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

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1. Introduction

**FDTD method**

Electromagnetic field analysis method in the time domain

**Advantage**
Easy modeling, Good PC memory efficiency,
Suitable for vectorization and parallelization

**FDTD Application**
EM field analysis of the *Products of complex structure* and *Human body*

*Products of complex structure* (Smartphone, TabletPC, etc)

*Human body and the antenna*
It requires **Long Calculation time**

- **FDTD Disadvantage**
  - By the constraint that Cournt’s stability condition
  - Need a small cell for modeling
  - **FDTD Disadvantage**
    - Low-frequency EM field Application
      - WPT system (kHz or MHz band)
      - Lightning Induced effect on aircraft
        - Human body
        - Aircraft
        - Smartphone
For example, Calculation of low-frequency EM field problem

- **Analysis condition**
  - Cell size: 5mm cubic cell
  - Time step: $dt=9.5\,\text{ps}$

- **Low frequency wave**
  - (MHz or kHz band sin-wave)

- **Calculated By FDTD**

- **Time until steady state**: $T=18\,\mu\text{s}$
- **Time step**: $dt=9.5\,\text{ps}$

- **The number of time steps**
  - $= \frac{T}{dt}$
  - $= 1,900,000\,\text{steps}$
Purpose of This study

Electromagnetic field analysis in low frequency

Analysis of the antenna characteristics

Two proposed method

1. Estimation of Rational functions with the Auto-Regressive Moving Average (ARMA)

Value of the time domain

\( x(t) \) : Input signal
\( y(t) \) : Output signal

Calculated by ARMA

2. Estimation method of Electromagnetic (EM) field using a transfer function

Input Impedance

Transfer function

Estimated EM field

Transfer function

pulse
Calculation contents in this study

 Tested for two types of problem

 1. Steady state E field in time domain
 2. Reflection coefficient of loop antenna in frequency domain

We will evaluate Calculation accuracy and The number of time steps
2. Proposed method

2.1 ARMA/FDTD Algorithm

To approximate the rational function in the frequency domain

$$H(Z) = \frac{Y(Z)}{X(Z)} = \frac{a_0 + a_1 Z^{-1} + a_2 Z^{-2} + \cdots + a_q Z^{-q}}{1 + b_1 Z^{-1} + b_2 Z^{-2} + \cdots + b_p Z^{-p}} \ldots (1) \quad Z = \exp(j \omega T)$$

$p, q$ : The order of the rational function model
$T$ : Sampling time

Solve the (2) in order to determine

Equation of ARMA model

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

$x(n)$ : Input signal (impressed voltage or current)
$y(n)$ : Output signal (electric field, current, etc.)

We checked that all poles are placed the stability region in z-plane by using unknown coefficients $a_j$ and $b_i$. 

$FDTD$ $\cdot$

$\cdot$ARMA/FDTD

\begin{itemize}
  \item input $x(n)$ : Input signal (impressed voltage or current)
  \item output $y(n)$ : Output signal (electric field, current, etc.)
\end{itemize}
2.2 Estimation method of Electromagnetic field using a transfer function

Input signal

\[ \text{Voltage}[\text{V}] \]

\[ \text{time}[\text{ns}] \]

Calculated by FDTD

Output signal

\[ E[\text{V/m}] \]

\[ \text{time}[\text{ns}] \]

ARMA algorithm

Transfer function

\[ \text{Frequency}[\text{Hz}] \]

Calculated by ARMA algorithm

Estimated by Transfer function
3. Simulation result
3.1 Calculation of the steady state E field

Analysis Model: Wireless Power Transfer System (WPT System)

Calculation of the steady state E field when \textbf{sin wave of 5.5MHz} was the input signal

WPT System model

Unit: mm

Resistor = 50 \, \Omega

Skin: \varepsilon_r = 547 \, [-] \, \sigma = 0.122 \, [S/m]

Muscle: \varepsilon_r = 282 \, [-] \, \sigma = 0.594 \, [S/m]

Bone: \varepsilon_r = 55.1 \, [-] \, \sigma = 0.0380 \, [S/m]
The calculated data for Transfer function

Calculation of Transfer function

\[ H(Z) = \frac{Y(Z)}{X(Z)} = \frac{\mathcal{F}[y(t)]}{\mathcal{F}[x(t)]} \]

- \( y(n) \): \( E(t) \) [V/m]
- \( x(n) \): Input Voltage [V]

The E field at each calculation point

Input Voltage

\[ V(t) = \sin 2\pi ft \]

\( f = 100 \text{MHz} \), \( 0 \leq t \leq 1/2f \)

Calculated by FDTD

Calculation point
Comparison Result: **Transfer function**(skin)

Calculation accuracy: Original FDTD ≡ ARMA/FDTD

The number of time steps: Original FDTD > ARMA/FDTD

(240,000 steps) (80,000 steps)
Calculation Result: **E field in time domain (x-direction component)**

Calculated accuracy: Original FDTD ≅ ARMA/FDTD
The number of time steps: Original FDTD > ARMA/FDTD
(1,900,000 steps)  (80,000 steps)
3.2 Calculation of the Reflection coefficient

Model 1: Loop antenna of WPT system

Unit: mm

Feed Point

Model 2: Loop antenna of WPT system near three layered dielectric

Unit: mm

Feed Point

Resistor = 50 Ω

Skin: $\varepsilon_r=547$ [-] $\sigma=0.122$ [S/m]

Muscle: $\varepsilon_r=282$ [-] $\sigma=0.594$ [S/m]

Bone: $\varepsilon_r=55.1$ [-] $\sigma=0.0380$ [S/m]
The calculated data for Reflection coefficient

Calculation of Impedance

\[ H(Z) = \frac{Y(Z)}{X(Z)} = \frac{\mathcal{F}[y(t)]}{\mathcal{F}[x(t)]} \]

\( y(n) \): Input Voltage [V]
\( x(n) \): Input Current [A]

Input Voltage output signal \( y(t) \)

Gaussian pulse

Calculated by FDTD

The input current at each model

Input signal \( x(t) \)

Model1

Input Voltage

output signal \( y(t) \)

Gaussian pulse

Model2

Calculation of Impedance

\[ H(Z) = \frac{Y(Z)}{X(Z)} = \frac{\mathcal{F}[y(t)]}{\mathcal{F}[x(t)]} \]

\( y(n) \): Input Voltage [V]
\( x(n) \): Input Current [A]
Comparison Result: **Reflection coefficient**

**Model1**: Loop antenna of WPT system  
**Model2**: Loop antenna of WPT system near three layered dielectric

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![Diagram of Model1](image1)

![Diagram of Model2](image2)

**Calculation accuracy**: Original FDTD $\neq$ ARMA/FDTD  
The number of time steps: Original FDTD $>$ ARMA/FDTD  
(1,000,000 steps) (100,000 steps)
4. Conclusion

- Our proposed method
  1. ARMA/FDTD method
  2. The estimation method of EM filed using a transfer function

- We tested the our proposed methods by the calculation of the steady state E field and Reflection coefficient. The simulation result:
  - Calculation accuracy: Original FDTD ≠ Proposed method
  - The number of time steps: Original FDTD >> Proposed method

**Our proposed method can reduce calculation time of FDTD method**