Analysis of the Finite PEC plate Effect on Wireless Power Transfer using Characteristic Mode Method

Jongmin Park[1], Sangwook Nam[2]

[1]Spaceborne SAR R&D Lab., LIGNex1 Co. Ltd., Korea

[2]The School of Electrical Engineering and INMC, Seoul National University Seoul 151-742, Korea

***Abstract* — The finite PEC plate effect on Wireless Power Transfer (WPT) was investigated. The characteristic mode method was suggested to analyze the effect of the finite PEC plate. For electrically small size bodies, only a few characteristic modes are needed to characterize the electromagnetic behavior of the body. The theory is verified by a simulation with small loops and a small size PEC plate.**

***Index Terms* —Wireless power transfer, Near-field coupling, Characteristic mode.**

I. INTRODUCTION

WPT has application to various electronic equipment. In that case, the effect of a metal should be considered. The guidelines have been suggested regarding the accuracy of using image theory for electrostatic problems involving finite conducting structures [1]. Image theory is invalid for the small size metal case. The characteristic mode (CM) method is well known for the ability to provide a series of fundamental modes for arbitrarily shaped conducting bodies, regardless of the feeding methods [2]. During the past years, the CM method is widely used in the synthesis and optimization of various antennas and scatters [3]–[4]. The CMs are the linear superposition of the surface current components on all the bodies. Also, only a few CMs are needed to characterize the electromagnetic behavior of the electrically small size body. In this paper, we investigate the effect of finite size PEC plate using CM method.

II. CHARACTERISTIC MODE THEORY

CMs can be obtained as the eigenfunctions of the following particular weighted eigenvalue equation:

$$X\left(J_n\right)=\lambda_n R\left(J_n\right) \tag{1}$$

where the λ_n are the eigenvalues, the J_n are the eigenvectors or characteristic modes. This impedance operator is obtained after formulating an integro-differential equation. The J_n must satisfy the usual orthogonality relationships which can be summarized as:

$$\left\langle J_m, RJ_n\right\rangle=\left\langle J_m^*, RJ_n\right\rangle=\delta_{mn} \tag{2}$$

$$\left\langle J_m, XJ_n\right\rangle=\left\langle J_m^*, XJ_n\right\rangle=\lambda_n\delta_{mn} \tag{3}$$

where δ_{mn} is the Kronecker delta. The CMs are of indeterminate amplitude. So each characteristic current can be normalized the radiating power. Due to the orthogonality properties, characteristic modes can be used as a basis set in which to expand the unknown total current, J, on the surface of the conducting body as:

$$J=\sum_n \frac{V_n^i}{1+j\lambda_n}\frac{J_n}{\left\langle J_n, RJ_n\right\rangle} \tag{4}$$

V_n^i is called the modal excitation coefficient. It is defined as:

$$V_n^i=\left\langle J_n, E^i\right\rangle=\oiint_S J_n\cdot E^i ds \tag{5}$$

The effect of the PEC plate on WPTS can be expressed in matrix form as (6) using kirchhoff's voltage law. Z_{Tx} and Z_{Rx} are impedance of the isolated transmitting and receiving antenna, respectively. Φ_{α_β} means the magnetic flux, which pass through α antenna, occurred by β current. PEC_{Tx} and PEC_{Rx} is the current at the PEC plate induced by the transmitting and receiving antenna, respectively. The current at the antennas set up a unit current.

$$\begin{bmatrix} V_s \\ 0 \end{bmatrix}=\begin{bmatrix} Z_{Tx}+j\omega\left(\Phi_{Tx\_PEC_{Tx}}\right) & j\omega\left(\Phi_{Tx\_Rx}+\Phi_{Tx\_PEC_{Rx}}\right) \\ j\omega\left(\Phi_{Rx\_Tx}+\Phi_{Rx\_PEC_{Tx}}\right) & Z_{R2}+Z_{Load}+j\omega\left(\Phi_{Rx\_PEC_{Rx}}\right) \end{bmatrix}\begin{bmatrix} I_{Tx} \\ I_{Rx} \end{bmatrix} \tag{6}$$

The flux is represented as

$$\Phi_{\alpha\_\beta}=\int_{S_\alpha} B_\beta\bullet dS_\alpha=\oint_{C_\alpha} A_\beta\bullet dl_\alpha \tag{7}$$

From the Z-matrix (6), the maximum power efficiency and the optimum load impedance can be find.

