ACCELERATED WIDE-BAND FREQUENCY/TIME-DOMAIN HYBRID COMPUTATIONAL ELECTROMAGNETIC TECHNIQUE

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ABSTRACT

A hybrid technique is proposed for computation of broadband characteristics of an antenna in the presence of a dielectric scatterer. The technique links the frequency domain Method of Moments (MoM) and the Finite Difference Time Domain (FDTD) method. The coupling of these methods is achieved by using the Equivalence Principle, applied over the intervening surface. A great reduction in computation time is achieved in the MoM domain by using an impedance interpolation technique. The Gaussian pulse (GP) and Derivative Gaussian pulse (DGP) are investigated as the excitation sources for the MoM. Examples are given and the results found to be in good agreement with alternative methods.

INTRODUCTION

Hybrid techniques linking the frequency-domain Method of Moments (MoM) and the Finite Difference Time Domain (FDTD) method provide a powerful and flexible approach to the numerical solution of a complex antenna structure in the presence of a large lossy dielectric [1-4]. If broadband analysis is required, such as the transient response for sub-surface radar, this can be accurately investigated by computing the field propagation over the two different domains and on the equivalence-principle surface (the surface that couples the two domains), over the entire bandwidth.

In earlier work, Rubio Bretones et al. presented [5] a time-domain version of MoM in a hybrid approach for studying the transient excitation of a thin wire antenna located in the proximity of an inhomogeneous dielectric scatterer and above a perfectly electrically conducting (PEC) ground plane. Also, Cerri et al. [6] used a time-domain version of MoM for developing a hybrid technique. The method has the advantage of generating information over a wide frequency band: it does not require an iterative procedure to couple with FDTD, but it requires very large run-times when treating a junction with more than two wires [7]. Huang et al. [8] employed a hybrid technique for modelling the interaction of ground-penetrating radar (GPR) with complex ground, using a combination of frequency domain MoM, Fourier transformation and iterations. In [8] the reaction of the back-scattered field and the source is not discussed in detail; the field computation from the MoM part is also very time-consuming for a large source region. Recently, another hybrid MoM/FDTD method [9] was applied for numerical simulations of SAR and the magnetic field of shielded RF coils loaded with a human head for a biomedical application. In [10] the source antenna is modelled as a stack of Hertzian dipoles. However, in [9] and [10] the authors neglect the effect of the back-scattered field on the source. The same approximation is used in [11], which is oriented towards two-dimensional UHF/VHF propagation problems: the FDTD is excited just by a vertical slice near the problem area.

Rubio Bretones et al have recently published a method to combine the NEC with FDTD [12]. Unfortunately, the back-scattered field on the wire is calculated in a way that entails running the FDTD code N_s times (where N_s is the number of the basis functions on the wire antenna). This requires extensive computational time, which will cause difficulties with many practical problems. Some interesting comparisons between the MoM and FDTD numerical methods are published in [13], for modelling electrically small antennas, and in [14] for radiation and scattering involving dielectric objects. The advantages of each technique are discussed: this shows that the hybrid method is a promising and effective technique.

In the present paper, the fields are computed using the method of interpolation of impedance/admittance matrices on the antenna side, using MoM [15]. This saves execution time and memory requirements for the MoM. Basically, the Inverse Discrete Fourier Transform (IDFT) is performed on the equivalence-principle surface within the FDTD domain and the Discrete Fourier Transform (DFT) is used to account for the back-scattered fields for the MoM domain. The number of frequency samples required to predict the coupling fields between the two domains over the entire bandwidth was investigated. The positions of these samples over the selected bandwidth were also studied in relation to their effect on recovery of the time-domain fields for different resonant structures.

SUMMARY OF THE METHOD

Consider Fig. 1, which shows two different regions. One contains a source and the other a scatterer. The coupling domains between the two regions have been addressed fully in refs. [1-3]. Usually the coupling is implemented using a single excitation frequency with iteration across the equivalence-principle surface. The forward fields from the source to the scatterer (E(jω), H(jω)) are computed using the frequency domain MoM. The induced surface currents $J_{si}(j\omega)$ and $M_{si}(j\omega)$ that represent the FDTD excitation over the closed surface S_{ci} can be given by:

$$M_{si}(j\omega) = E(j\omega) \times \hat{n} \quad (1)$$

$$J_{si}(j\omega) = \hat{n} \times H(j\omega) \quad (2)$$

where $\hat{n}$ is the normal vector directed outward from the closed surface S_{ci}. The back-scattered fields ($E_b(t)$, $H_b(t)$) on the enclosing surface are derived from the FDTD computation. Then the reaction of these fields on the source region can be stated as:

$$\begin{aligned} R_B &= \langle E_{ts}, J_{ib} \rangle - \langle H_{ts}, M_{ib} \rangle \\ &= \int_{S_{cb}} (E_{ts} \bullet J_{ib} - H_{ts} \bullet M_{ib}) ds_{cb} \end{aligned} \quad (3)$$

where E_{ts} and H_{ts} are the test electric and the magnetic fields from the source. M_{ib} and J_{sb} are the induced magnetic and electric surface currents on the closed surface S_{cb}. '<>' and '•' are the inner product and the dot vector product respectively. The procedure is repeated until a steady state solution is reached. In general, if broadband antenna analysis is required, many frequency samples are required to cover the entire bandwidth on the MoM side to predict the required time variations of the induced surface current on the enclosed equivalent surface. Using IDFT, these samples can be combined as the excitation of the FDTD domain. The main problem is the computational time required to evaluate these samples on the MoM side, because it has to be executed once for each sample.

