Electromagnetic field analysis of the wire antenna in the presence of a dielectric with three-dimensional shape

H. Tsuboi[*] H. Tanaka[†]

M. Fujita[‡]

[*]Okayama University

[†]Okayama University

[‡]Fuji Electric Corporate Research and Development, Limited

ELECTROMAGNETIC FIELD ANALYSIS OF THE WIRE ANTENNA IN THE PRESENCE OF A DIELECTRIC WITH THREE-DIMENSIONAL SHAPE

H. Tsuboi and H. Tanaka
Department of Electrical and Electronic Engineering,
Okayama University, Okayama 700, Japan

M. Fujita
Fuji Electric Corporate Research and Development, Ltd.,
Ichihara, Chiba 290, Japan

Abstract: A numerical method which can take account of lossy dielectrics near the antenna has to be developed for the design of the radio frequency antenna in magnetic resonance imaging, because the human body is a lossy dielectric. In this paper, a combined method of the moment method and the boundary element method is proposed. For the verification of the proposed method, a helical antenna loaded with cylinder was chosen as a calculation model, and the calculated results were compared with the experimental results.

Introduction

In the design of the radio frequency (RF) antenna for magnetic resonance imaging (MRI), the moment method can be used to determine the geometry of the antenna and to improve the current distribution on the antenna[1]. Because the human body is a lossy dielectric, a numerical method which can take account of lossy dielectrics near the antenna[2] has to be developed.

In order to analyze the electromagnetic field of the wire antenna in the presence of a dielectric body with three-dimensional shape, we propose a combined method of the moment method and the boundary element method. We can use the moment method for the analysis of wire antennas[3] and the boundary element method for the analysis of three-dimensional scattering problems[4],[5]. In the proposed method, the scattering field of dielectrics in the moment method is calculated by using the equations of the boundary element method, and the impressed field of current distribution in the boundary element method is calculated by using the approximation of the current distribution in the moment method.

Formulation

Figure 1 shows a simple wire antenna model in the presence of a dielectric body. In order to combine the moment method with the boundary element method, the interactions between the two methods have to be considered.

In the moment method, the boundary condition at the field point l on the wire surface is given by

$$(\mathbf{E}^i + \mathbf{E}^s)\cdot \hat{l} = 0 \qquad (1)$$

where $\mathbf{E}^i$ is the impressed electric field, $\mathbf{E}^s$ is the scattered electric field and $\hat{l}$ is the unit vector along the wire axis. $\mathbf{E}^s$ is given by the sum of the scattered fields from the wire and the dielectric. $\mathbf{E}^w$ is given by the following equations:

$$\mathbf{E}^s = \mathbf{E}^d + \mathbf{E}^w \qquad (2)$$

$$\mathbf{E}^w = -j\omega\mathbf{A} - \nabla\psi \qquad (3)$$

where

$$\mathbf{A} = \int_L \mu_0 \mathbf{I}\phi \, dl$$

$$\psi = \int_L \frac{\rho}{\varepsilon_0}\phi \, dl$$

$\mathbf{I}$ and ρ are the current and the charge density, respectively, and ϕ is given by

$$\phi = \frac{e^{-jkr}}{4\pi r} \qquad (4)$$

The charge density ρ is obtained from the distribution of the current I by using the continuity condition of the current.

$$\rho = -\frac{\nabla\cdot\mathbf{J}}{j\omega} = -\frac{1}{j\omega}\frac{dI}{dl} \qquad (5)$$

$\mathbf{E}^d$ is given by the boundary element formulation.

The equation of the moment method at segment l is obtained as follows:

$$(\mathbf{E}^d{}_l + \mathbf{E}^w{}_l)\cdot \boldsymbol{l} = -\mathbf{E}^i{}_l \cdot \boldsymbol{l} = V_l \qquad (6)$$

where V_l is the applied voltage at segment l.

