Acceleration of FDTD calculation of EM fields due to loop antennas used for MHz band wireless transfer system placed near human body

Keita Asano, Toru Uno, and Takuji Arima

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 cases, however, it is often encountered for obtaining the valid EM response that the number of FDTD iteration increases dramatically in low frequency range when finer mesh is used. This is due to the Courant stability condition. This paper studies a predicting technique of the steady state responses from the transient data by using the auto-regressive moving average (ARMA) algorithm. The effectiveness of this method is numerically confirmed by analyzing the electromagnetic fields due to loop antennas used for a MHz band wireless power transfer (WPT) system, which are placed near a rectangular human body phantom.

Keywords: FDTD method, ARMA algorithm, WPT system

Classification: Antennas and Propagation

References

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1 Introduction

The FDTD method has been applied to various electromagnetic problems in the fields of antennas, microwave and optical devices, and electromagnetic compatibility including an interaction between the EM fields and the human body, because the modeling algorithm is very simple and a practical level of the accuracy can easily be obtained [1, 2]. However, applying the fine-mesh FDTD to the very slowly changing EM field problem such as the wireless power transfer system at MHz and/or kHz frequency band, the number of iteration increase dramatically because that the time increment Δt reduces to a very small value due to the Courant stability condition. For example, Δt is to be set as 1.9 ps when 1 mm cubic cell is used. Therefore, more than 1,000,000 iterations are needed only for one period of 1 MHz signal. Moreover, the EM fields reach steady state after few periods at least in most cases. On the other hand, the time domain signals come down to zero extremely slowly for the narrow band antenna and/or for structures such as metamaterials and waveguides excited by a pulsed signal. As a result, the Fourier transfer cannot be calculated numerically to obtain the frequency domain characteristics. To overcome this difficulty, the auto-regressive moving average (ARMA) model used in the signal processing area has been introduced into the FDTD method [3, 4]. This ARMA/FDTD method has also been applied to the dipole antenna near a lossy sphere [5], however the effectiveness was not clear because the dipole antenna radiates only a little power in low frequency.

In this paper, the FDTD method combined with the ARMA estimator is applied to estimate the rectangular loop antennas used in the MHz band WPT system [6]. The transmitting and receiving antennas are placed near the four layered lossy medium which is a model of human body. It will be numerically shown that the frequency characteristic of the antennas and the electric field in the body can be estimated accurately and efficiently by using the ARMA/FDTD method.
2 ARMA estimator for transfer function

In this section, we will briefly review the ARMA algorithm for predicting the transfer function of a linear system in order to understand the technique of combining the ARMA into the FDTD method.

The transfer function of the linear system can be modeled by

\[
H(z) = \frac{Y(z)}{X(z)} = \frac{a_0 + a_1z^{-1} + a_2z^{-2} + \cdots + a_qz^{-q}}{1 + b_1z^{-1} + b_2z^{-2} + \cdots + b_pz^{-p}}
\]

where \(X(z)\) and \(Y(z)\) are z-transform functions of the input signal \(x(n)\) and output signal \(y(n)\) that are the electromagnetic fields, a current on antenna conductor and so on, which are all calculated by the FDTD method. The constant \(T_s\) in the variable \(z = \exp(-j\omega T_s)\) is a sampling time and corresponds to the time increment \(\Delta t\) in the FDTD method. The constants \(a_j(j = 0, 1, \ldots, q)\) and \(b_i(i = 1, 2, \ldots, p)\) are the unknown coefficients, and are determined by the input/output signals as described below. Transforming Eq. (1), we obtain the output signal \(y(n)\) at \(t = nT_s\) as follows.

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

where \(x(m)\) and \(y(m)\) are the transient input and output signals sampled at \(t = mT_s\).

Coefficients \(a_j(j = 0, 1, \ldots, q)\) and \(b_i(i = 1, 2, \ldots, p)\) are determined by \(N = p + q + 1\) data calculated by the FDTD method and a matrix equation derived from Eq. (2). When \(N \neq p + q + 1\), the least mean square method, that is a general inverse matrix will be used alternatively [1, 4].