Thus, an impedance/admittance interpolation method on the MoM side was developed to predict these fields on the equivalence-principle surface. The method requires storage of impedance matrices for a few different frequencies over the specified bandwidth. Then, using the quadratic interpolation method (requiring three selected points), the impedance can be found at any frequency between these points, as follows. The [Z] matrices for the three selected frequencies are directly computed by MoM [1-3]. The elements of [Z] for the intermediate frequencies are approximated by a quadratic function:

$$Z_{mn}(f) = A_{mn} f^2 + B_{mn} f + C_{mn} \quad (4)$$

Where f denotes frequency and A_{mn}, B_{mn}, and C_{mn} are the mn^{th} elements of the complex coefficient matrices [A], [B], and [C]. Equation (4) can be cast into a system of three equations and three unknowns. These equations, together with the elements of the directly computed [Z] matrices that are calculated at three selected frequencies, are used to determine the coefficient matrices. If the frequency band of interest is especially wide, it may be necessary to divide the band into several interpolation frequency ranges and implement a process of stepping through them.

The frequency characteristics of the [Z] matrix elements can be determined by the Electric Field Integral Equations (EFIE) and the form of the basis and test functions used [15]. These equations reveal that the term exp(-jkR) dominates the frequency behaviour of the [Z] elements. For matrix element Z_{mn}, R equals $r_{mn}=|r_m-r_n|$ where r_m is the observation location and the r_n is the source location. When the observation point and the source are close to each other, r_{mn} is small and the $\exp(-jkr_{mn})$ varies slowly with frequency. When they are far from each other, r_{mn} is large and $\exp(-jkr_{mn})$ fluctuates rapidly with frequency and thus dominates the frequency variations of the [Z] matrix elements. The improved computation of [Z] elements in this case can be evaluated from direct interpolation of the [Z] elements, divided by the factor $\exp(-jkr_{mn})$ and then the resultant interpolation value is multiplied by the same factor [15]. Thus, the currents for a particular frequency, resulting from a wideband excitation (e.g. a Gaussian Pulse or Derivative Gaussian Pulse) can be found once the impedance matrix at that frequency can be predicted [1-3].

SIMULATION AND RESULTS

Several examples are given to highlight the proposed method. The results are compared with those from some homogeneous time-domain methods such as pure FDTD and TDIE [16]. In all cases, the dielectric volume was considered to be free space. This is adequate to test the stability of the method and its agreement with the results of other methods. The examples are:

Example 1. A straight wire antenna of length 0.5m and radius 1mm was analysed when driven by a differential Gaussian pulse with $g=1.5\times109\ s^{-1}$ and $t_d=2.5$ ns. The number of frequency samples for the Z-matrix interpolation used here was 9. The proposed method was executed over the entire bandwidth of 1.5GHz. The number of frequency samples over the bandwidth was chosen to be 64 and 128 in order to match the inverse discrete Fourier transforms. A uniform discretisation technique was used in this case. The source current versus time is shown in Figure 2 and the results are compared with those from standard packages implementing the FDTD and TDIE methods. The results of the proposed method are in excellent agreement with those obtained from FDTD and TDIE.

Example 2. A source antenna represented by two-arm square-spiral wires and a scatterer formed by two crossed wire dipoles was investigated, as shown in Fig. 3. The square spiral was selected here simply to compare the results with FDTD. The radius of the wires for the source and the scatterer were chosen to be 1mm. The spiral was located 3cm above the cross point (origin point) of the cross dipoles. The source excitation was placed at the centre of the spiral as a DGP having the same configuration as given in example 1. The spiral antenna was replaced by the closed equivalence-principle surface inside the FDTD region that represents the scattered fields, as shown in Fig. 3. The size of the closed surface was 16×18×4 cells (cell size = 1cm). The number of frequency samples predicted from the selected frequency points was 256. The memory required to store the fields on the equivalent surface was 2Mbyte. The near electric field was recorded at x=0.0m, y=0.08m, z=0.03m, as shown in Fig. 4. There is good agreement between the two methods although the peak values differ by approximately 3%. The total simulation time was two hours on a Sun Sparc 10 workstation.

