ARMA/FDTD Analysis of Loop Antennas near Human Body for MHz Band Wireless Power Transfer System

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Abstract — **The finite difference time domain(FDTD) method is widely used for analyzing various electromagnetic problems including an interaction between antennas and human body. The FDTD method provides the accurate results in most case, however, a number of iteration times for obtaining the EM response increase dramatically in low frequency range when fine mesh is used. This is due to the Courant stability condition. This paper proposes a predicting technique of the steady state responses not performing a long time FDTD calculation by applying the auto-regressive moving average (ARMA) model to input/output signals. The effectiveness of the method is numerically confirmed by calculating the EM fields radiated from a loop antenna for wireless power transfer system.**

Index Terms — **FDTD method, ARMA algorithm, WPT**

1. Introduction

The FDTD method has been applied to various electromagnetic problems in the fields of antennas, microwave, and electromagnetic compatibility including interaction between the EM fields and the human body, because the modeling algorithm is simple and a practical level of the accuracy can easily be obtained[1],[2]. However, applying the fine –mesh FDTD to the very slowly EM field problem such as the wireless power transfer system at MHz and/or kHz frequency band, the number of iteration times increase dramatically because of the time step Δt reduces to a very small value due to the Courant stability condition. For example, Δt=9.5 ps for a 5 mm cubic cell, hence more than 100,000 times iterations are needed only for one time period calculation for 1 MHz signal. Moreover, it is usual that the EM fields reach steady state after few periods at least. On the other hand, it has been shown that the eigenmode characteristics propagation in the periodic structure can be obtained accurately by applying the auto-regressive moving average (ARMA) estimator to the time domain signals that is calculated by the FDTD method [3]. The ARMA estimator has also been applied to the FDTD analysis of dipole antenna placed near the lossy layered sphere [4].

In this paper, ARMA/FDTD method is applied to analyze the rectangular loop antennas used in the MHz band wireless power transfer system.[6] Antennas are placed near the four lossy layered medium that is a model of human body. It will be shown the steady state characteristics can be estimated accurately and efficiently by combining the ARMA model and FDTD method.

2. ARMA algorithm

In the narrow band antenna system and/or structures such as metamaterial and waveguides in which the surface wave is dominant, time domain data come down to zero extremely slowly. As a result, the Fourier transform cannot be used to obtain the frequency domain feature. To overcome this difficulty, the ARMA model used in the signal processing area can be utilized to process the time domain data. The transfer function of the linear system is modeled by

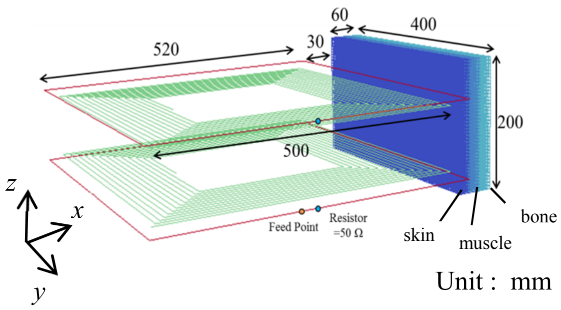
$$H(z) = \frac{Y(z)}{X(z)} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_q z^{-q}}{1 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_p z^{-p}} \qquad (1)$$

where $X(z)$ and $Y(z)$ are z-transform functions of the input signal $x(i)$ and output signal $y(i)$ that is calculated by the FDTD method , respectively. The constant Ts in the variable $z=\exp(-j\omega \mathrm{Ts})$ is a sampling time. $a_j(j=0,1,\ldots,q)$ and $b_i(i=1,2,\ldots,p)$ are the unknown coefficients that are determined by the input/output signals. Transforming (1) ,we obtain the output signal $y(n)$ at $t=n\mathrm{Ts}$ as follows.

$$y(n) = -\sum_{i=1}^{p} b_i y(n-i) + \sum_{j=0}^{q} a_j x(n-j) \qquad (2)$$

3. Calculations of EM fields

The geometry of the problem considered here is illustrated in Fig.1. The two rectangular loop antennas are placed parallel to the human body model at a distance of 30 mm, which are transmitting antenna fed by a delta-gap voltage having a 50 Ω inner resistance and receiving antennas of the wireless power transfer system, respectively. The 13-turn coils lies on the same plane of each antenna. The human body consists of skin, muscle and bone. The values of constitutive parameters are indicated in Fig.1 as well.



