Flexibility of Contactless Power Transfer using Magnetic Resonance Coupling to Air Gap and Misalignment for EV

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Abstract

Nowadays, the establishment of the technologies of contactless power transfer (CPT) for electric vehicles (EVs) are needed. The system can provide people with a convenient charging system which can powers their EVs wirelessly and automatically when they park. Traditional CPT solutions have the problem of distance between transmitting antennas and receiving antennas (air gap), as well as from the misalignment of the antennas. Those systems cannot power at a great distance and the efficiency is very low. In this paper, CPT by magnetic resonance couplings and small antennas are proposed. These techniques more easily span air gaps and are more forgiving to antennas misalignments than traditional solutions. The Efficiencies are still high when the air gaps are longer than the diameter of the antennas. As well, the efficiencies are over 90% when the antennas are half a diameter out of alignment. For example, when the air gap and the displacement is 150mm, the efficiency is about 96%. The magnetic resonant couplings can power wirelessly even if there is a weak connection. Thus, a large air gaps with high efficiency are possible. The relation between two resonant frequencies and the coupling coefficient are described using the method of equivalent circuits. As well, the relation between resonant frequencies and the efficiencies, especially the moment of decreasing, are described.

Keywords: wireless power transfer, contactless power transfer, magnetic resonance couplings, electric vehicle, antenna

1 Introduction

Nowadays, EVs are being widely researched and developed. Due to the high power density enhanced in rechargeable batteries, a wide use of Electric vehicles (EVs) could soon become available. But, this energy is not enough for the EVs to be driven for a week without being charged. The EVs need to be charged once a day. EV batteries are commonly recharged by connecting them to power sources. However, in this way, a code is needed and it needs to be plugged in. In that way, recharging is not convenient. A novel solution that does not require the user to connect the batteries to a power source could be Contactless Power Transfer (CPT). In this way, CPT can add more value to EVs to surpass the gasoline vehicle in terms of convenience. In fact, by using this technology, the user does not have to think about connecting the EV to a power source, because the charging is done automatically by the wireless technology.

However, the traditional CPT has the problem of distance between the transmitting and receiving antennas (air gap) as well as from the antennas' misalignment. This system needs the flexibility to be effective when the antennas are not aligned; otherwise we need to perfectly align the vehicle directly over the transmitting antenna so that the receiving antenna under the chassis can properly receive the charge.

CPT technology can be classified into: electromagnetic induction, microwave power transmission and electromagnetic resonant coupling. In electromagnetic induction, the air gap is short (10 cm) and the alignment must be accurate (within 1-2cm) [1]. In microwave power transmission, air gap is very long but efficiency is very low [2][3]. The electromagnetic resonant couplings method has a long air gap and is forgiving when it comes to alignment [4][5]. Antennas are very important for contactless power transfer technology. In this paper, parameters and design of suitable antenna EVs are proposed. The proposed antennas are forgiving for air gaps and axis variations.

2 Experimental setup

In this paper, parameters and designs of suitable antennas for EVs are proposed. The entire system of contactless power supply is shown in Fig. 1. The system consists of the contactless power supply of a high frequency power source, a transmitting antenna, a receiving antenna, a rectifying circuit and electric power storage (batteries or electric double layer capacitors [EDLCs]). In this paper, antennas will be the main focus.

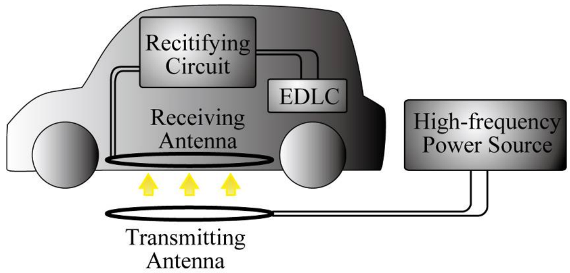


Fig. 1 System of contactless power transfer

In fig.2, the parameters of the antennas used are shown. *r* is the radius of the antennas. *g* is the air gaps between the transmitting and receiving antenna. *d* is the displacement of antennas. *p* is the pitch of the antennas. *n* is the turns of the antennas. In this paper, r = 150mm and p = 5mm.

