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A Generalized Fast Frequency Sweep Algorithm for Coupled Circuit-EM Simulations

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INTRODUCTION

Frequency domain techniques are popular for analyzing electromagnetics (EM) and coupled circuit-EM problems. These techniques, such as the method of moments (MoM) and the finite element method (FEM), are used to determine the response of the EM portion of the problem at a single frequency. Since only one frequency is solved at a time, it may take a long time to calculate the parameters for wideband devices.

In this paper, a fast frequency sweep based on the Asymptotic Wave Expansion (AWE) method is developed and applied to generalized mixed circuit-EM problems. The AWE method, which was originally developed for lumped-load circuit simulations, has recently been shown to be effective at quasi-static and low frequency full-wave simulations [1]. Here it is applied to a full-wave MoM solver, capable of solving for metals, dielectrics, and coupled circuit-EM problems.

FORMULATION

The AWE formulation consists of solving for the unknowns and their derivatives with respect to frequency at one frequency, then using this information in a Pade rational function approximation to find the result at other frequencies. To approximate the derivatives efficiently, the system matrix is first split into several matrices, each with a known frequency variation. The Electric Field Integral Equation (EFIE) with surface impedance, given by

$$j\omega\mathbf{A} + \nabla\Phi + Z_S\mathbf{J}_S = -\mathbf{E}^i, \tag{1}$$

where $\mathbf{A}$ is the magnetic vector potential, Φ is the electric scalar potential, Z_S is the surface impedance, $\mathbf{J}_S$ is the unknown current, and $\mathbf{E}^i$ the impressed electric field, is separated versus frequency content as

$$\left[\frac{B_0}{g} + B_1 + \sqrt{g}B_2 + gB_3\right]\left[X\right] = \left[Y\right], \tag{2}$$

where $g = j\omega$, X is the unknown vector, and Y is the forcing function. Since the separation does not take into account inter-element phasing from the Green's Function, it works best for electrically small problems where this phasing is at a minimum.

Once the separation is complete, combinations of the B matrices may be used to approximate the derivatives of the system matrix needed for the AWE process, while the forcing function derivatives may be found exactly from the excitation data [1]. The system is then solved recursively to obtain the solution and its derivatives at each unknown, as in the standard AWE method.

If the derivatives are used to form a Pade approximation, the approximate solution may be more likely to converge near resonances than a Taylor series approximation. Since the Pade approximation is a rational function, it may match resonant behavior better than a truncated power series. The Pade rational function is then computed for each unknown at each desired frequency to obtain the approximate solution [2].

The AWE method may be applied to other integral equations where the operators may be separated by frequency content. For the PMCHWT dielectric formulation, the electric and magnetic fields are given by

$$\mathbf{E}(\mathbf{J},\mathbf{M}) = -j\omega\mathbf{A}(\mathbf{J}) - \nabla\Phi(\mathbf{J}) - \frac{1}{\varepsilon}\nabla\times\mathbf{F}(\mathbf{M}) \tag{3}$$

and

$$\mathbf{H}(\mathbf{J},\mathbf{M}) = -j\omega\mathbf{F}(\mathbf{M}) - \nabla\Psi(\mathbf{M}) + \frac{1}{\mu}\nabla\times\mathbf{A}(\mathbf{J}), \tag{4}$$

where F is the electric vector potential, ε is the permittivity, and μ is the permeability. To incorporate this into the AWE method, both vector potentials **A** and **F** need to be put into B_3 in (2), while the scalar potentials have an inverse frequency dependence and are placed into B_0. The vector potential curl terms lack an explicit frequency dependence and are put into B_1. The jump potentials on the self term of the electric vector potential are separated and placed into B_1.

