{\omega C}\right) + Z_0^2} \quad (3)$$

$$\frac{1}{\omega L_m} + \frac{2}{\omega(L - L_m) - \frac{1}{\omega C}} = 0 \quad (4)$$

$$\omega_m = \frac{\omega_0}{\sqrt{1+k}} = \frac{1}{\sqrt{(L+L_m)C}} \quad (5)$$

$$\omega_e = \frac{\omega_0}{\sqrt{1-k}} = \frac{1}{\sqrt{(L-L_m)C}} \quad (6)$$

$$k_m = \frac{L_m}{L} = \frac{\omega_e^2 - \omega_m^2}{\omega_e^2 + \omega_m^2} \quad (7)$$

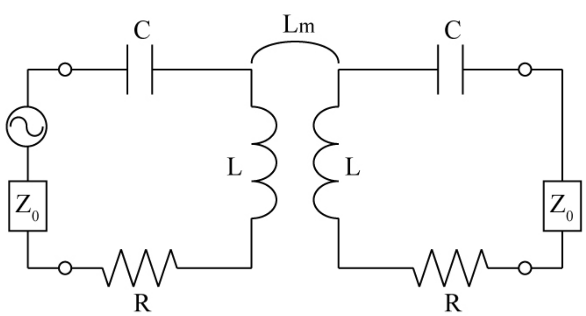


Fig. 10 Equivalent circuit of magnetic resonant coupling

Theoretically, the efficiency of power transfer does not depend on the amount of power which is described in equations (2) and (3). Therefore, the efficiencies should be constant. Experimental verification is needed, however, because the effect of heat, arc, etc. is not known until constant power efficiency is confirmed. The air gap is 200mm and the frequency is set to act maximum efficiency of 15.9MHz.

In this case, the power is low and is measured by VNA. The power is changed from -15dBm to 5dBm. This result is shown in Fig. 11. The result shows the efficiencies are approximately 95-96% and are almost constant. In this case, the power is high and is measured by a power meter. The power is changed from 5W to 100W and the efficiencies are almost the same as the efficiencies of low power. In this case, the input power is 104.2W and the received power is 100.0W. The efficiency is 96.0%. In this experiment, the exactly temperatures aren't measured; however the antennas aren't heated at all and no arc is observed.

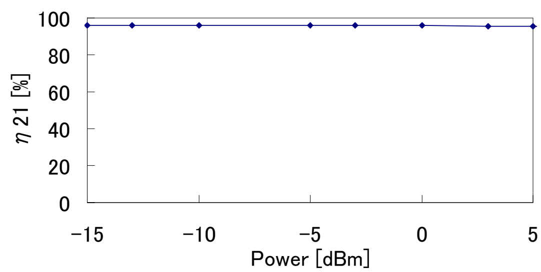


Fig. 11 Power vs. efficiency in low power

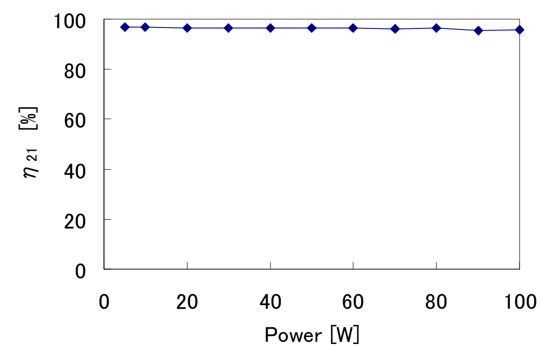


Fig. 12 Power vs. efficiency in high power

V. CONCLUSION

We have studied the characteristics of antennas for magnetic resonance couplings by equivalent circuits, electromagnetic analysis and experimentation. The antenna's size is small enough to be equipped to the bottom of the EV. The resonant frequencies change from two points to one point depending on the length of the air gaps. Until a certain distance, the maximum efficiencies at resonant frequency are not changed. The efficiencies are approximately 95-97%. Wireless power transfer across large air gaps while maintaining such a high efficiency is possible, even when the coupling coefficient is 0.057. Weak couplings can transfer power wirelessly though they have large air gaps. Characteristics of efficiency at low and high power are same have been shown.

REFERENCES

[1] Y. Kamiya, T. Nakamura, T. Sato, J. Kusaka, Y. Daisho, S. Takahashi, K. Narusawa, "Development and performance evaluation of advanced electric micro bus equipped with non-contact inductive rapid-charging system", Proceedings of the 23rd international electric vehicle symposium (EVS), Electric/ hybrid-electric session, pp. 1- 14(CD-ROM). 2007. 12

[2] Brown W.C., "Status of the Microwave Power Transmission Components for the Solar Power Satellite", IEEE Transactions on Microwave Theory and Techniques, vol.Mtt-29, NO.12, December 1981.

[3] N. Shinohara, H. Matsumoto, "Wireless Charging System by Microwave Power Transmission for Electric Motor Vehicles", IEICE. C, Vol.J87-C, No.5, pp.433-443, 2004.

[4] André Kurs, Aristeidis Karalis, Robert Moffatt, J. D. Joannopoulos, Peter Fisher, Marin Soljačić, "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," in Science Express on 7 June 2007, Vol. 317. no. 5834, pp. 83 – 86.

[5] Aristeidis Karalis, J.D. Joannopoulos and Marin Soljačić, "Efficient wireless non-radiative mid-range energy transfer," Annals of Physics, Volume 323, Issue 1, January 2008, Pages 34-48, January Special Issue 2008.