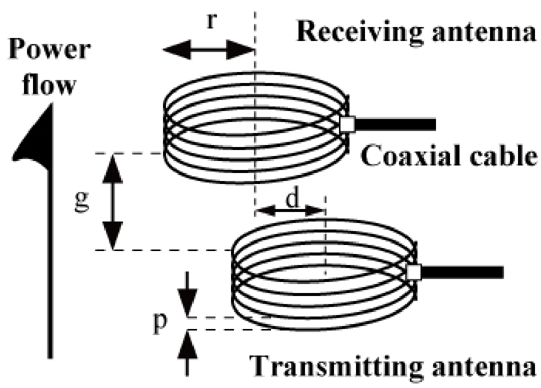


Fig. 2 Parameters of antennas

Reflection and transmission are shown in equations (1) and (2). η_{11} is the percentage of power reflection and η_{21} is the percentage of power transmission. In other words, η_{21} is the efficiency of power transmission. S_{11} is the coefficient of reflection and S_{21} is the coefficient of transmission.

$$\eta_{11} = S_{11}^2 \times 100 \quad [\%] \qquad (1)$$
$$\eta_{21} = S_{21}^2 \times 100 \quad [\%] \qquad (2)$$

The experimental set up is shown in Fig. 3 where the vector network analyzer (VNA) is used. The VNA put out power from port 1 to the transmitting antenna through a coaxial cable and swept the frequencies. The power was transferred wirelessly to the receiving antenna and put in port 2.

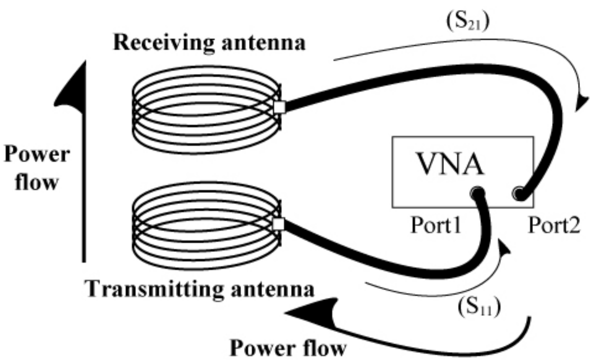


Fig. 3 Experimental set up

The experimental antennas are shown in Fig. 4. At the bottom is the transmitting antenna and at the top is the receiving antenna. Fig. 5 shows the displacement of the antennas.

For the electromagnetic field analysis, the method of moments (MoM) is used.