Constitutive parameters

skin : ε_r=547 [-] σ=0.122 [S/m]
muscle : ε_r=282 [-] σ=0.594 [S/m]
bone : ε_r=55.1 [-] σ=0.0380 [S/m]

Fig.1. Analysis model

First of all, we estimated the transfer function (1) using eq. (2), where input signal $x(t)$ is chosen as an incident voltage $v(t)$ at the feed point, and its wave form of $v(t)$ was set

$$v(t) = \begin{cases} \sin\omega_p t & 0 \le t \le \pi/\omega_p \\ 0 & t > \pi/\omega_p \end{cases} \qquad (3)$$

The output signal $y(t)$ is the electric field calculated by the FDTD method. The frequency characteristic of the predicted transfer function in the skin region is shown in Fig.2. It is found that the ARMA/FDTD method is agree extremely well with the one calculated by the original FDTD over the wide frequency range. The required number of time steps was 80,000 when a 5 mm cubic cell is used.

The steady state EM fields at $\omega=\omega_0$ can be calculated simply by Re $[H(\omega_0)]$. The x component electric fields at the frequency of 5.5 MHz in the skin, muscle and bone calculated by the ARMA/FDTD method and the original FDTD method are shown in Fig.3. It is found that both results agree very well each other. In the original FDTD calculation, the number of time steps was 1,900,000. Thus the requited time steps have been reduced to 1/24.

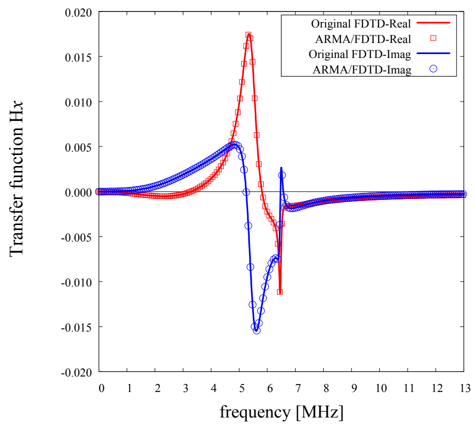


Fig.2. Predicted transfer function in the skin

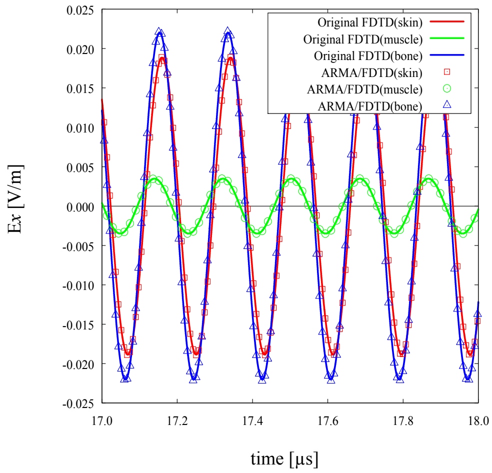


Fig3. Electric field E*x* in the skin, muscle and bone

4. Conclusion

In this paper, we have applied the ARMA/FDTD method in order to reduce the computation time for precisely predicting the steady state EM fields in the human body placed near the loop antennas used for the wireless power transfer system. It has been found that the computation time was reduced to 1/24 comparing with the original FDTD method for the treated model in this paper. We consider that this method can be applied to many problems that contain very low frequency spectrums.

References

[1] T.Uno. Electromagnetic field and antenna analysis by the FDTD method. Corona :1998. (in Japanese)

[2] A.Taflove and S.C.Hagness, Computational Electrodynamics,The Finite-Difference Time-Domain Method, Antech House,3-rd ed.(2005)

[3] E.Perrin and C.Guiffaut "Using Transfer Function Calculation and Extrapolation to Improve the Efficiency of the Finite-Difference Time-Domain Method at Low Frequencies" Trans. Electromagn. Compat., vol. 52, no. 1, pp.173-178,Feb 2010

[4] F.Yang, A.Elsherbeni, and J.Chen, "A Hybrid Spectral-FDTD/ARMA Method for Periodic Structure Analysis" ,IEEE AP-S, pp 3720-3723,Juen 2007

[5] K.Kuwabara,T.Uno, and T.Arima "An Efficient MHz Range Analysis by ARMA-FDTD Method with AIC" Proceedings of ISAP 2014, Kaohsiung, Taiwan, pp-141-142,Dec,2014

[6] A.Christ, M.G.Duglas, J.M.Roman "Evaluation of Wireless Resonant Power Transfer Systems With Human Electromagnetic Exposure Limits" Trans. Electromagn. Compat., vol. 52, no. 2, pp. 265-274, April 2013