Once the transfer function \(H(z)\) has been determined as described above, the steady state response at \(\omega = \omega_0\) can simply be calculated by \(\text{Re}[H(z = \exp(-j\omega_0 T_s))]\). If the time interval for reaching the steady state is very long, and \(H(z)\) can be determined by the small iteration number of the FDTD calculation compared with the above mentioned time interval, then the use of ARMA estimator is certainly valuable.

3 Calculated results

The geometry of the problem considered here is shown in Fig. 1. Two parallel rectangular loop antennas are placed near the rectangular human body phantom which consists of skin, muscle and bone. One of which is the transmitting antenna fed by a delta-gap voltage having 50 \(\Omega\) inner resistance, and other the receiving antenna. The 13-turn coil is parallel to each antenna.
First, we chose an input impedance of transmitting antenna as the transfer function \( H(z) \). In this calculation, the input signal \( x(t) \) is the current at feed point calculated by the FDTD, and the output signal \( y(t) \) is the feed voltage \( v(t) \) which is given a priori, and its wave form was chosen as a Gaussian pulse:

\[
v(t) = \begin{cases} 
  e^{-\alpha(t-t_0)} & 0 \leq t \leq 2t_0 \\
  0 & t > 2t_0 
\end{cases}
\]  

where \( \alpha = (4/t_0)^2 \) and we set \( t_0 = 9.6 \times 10^{-8} \) sec. The reflection coefficients calculated from the input impedance are shown in Fig. 2(a). In this calculation, the input signal is calculated 5 periods of 5 MHz, because, 5 periods will be good enough to get a good result in almost case [7]. It is found that the ARMA/FDTDs agree very well with the full FDTDs which were obtained from the all transient data until the current has reduced to zero completely. In order to obtain the results of ARMA/FDTD, we needed 950 input data and 950 output data, respectively. It sounds that the ARMA/FDTD is not so effective, but the required number of data, that is the number of iterations, are about \( 1/9 \sim 1/10 \) depending on whether the human phantom is present or not, as indicated in Table I. In addition, the required computation times are dramatically decreased for both cases.

Next we calculated the temporal electric field at an observation point \( P \) in the human phantom shown in Fig. 1. In this calculation, we have chosen \( x(t) \) the feed voltage expressed by eq. (3), \( y(t) \) the \( x \)-component electric field. And we calculated output signal \( y(t) \) of about 5 periods of 5 MHz by FDTD. The temporal electric field is shown in Fig. 2(b). It is found that the ARMA/FDTD agrees very well with the full FDTD. The required number of the data and computation time are indicated in Table I. Thus, the ARMA/FDTD is very effective compared with the full FDTD, however, the required number of data may depends on the accuracy, the wave form of input voltage, dielectric properties located near antennas and so on [8].
### Table I. Required number of data steps and computation time

| Calculation Model | full FDTD | ARMA/FDTD |
|-------------------|-----------|-----------|
| w/o dielectric    | 800,000   | 90,000    |
| (Reflection coefficient) | 41 m 44 s | 4 m 52 s |
| w/ dielectric     | 1,000,000 | 100,000   |
| (Reflection coefficient) | 52 m 45 s | 5 m 27 s |
| w/ dielectric     | 1,900,000 | 100,000   |
| (E field in time domain) | 92 m 30 s | 5 m 25 s |

Fig. 2. Reflection coefficients and temporal electric fields
4 Conclusions

In this paper, we have applied the ARMA/FDTD method for predicting the steady state responses of EM fields due to loop antennas used for HMz band wireless transfer system which is located near the human body. It has been shown that all of the calculation results agrees very well with the full FDTD results, and that the number of required time steps can be reduced to about 1/10 or less comparing with the full FDTD method. Therefore, we consider that this method can adequately be applied to many problems in very low frequency region, after the dependence of physical and/or mathematical properties of the EM fields on the coefficients including the transfer function will be made clear adequately. This will be one of next study works.