For mixed circuit-EM simulation, two options are implemented: a contact-connection model and an N-port representation of the EM system. For the contact-connection model, the current continuity equation is enforced for EM elements that are connected to circuit nodes. In addition, the scalar potential is pinned to the circuit node voltage for connecting elements. This leads to a coupled system matrix equation,

$$\begin{bmatrix} EM & X \\ X^T & MNA \end{bmatrix}\begin{bmatrix} I_{EM} \\ I_{ckt} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \tag{5}$$

Here, the matrix X expresses the coupling between the electromagnetic (*EM*) and Modified Nodal Analysis circuit (*MNA*) parts of the system. Also, I_{EM} is the electric current, and I_{ckt} is the circuit current. The connectivity portions of the matrix (X and X^T) are frequency independent, while components of the *MNA* are filled according to frequency dependence [3].

The N-port model is used instead of the contact model if the EM system is to remain fixed while the circuit system is varied. The N-port result is a port admittance matrix showing the relation between the voltages and currents at each port for a given frequency. This information can then be incorporated into the circuit model, and used to quickly and accurately evaluate many circuits using the same EM pieces. The N-port representation is given by

$$\left[N_{port}\right] = [X^T][EM][X]. \tag{6}$$

In order to solve for the N-port representation using AWE, it is expressed as a linear matrix equation with multiple right hand sides using an intermediate matrix M as

$$\begin{aligned} [M] &= [EM]^{-1}[X] \\ \left[N_{port}\right] &= [X^T][M] \end{aligned}. \tag{7}$$

In (7), the linear system is solved for M using the AWE method. Then, the N-port representation is found by multiplying M by the connectivity matrix. This increases the cost per approximate frequency by O(*number of ports squared*) over the contact connection model. However, it reduces the total unknowns in the system by the number of circuit nodes.

In many cases a single frequency expansion point cannot be used to accurately calculate the approximations over the entire frequency range of interest, requiring a multipoint expansion. Several frequency expansion points are used, and the AWE method is applied to each one independently. Each expansion point is used to form the approximations for frequencies within a certain range of its center frequency. This multipoint method allows for a tradeoff between accuracy and efficiency [4]. The fewer expansion points used, the quicker the solution and the lower the accuracy. An automated method of choosing expansion frequencies was implemented to ensure that error remained within required tolerances across the band.

RESULTS

A number of test cases were run to test the AWE implementation. To test the basic EFIE implementation, a strip dipole made of triangles was used. There were 23 unknowns on the dipole and it was fed by a delta-gap source at its center. The dipole dimensions were 39 cm × 1 cm, giving a resonant frequency of about 1.3 GHz. The automated AWE frequency sweep was used and the resulting errors are shown in Figure 1. The error norm of the approximation compared to the exact solution is shown by the crosses and each expansion point frequency is shown as a square. It is clear by the clustering of the expansion points near the upper bound that the AWE approximation becomes worse at higher frequencies.

For the frequency sweep up to 300 MHz, the exact solution took 77.11 seconds, while the AWE sweep completed in 12.4 seconds. This gives an improvement ratio of 6.2. If the exact solution was needed at more points, the improvement from the AWE would be even more dramatic, as each frequency point requires a complete fill and solution for the standard method, while it only requires a simple O(N) calculation for the AWE.

A very simple test of the coupled circuit-EM formulation is a resistive interconnect. The interconnect was modeled using the PMCHWT formulation, with a conductivity of 5.7E8 ℧/m on the interior. The dimensions of the interconnect are 1 mm × 1 mm × 4 mm. The interconnect is excited by a circuit voltage source which is connected to contacts on its ends, as shown in Figure 2.

The terminal resistance across the interconnect for both the AWE frequency sweep and the standard method is shown in Figure 3. The AWE required 24 minutes, while the exact method required 168 minutes. This test showed that coupled circuit-EM problems may be solved successfully using the AWE method.

SUMMARY

The Asymptotic Wave Expansion method was developed and applied to a full wave computational electromagnetic code. The AWE method was expanded to include the PMCHWT dielectric formulation, lumped loads, and coupled circuit-EM problems. A simple adaptive sweep was shown to be effective for some problems. Good results were demonstrated for test problems including resistors and printed circuit dipoles.