CONCLUSIONS

A method to obtain broadband antenna responses from the hybrid technique using the frequency-domain Method of Moments and the Finite Difference Time Domain method has been presented. A [Z]-matrix interpolation methodology on the MoM side was used in order to significantly reduce the computational time required for wide-band performance evaluation of antennas. Quadratic interpolation was found sufficient to predict the time-limited responses. The use of non-uniform frequency samples on sharp resonances is recommended for minimisation of computational and memory requirements. The results were in good agreement with the available data from relevant single-algorithm methods. The method is suitable tool for scattering problems of complex antenna structures adjacent to large lossy media. The antennas can include curved wires, strips and surfaces, which are difficult to model using FDTD alone.

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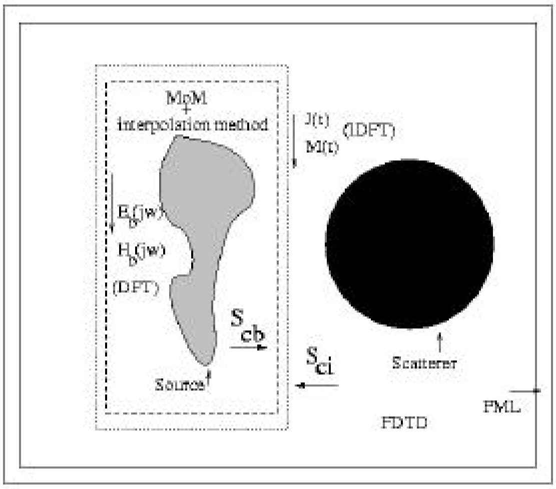

Fig. 1. Basic geometry of the hybrid combination of frequency domain MoM and FDTD.

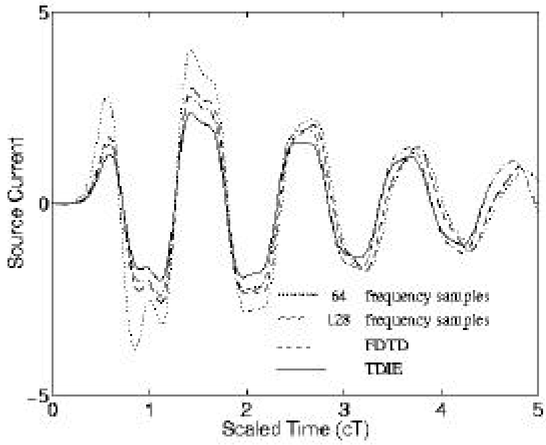

Fig. 2. The input source current versus scaled time for a dipole excited by a DGP.

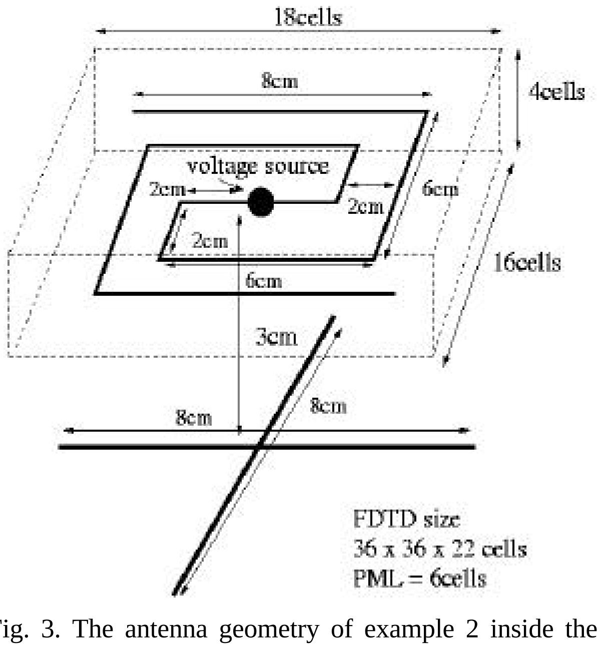

Fig. 3. The antenna geometry of example 2 inside the hybrid method domain.

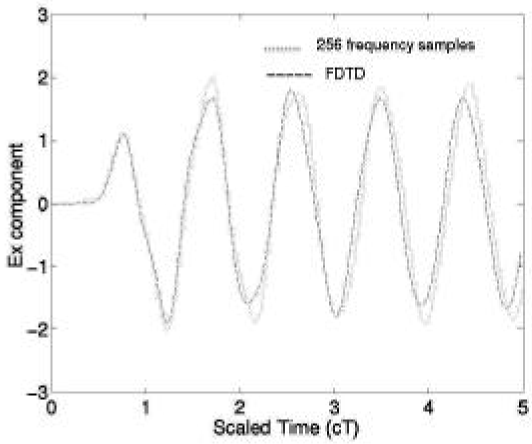

Fig. 4. The E_x component versus the scaled time at a position point x=0.0m, y=0.08m, z=0.03m of Fig. 3.