In the boundary element method, the electric field $\mathbf{E}_i$ and the magnetic flux density $\mathbf{B}_i$ at the field point i in the region V is given by

$$\frac{\Omega_i \mathbf{E}_i}{4\pi} = \mathbf{E}^d{}_i - \int_V \left(j\omega\mu\mathbf{J}\phi + \frac{\rho}{\varepsilon}\nabla\phi \right) dv \qquad (7)$$

$$\frac{\Omega_i \mathbf{B}_i}{4\pi} = \mathbf{B}^d{}_i + \int_V (\mu\mathbf{J}\times\nabla\phi)\, dv \qquad (8)$$

where

$$\mathbf{E}^d{}_i = \int_S \{-j\omega(\mathbf{n}\times\mathbf{B})\phi + (\mathbf{n}\times\mathbf{E})\times\nabla\phi + (\mathbf{n}\cdot\mathbf{E})\nabla\phi\}\, ds$$

$$\mathbf{B}^d{}_i = \int_S \{j\omega\mu\varepsilon(\mathbf{n}\times\mathbf{E})\phi + (\mathbf{n}\times\mathbf{B})\times\nabla\phi + (\mathbf{n}\cdot\mathbf{B})\nabla\phi\}\, ds$$

S is the boundary surface of the region V, Ω_i is the solid angle subtended by S, $\mathbf{E}^d$ and $\mathbf{B}^d$ are the electric field and the magnetic flux density induced by the dielectric body. In Eqs. (7) and (8), the integrals including $\mathbf{J}$ and ρ are rewritten by using the current I on the wire antenna as

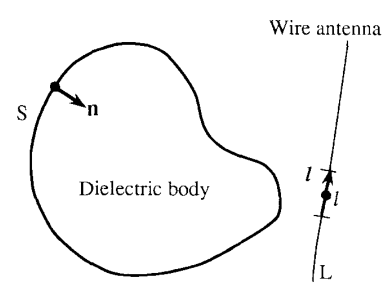

Fig.1 A simple wire antenna in the presence of a dielectric body.

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$$\int_V j\omega\mu_0 \mathbf{J}\phi dv = \int_L j\omega\mu_0 2\pi a \mathbf{J}\phi dl = \int_L j\omega\mu_0 \mathbf{I}\phi dl \qquad (9)$$

$$\int_V \frac{\rho}{\varepsilon_0} \nabla\phi dv = -\int_L \frac{1}{j\omega\varepsilon_0}\frac{dI}{dl} \nabla\phi dl \qquad (10)$$

$$\int_V \mu_0 \mathbf{J}\times\nabla\phi dv = \int_L \mu_0 2\pi a \mathbf{J}\times\nabla\phi dl = \int_L \mu_0 \mathbf{I}\times\nabla\phi dl \qquad (11)$$

The electric field $\mathbf{E}_i$ and the magnetic flux density $\mathbf{B}_i$ at the field point i on the dielectric surface S are obtained as follows:

$$\frac{1}{2}\mathbf{E}_i = \mathbf{E}^d_i + \mathbf{E}^w_i \qquad (12)$$

$$\frac{1}{2}\mathbf{B}_i = \mathbf{B}^d_i + \mathbf{B}^w_i \qquad (13)$$

where

$$\mathbf{E}^w_i = -\int_L \left(j\omega\mu_0 \mathbf{I}\phi - \frac{1}{j\omega\varepsilon_0}\frac{dI}{dl}\nabla\phi \right) dl$$

$$\mathbf{B}^w_i = \int_L \left(\mu_0 \mathbf{I}\times\nabla\phi \right) dl$$

Finally, the simultaneous equations for the unknown electric fields, unknown magnetic flux densities on the dielectric surface and unknown currents on the wire surface are formed.

$$\begin{bmatrix} \{CB\} & \{CI\} \\ \{CE\} & \{CM\} \end{bmatrix} \begin{Bmatrix} \begin{Bmatrix} E \\ B \end{Bmatrix} \\ \{I\} \end{Bmatrix} = \begin{Bmatrix} \{0\} \\ \{V\} \end{Bmatrix} \qquad (14)$$

where {CB}, {CE}, {CI} and {CM} are the coefficient matrices defined by $\mathbf{E}^d_i$ on the dielectric surface, $\mathbf{E}^d_l$ on the wire antenna surface, $\mathbf{E}^w_i$ and $\mathbf{B}^w_i$ on the dielectric surface and $\mathbf{E}^w_l$ on the wire antenna respectively in Eqs. (6), (12) and (13), and {V} is the applied voltage matrix to the wire antenna.