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REFERENCES

[1] V. Jandhyala and T. West, “A fast frequency sweep method for mixed electromagnetic and circuit simulation”, University of Washington Internal Report.

[2] L. Goins and W.T. Smith, “Reduced order modeling of thin wire scatterers”, *1999 IEEE Southeastcon*, Lexington, KY, March 1999, pp. 323 - 328.
[3] Y. Wang, D. Gope, V. Jandhyala, and C.J.R. Shi, "Integral equation-based coupled electromagnetic eircuit simulation in the frequency domain ," *2003 IEEE AP-S International Symposium and North American URSI Radio Science Meeting*, Columbus, OH, June 2003, pp. 328-331.
[4] E. Chiprout and M. Nakhla, “Transient waveform estimation of high-speed MCM networks using complex frequency hopping”, *1993 IEEE Multi-Chip Module Conference*, Santa Cruz, CA, March 1993, pp. 134 – 139.

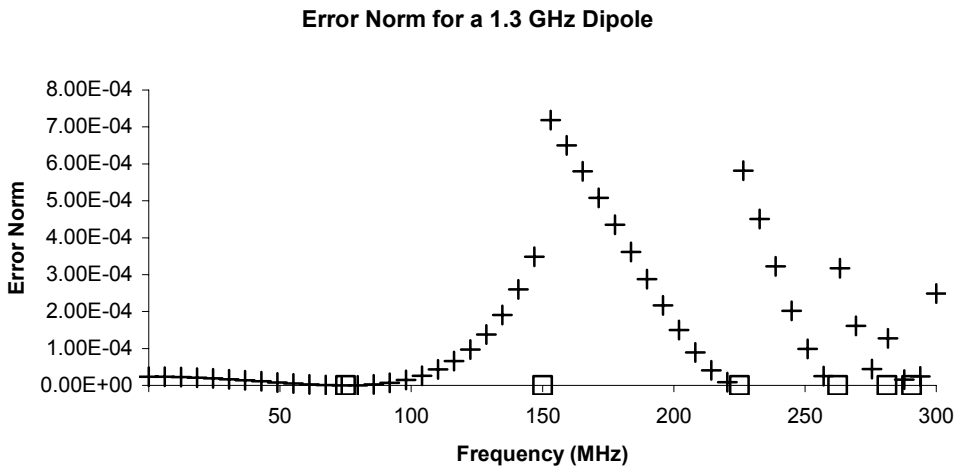

Figure 1. Error norm for a PEC dipole in free space. The + indicates the error of AWE versus exact simulation. The squares show the expansion frequencies.

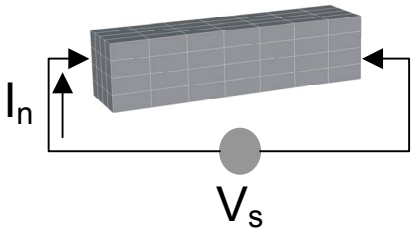

Figure 2. The geometry for the copper interconnect.

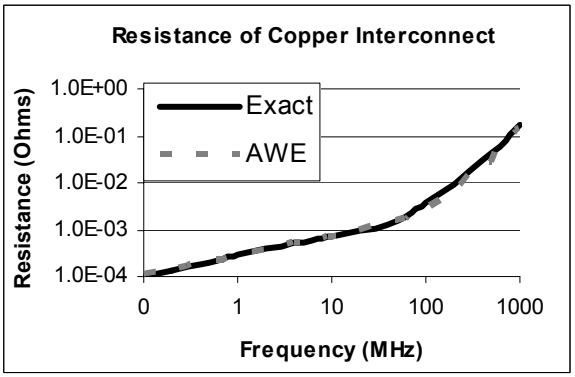

Figure 3. Terminal resistance of the copper interconnect for both the fast and standard method.