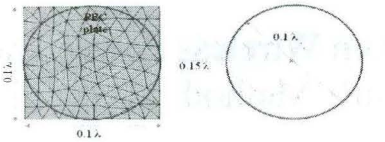

Fig. 1. Small loop antenna with PEC plate (diameter = 0.1 λ, distance between antennas = 0.15 λ, PEC plate = 0.1 x 0.1 λ^2).

III. EXAMPLE

To verify the theory, we compare the power transfer efficiency of actual antennas. A small loop antenna is chosen as illustrated in Fig. 1. Material of loop antennas is copper and diameter of wire is 1 mm. We complement series capacitances to prevent a change of phase. Three capacitances of 2.2 pF are used. The impedance matrix were obtained by a simulation using FEKO, a commercially available software. From (1), CMs and eigenvalues of the PEC plate are obtained. Computation of CMs was done using 191 Rao-Wilton-Glisson (RWG) basis functions for expansion and testing. Eigenvalues of the three characteristic current mode are shown in TABLE 1.

TABLE 1
Eigenvalues of Six Characteristic Current

Mode	Eigenvalue (λ)
1	-7.33 E1
2	-7.36 E1
3	1.93 E2

Magnitude of Eigenvalues gives information about how well the associated mode radiates. In contrast, reactive power is proportional to the magnitude of the eigenvalue. The sign of the eigenvalue determines whether the mode contributes to storing magnetic energy or electric energy. Mode current 1 and 2 present capacitive nature due to its currents forming opened lines. On the other hand, mode current 3 depicts inductive nature due to its currents forming closed loops over the plate. In this simulation, antenna type is loop. So modal excitation coefficient of mode current 3 is maximized. We can easily expect that the mode current 3 is dominant mode. When the height between PEC plate and transmitting antenna is closer, the coupling between the loop antennas is weaker. The results agree with the calculation results using characteristic modes. Fig. 2 shows the power transfer efficiency with PEC plate. We can predict the power transfer efficiency according to the height. When the height is closer, the power transfer efficiency is smaller. The results agree with the results of CM method using only 1 CM.

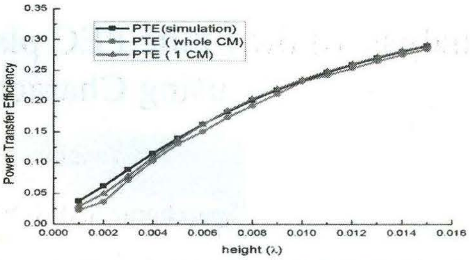

Fig. 2. Power transfer efficiency with PEC plate.

IV. CONCLUSION

We investigated the effect of finite size PEC plate on WPT. To analyze the effect we use CM theory which is really helpful. First, The modified Z-matrix has been built as shown in (6). Then, the induced current on PEC plate is calculated using CM method. When PEC plate is small compared with antennas, image theory is invalid any more. But the scattering field at the PEC plate is easily analyzed using CM method which use only a few CM. Our method is simple compared with other analysis techniques. Finally, the Theoretical results agreed with the simulation results.

ACKNOWLEDGEMENT

This research was supported by a grant to Bio-Mimetic Robot Research Center funded by Defense Acquisition Program Administration, UD130070ID.

REFERENCES

[1] Nelson R., Jalil S., Mu J., "Using image theory for finite electrostatic problems-some observations and guidelines," *International Symposium on Electromagnetic Compatibility*, 1997, Austin, TX, pp. 527-532.

[2] Roger F. Harrington, Joseph R. Mautz, "Theory of Characteristic Modes for Conduction Bodies," *IEEE Trans. Antennas and Propag.*, vol. 19, no. 5, pp. 622–628, Sep. 1971.

[3] D. Liu, R. J. Garbacz, and D. M. Pozar, "Antenna synthesis and optimization using generalized characteristic modes," *IEEE Trans. Antennas Propag.*, vol. 38, no. 6, pp. 862–868, Jun. 1990.

[4] A. El-Hajj, K. Y. Kabalan, and A. Rayes, "Characteristic mode formulation of multiple rectangular apertures in a conducting plane with a dielectric-filled cavity," *IEEE Trans. Electromag. Compat.*, vol. 40, no. 2, pp. 89–93, May 1998.