Calculated and Experimental Results

In order to verify the applicability of the proposed method, a helical antenna model loaded with a dielectric cylinder shown in Fig. 2 was chosen. An epoxy cylinder ($\varepsilon=5.3\varepsilon_0$, $\sigma=0$), pure water ($\varepsilon=90\varepsilon_0$, $\sigma=0$) and city water ($\varepsilon=90\varepsilon_0$, $\sigma=2.1\times10^{-2}$) in a cylinder container are used as dielectrics. Input admittances of the helical antennas were investigated.

Figure 3 shows the input admittances of the helical antenna without loading (D_a=0.319). The number of segments of the helical antenna is 108. The calculated results only by the moment method agree with experimental results.

Figure 4 shows the input admittances of the helical antenna loaded with the epoxy cylinder (D_a=0.319, D_d=0.299, H=0.153). The number of the segments and the triangular elements are 108 and 500, respectively. Unknown electric field and magnetic flux density in the boundary element method are defined to be constant on each triangular element. The calculated results of the proposed method agree with the experimental results.

Figures 5 and 6 show the calculated results of the helical antenna loaded with pure water or city water in cylinder container (D_a=0.270, D_d=0.240, H=0.150). The number of the segments and the triangular elements are 93 and 500, respectively. In these cases, the calculated resonance frequencies slightly shifted from the experimental results.

Conclusion

For the analysis of the wire antenna in the presence of a dielectric body with three-dimensional shape, we proposed the combined method of the moment method and the boundary element method. In order to calculate the interactions between the thin wire approximation, the basic equations for the moment method and the boundary element method were modified. Furthermore, applicability of the proposed method was verified by the comparison between the calculated and experimental results of the helical antenna loaded with a cylinder dielectric.

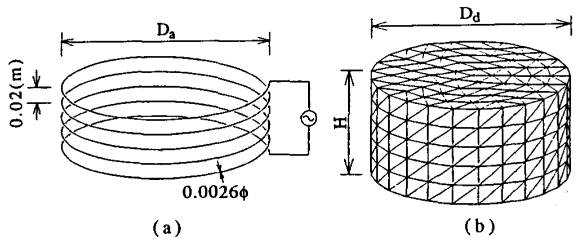
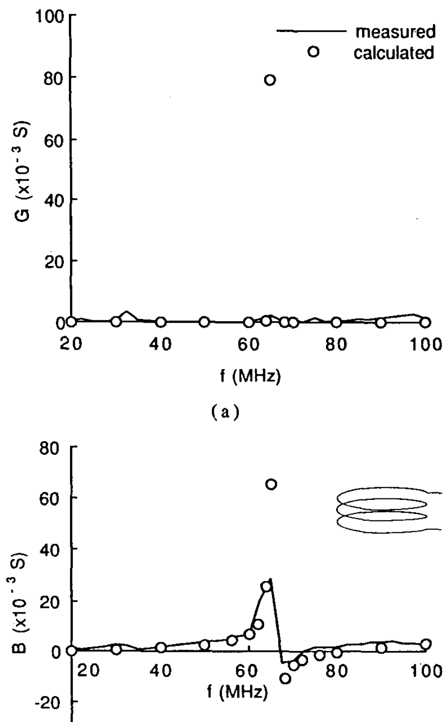


Fig.2 Computation model of the helical antenna and the dielectric cylinder, (a) helical antenna, (b) dielectric cylinder divided into triangular elements.



(b)

Fig. 3 Input admittance of the helical antenna without dielectric: D_a=0.319, (a) conductance G, (b) susceptance B.