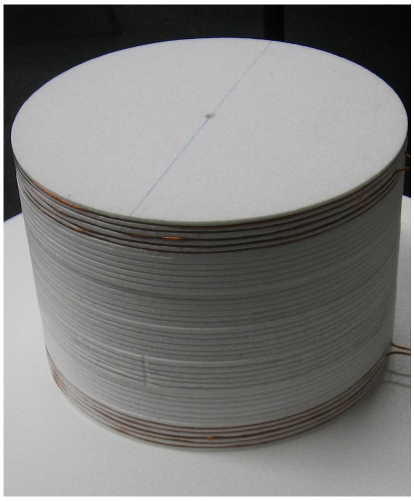


Fig. 4 Transmitting antenna and receiving antenna

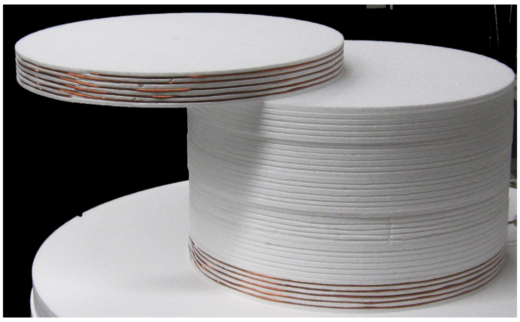


Fig. 5 Transmitting antenna and receiving antenna improperly aligned

3 Contactless power transfer results using electromagnetic resonant couplings

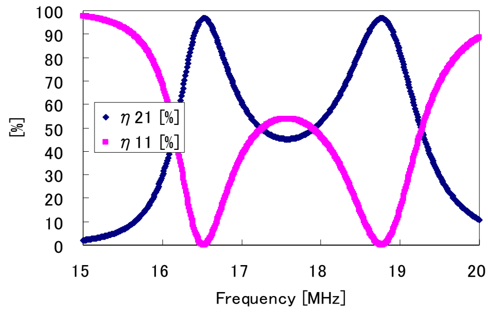
In this section, the flexibility in air gaps and alignment are discussed. The efficiency of contactless power transfer vs. air gaps are discussed in paragraph 3.1 and the efficiencies vs. axis alignment are discussed in paragraph 3.2.

3.1 Efficiency vs. air gaps

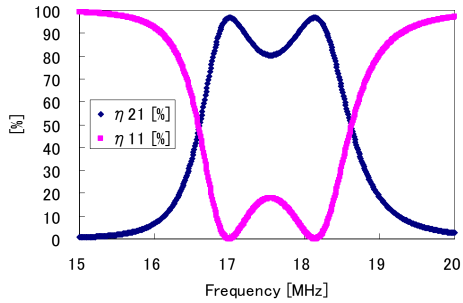
Fig. 6 shows the result of the efficiencies of CPT using the magnetic resonant couplings in respect to the air gaps which are calculated by the electromagnetic field analysis, MoM. η_{11} is the percentage of power reflection and η_{21} is the percentage of power transmission. It is shown how resonant frequencies and efficiency change in respect to the air gaps. In this case, there is no displacement and there are 5 coils.

When air gaps (g) are short, numbers of resonant frequencies are two. As the length of air gaps become larger, the two resonance frequencies, f_m and f_e ($f_m < f_e$), approach to each other and become one frequency. Until the numbers of resonance frequencies become one, the maximum value of the efficiency is almost the same and the efficiencies are around 96-97% (Fig. 6 (a), (b), (c)). After the numbers of resonance frequencies are one, the efficiency becomes worse and decrease to zero (Fig. 6 (d)).

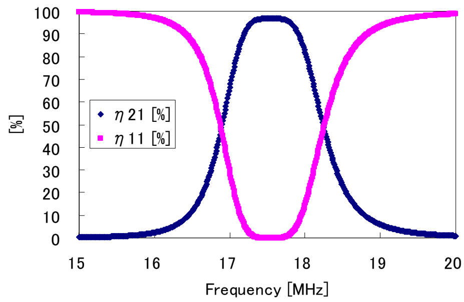
The equivalent circuit of the magnetic resonant coupling is shown in Fig. 7. The left side is the transmitting antenna and the right side is the receiving antenna. In a resonant coupling, the antenna resonates by itself, then, the antenna is represented by inductance and capacitance. Resonant frequencies and coupling coefficient can be calculated. L_m is the mutual inductance of two antennas and k_m is coupling coefficient which is representative of how much of the magnetic power link is and where air gaps are. L is self inductance, C is capacitance, R is resistance and Z_0 is characteristic impedance. In this case, Z_0 = 50 ohms.



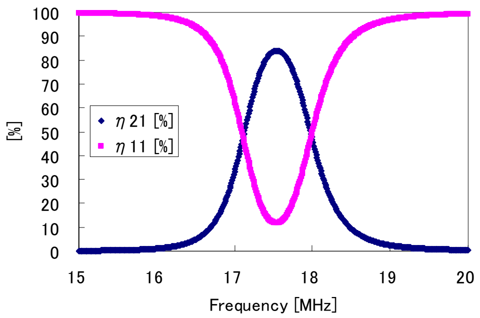
(a) g＝100mm



(b) g＝150mm



(c) g＝200mm



(d) g＝250mm

Fig. 6 Efficiency with air gaps

(r＝150mm, n＝5, p＝5mm)

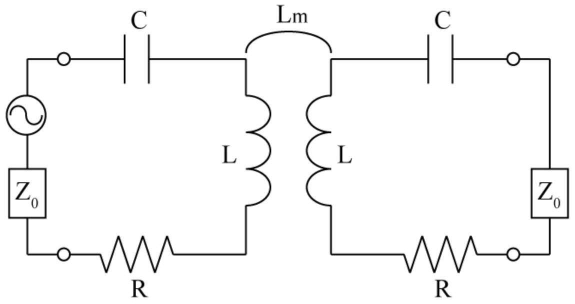


Fig. 7 Equivalent circuit of magnetic resonant couplings

Equation (3) represents the relation of reactance of the equivalent circuit at the resonance. This leads to equations (4) and (5). These represent two resonant angular frequencies. Equation (6) represents the coupling coefficient k_m and this means k_m is lead by two resonant frequencies.

$$\frac{1}{\omega L_m} + \frac{2}{\omega(L - L_m) - \frac{1}{\omega C}} = 0 \quad (3)$$

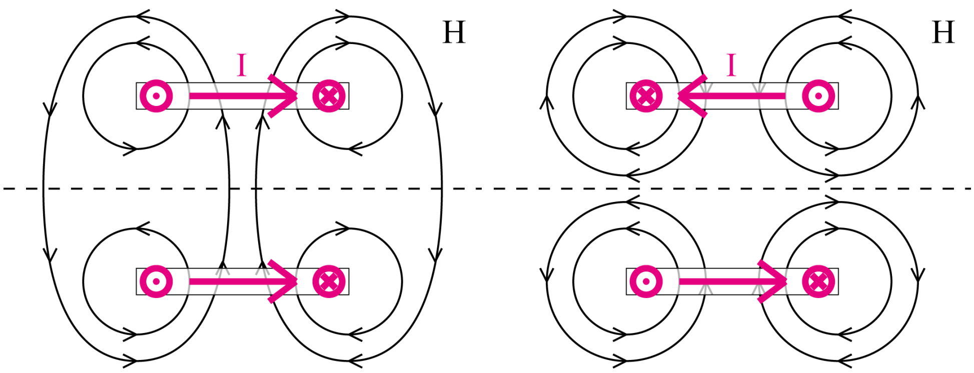
$$\omega_m = \frac{\omega_0}{\sqrt{1+k}} = \frac{1}{\sqrt{(L + L_m)C}} \quad (4)$$

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

$$k_m = \frac{L_m}{L} = \frac{\omega_e^2 - \omega_m^2}{\omega_e^2 + \omega_m^2} \quad (6)$$

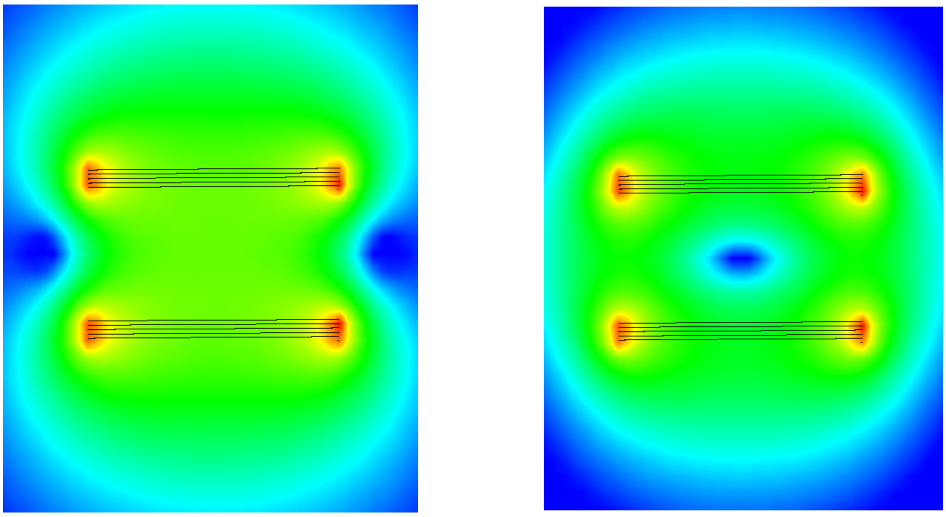
Fig. 8 shows the diagrams of magnetic field and currents from the side. Fig. 8 (a) is a depiction of low resonance frequency, f_m and Fig. 8 (b) is a depiction at high resonance frequency, f_e. In Fig. 8 (a) the currents are almost the same direction and the magnetic direction has become the same at the center of the coils. On the other hand, in Fig. 8 (b) the currents have reversed direction and the magnetic direction has become the same at the edge of the coils. The magnetic field is illustrated in Fig. 9 and the magnetic field is illustrated in Fig. 10. The strong coupling can be seen at magnetic power density on both resonant frequencies. The weak coupling, however, can be seen at electric power density. These results imply that the couplings are not electric but magnetic.