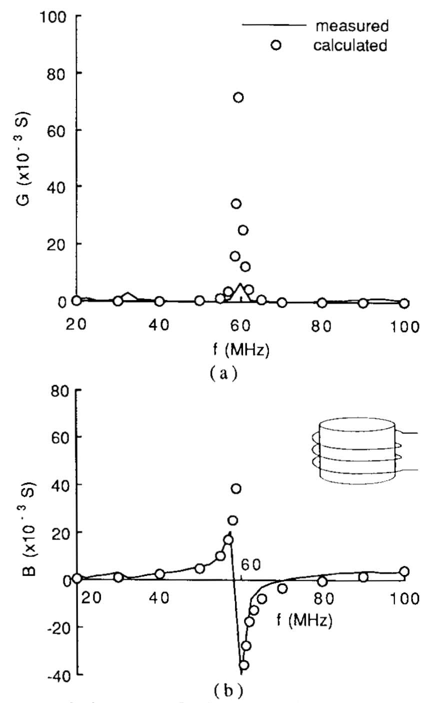


Fig. 4 Input admittance of the helical antenna in which the dielectric cylinder is inserted: D_a=0.319, H=0.153, D_d=0.299, $\varepsilon=5.3\varepsilon_0$, σ=0, (a) conductance G, (b) susceptance B.

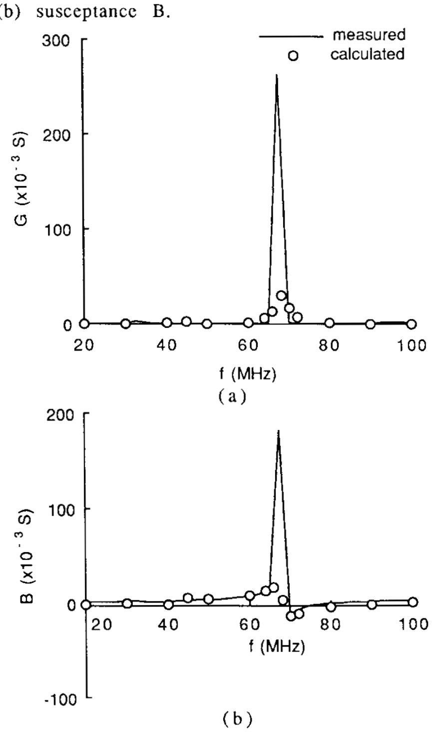


Fig.5 Input admittance of the helical antenna in which the pure water in cylinder container is inserted: D_a=0.270, H=0.150, D_d=0.240, $\varepsilon=90\varepsilon_0$, σ=0, (a)conductance G, (b) susceptance B.

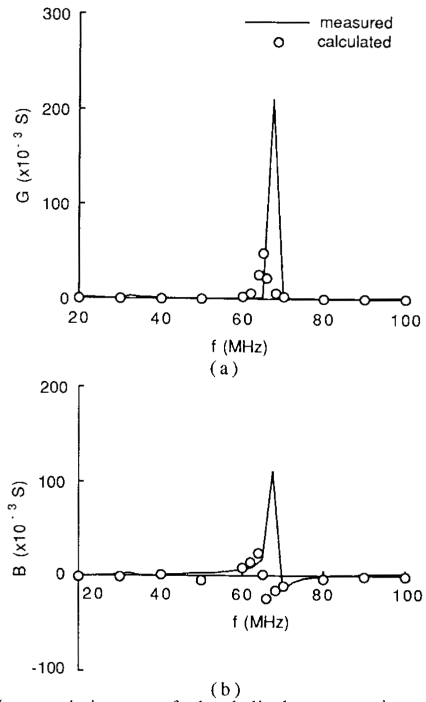


Fig. 6 Input admittance of the helical antenna in which the city water in cylinder container is inserted: D_a=0.270, H=0.150, D_d=0.240, $\varepsilon=90\varepsilon_0$, $\sigma=2.1\times10^{-2}$(S/m), (a) conductance G, (b) susceptance B.

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