The wirelessly transferred power does not radiate in magnetic resonance couplings. Therefore, the power remains inside and near antenna when there is only a transmitting antenna. When the receiving antenna moves in the field of the transmitting antenna and the resonance of the two antennas are the same, the wireless power transfer from the transmitting antenna to the receiving antenna has a high efficiency.



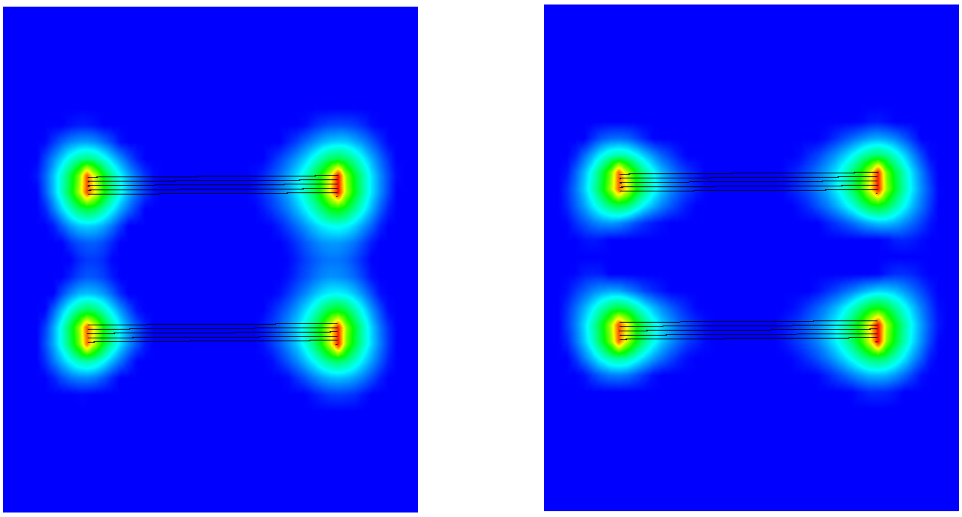
(a) Magnetic wall, f_m (b) Electric wall, f_e

Fig. 8 Schematic of magnetic field and current at resonant frequencies



(a) Magnetic wall, f_m (b) Electric wall, f_e

Fig. 9 Magnetic fields at resonant frequencies



(a) Magnetic wall, f_m (b) Electric wall, f_e

Fig. 10 Electric fields at resonant frequencies

3.2 Efficiency and resonant frequencies at alignment

Fig. 11 shows the efficiency of power transfer in respect to displacement (*d*) for several air gaps. The air gaps (*g*) range from 50mm to 200mm. The results are not only electromagnetic field analysis, but also experimental results. In this case, the plotted efficiency is the one of resonant frequency, f_m which is of the lower resonant efficiencies. When the displacement is smaller, the efficiencies are nearly all over 90% in each gap. When the gaps are short (*g* = 50mm, 100mm and 150mm) and the displacement is less than 150mm, this distance is equal to the radius, the efficiencies are nearly all over 90%. When the air gap is large (g = 200mm) the efficiencies decrease at *d* being over 50 mm.

The resonant frequencies are shown in Fig. 12 and two resonance frequencies are f_m and f_e ($f_m < f_e$). The resonant frequencies are two when the distance between the transmitting antenna and the receiving antenna is close, while they become one when the distance is long. The one frequency is equal to the resonant frequency of the single transmitting or the single receiving antenna.

Compared to Fig. 11 and Fig. 12, we can discover that the efficiency starts to decrease only after the two resonant frequencies become one (*g* = 50 mm and *d* = 190 mm, *g* = 150 mm and *d* = 130 mm and *g* = 200 mm and *d* = 0 mm).

The coupling coefficient (*k*) is shown in Fig. 13. When the gap and the displacement are short, the value of the coupling coefficient is large. When the gap and displacement is large, the coupling coefficient is close to zero, however, the efficiencies are still high. This means that even when the coupling is weak, the power can be transferred wirelessly. Thus, power can still be efficiently transferred through large air gaps.

k is defined by equation (6); however, the strictly accurate *k* is defined by f_m and f_e under Z_0 = 0 ohm, but this electromagnetic field analysis and experiment was done by Z_0 = 50 ohms is why there is small error.

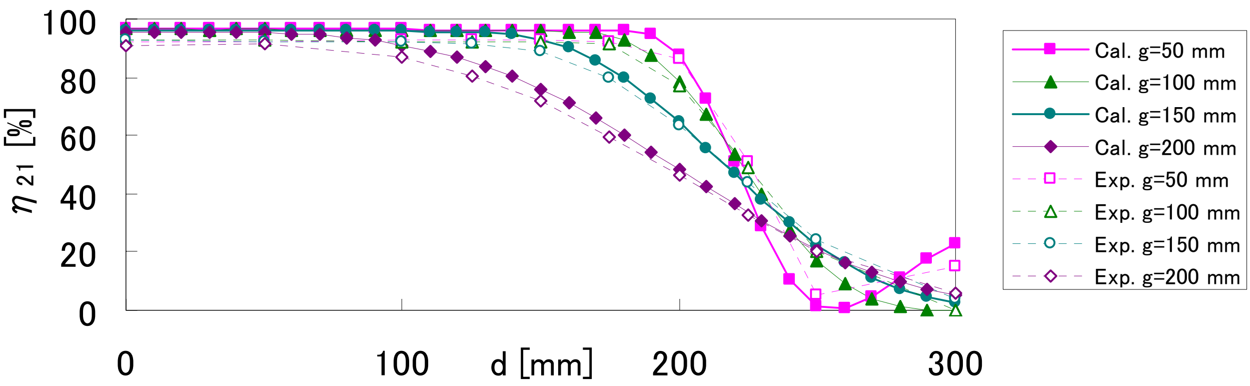


Fig. 11 Efficiency with alignment
(r＝150mm, n＝5, p＝5mm, Cal. is electromagnetic field analysis' results and Exp. is experimental results.)

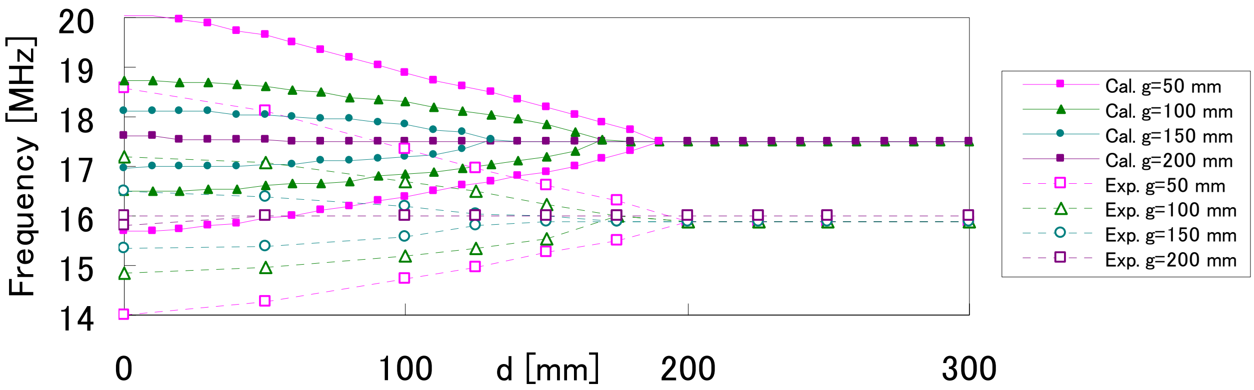


Fig. 12 Resonant frequencies with alignment
(r＝150mm, n＝5, p＝5mm, Cal. is electromagnetic field analysis' results and Exp. is experimental results.)

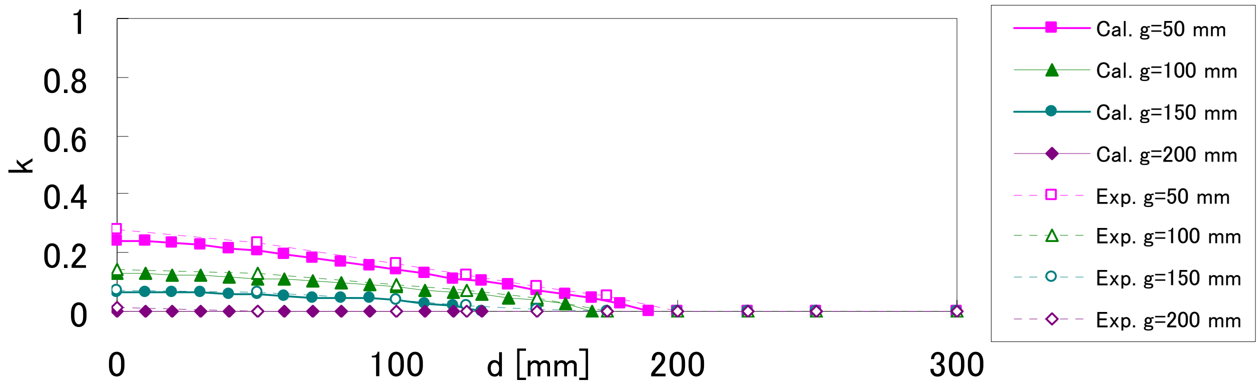


Fig. 13 Coupling coefficient with alignment
(r＝150mm,　n＝5,　p＝5mm, Cal. is electromagnetic field analysis' results and Exp. is experimental results.)

In Fig. 14, the electromagnetic field analysis' calculation efficiencies are shown as they are related to alignment in both the *d* and *g* direction when turns *n* are 5. These results are same in Fig. 11 and the plotted values of efficiencies are at lower resonant frequencies, however, more detail values are plotted.

In this figure, the top of the transmitting antenna is located at (*d*, *g*) = (0, 0) and the locations of the receiving antenna and the efficiencies of wirelessly transmitted power are plotted.

Fore example, when the receiving antenna is located at (*d*, *g*) = (0, 0), (200, 0), (0, 200) the efficiencies are over 90%. When (*d*, *g*) = (150, 150) the efficiency is about 96%. When (*d*, *g*) = (0, 300) the efficiency is 60-70%. When (*d*, *g*) = (150, 300) the efficiency is 10-20%. The area of efficiency that is over 90% is almost located less than 200 mm between the transmitting antenna and the receiving antenna. The area over 90% is almost forms a half circle.

In Fig. 15, turns *n* are 10. Then inductance of antennas increase and the area of power transfer with high efficiencies expand compared to the 5 turn antennas' results. For example, when the receiving antenna is located at (*d*, *g*) = (200, 200), (0, 300) the efficiencies are over 90%.

These results imply that the magnetic resonance couplings with the use of these antennas are better able to more efficiently and reliably cross air gaps and more flexibly alignment than more traditional solutions.

The minimum ground clearance of passenger vehicles is between about 90 mm to 200 mm. Therefore, 10 turn antennas are cover wider than 5 turn antennas, so 10 turn antennas are more suitable for EVs.

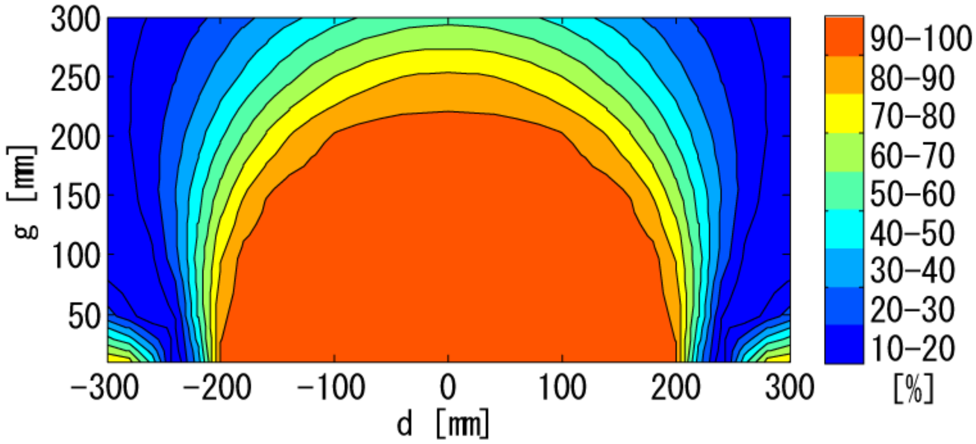


Fig. 14 Contour of efficiency with axis alignment at 5 turns

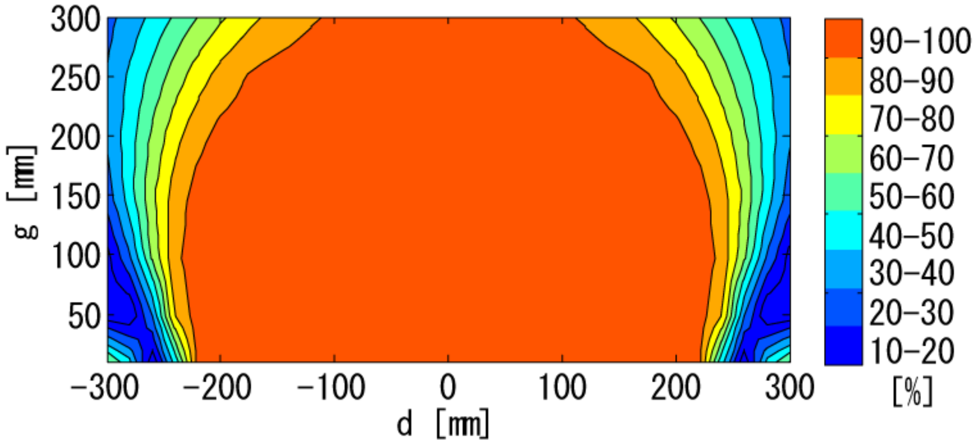


Fig. 15 Contour of efficiency with axis alignment at 10 turns

4 Conclusion

In this paper, the CPT system by electromagnetic resonant couplings is described and the feasibility of it is studied- especially about antenna characteristics.

The magnetic resonant couplings can power wirelessly even if there is a small connection, therefore, large air gaps with high efficiency can be achieved.

The efficiencies are higher than 90% between the length of transmitting antenna and the receiving antenna are less than 200 mm at resonant frequencies.

The minimum ground clearance of passenger vehicles is between about 90 mm to 200 mm. Therefore, 10 turn antennas are cover wider than 5 turn antennas, so 10 turn antennas are more suitable for EVs.

These results imply that the CPT system by electromagnetic resonant couplings is better suited to traverse air gap and easily align than more traditional solutions and are suitable to wireless power transfer to electric vehicles.

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