FAST SIMULATION OF ELECTROMAGNETIC SCATTERING FROM LARGE COMPLEX PEC OBJECTS USING THE ADAPTIVE INTEGRAL METHOD

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Abstract—In this paper, the authors use the adaptive integral method (AIM) to simulate the electromagnetic scattering from large complex PEC objects. The first problem that we have investigated is the scattering from a dihedral corner reflector that may lead to a better understanding of scattering mechanisms and properties of more complex geometries. The second problem investigated is scattering from a multiplate structure consisting of trapezoidal plates. The third problem investigated is the scattering from a composite PEC sphere and plate structure. The AIM simulation results are compared to the results obtained using the physical optics (PO) technique. In order to test the capability of AIM further, an aircraft model with many patches of flat surfaces has been built for this purpose. The mesh generation and the measurement of the scattering pattern of the aircraft model have been carried out by us. With the mesh and measurement results of the aircraft model, the simulation was carried out using AIM. The numerical results for all the test cases show that the AIM is an efficient method for analyzing electromagnetic scattering from large complex PEC objects.
1 Introduction

2 Formulation

3 Numerical Results

4 Conclusion

References

1. INTRODUCTION

The simulation of electromagnetic scattering from a PEC object can be carried out by solving a pertinent integral equation using the method of moments (MoM). The MoM is very accurate, but it is very cumbersome to use for the analysis of electrically large problems, due to excessive memory requirement and high computational complexity. One of the most powerful methods for the efficient MoM solution is the fast multipole method (FMM) and its multilevel version — the multilevel fast multipole algorithm (MLFMA) [1–5], which reduces the computational complexity and memory requirement to $O(N \log N)$ for the matrix equation of order $N$. Another powerful method for the efficient MoM solution is the adaptive integral method (AIM) that was developed by Bleszynski et al [6, 7]. Compared to the conventional MoM, AIM reduces computational complexity and memory requirement with the aid of auxiliary basis functions and the fast Fourier transform (FFT). The computational complexities of AIM are $O(N^{1.5} \log N)$ and $O(N \log N)$ for surface and volumetric scatterers, respectively. The corresponding memory requirements are $O(N^{1.5})$ and $O(N)$, respectively. The AIM has been successfully applied to the analysis of scattering and radiation from arbitrarily-shaped three-dimensional (3D) and planar structures [7–9]. The AIM has also been successfully applied to analyze microstrip circuits and finite large microstrip antenna arrays [10, 11]. The static version of AIM for fast capacitance modeling has been implemented using both the first-kind and second-kind integral equations [12, 13]. The problem of scattering by a closed conducting body can be solved using either the electric field integral equation (EFIE), the magnetic field integral equation (MFIE), or the combined field integral equation (CFIE). It has been found that, in addition to the elimination of the interior resonance problem suffered by both EFIE and MFIE, CFIE usually yields a better conditioned matrix equation and its iterative solution converges much faster than EFIE and MFIE [14]. The AIM implementation of CFIE and its convergence behavior have
been studied, and the numerical results for several simple objects have demonstrated the efficiency of AIM in [9].

In this paper, the authors use the adaptive integral method (AIM) to simulate the electromagnetic scattering from large complex PEC objects. The first problem that we have investigated is the scattering from a dihedral corner reflector that may lead to a better understanding of scattering mechanisms and properties of more complex geometries. The second problem investigated is scattering from a multiplate structure consisting of trapezoidal plates. The third problem investigated is the scattering from a composite PEC sphere and plate structure. The AIM simulation results can be compared with the results obtained using the physical optics (PO) technique [15–17]. In order to test the capability of AIM further, an aircraft model with many patches of flat surfaces has been built. The mesh generation and the measurement of the scattering pattern of the aircraft model have been carried out by us. With the mesh and measurement results of the aircraft model, the simulation was carried out using AIM. The numerical results for all the test cases show that the AIM is an efficient method for analyzing electromagnetic scattering from large complex PEC objects.

2. FORMULATION

Consider an arbitrarily-shaped 3D conducting object illuminated by an incident field \( \mathbf{E}^{inc}(\mathbf{r}) \). The EFIE is given by

\[
\hat{n} \times \int \int_{S} \mathbf{G}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}(\mathbf{r}') d\mathbf{r}' = \frac{1}{jk_0 \eta_0} \hat{n} \times \mathbf{E}^{inc}(\mathbf{r}) \quad \text{on} \quad S
\]  

where \( S \) denotes the conducting surface of the object, \( \hat{n} \) is an outwardly directed normal, and \( \mathbf{G}(\mathbf{r}, \mathbf{r}') \) is the well-known free-space dyadic Green’s function given by

\[
\mathbf{G}(\mathbf{r}, \mathbf{r}') = \left( \mathbf{I} + \frac{\nabla \nabla}{k_0^2} \right) g(\mathbf{r}, \mathbf{r}'), \quad g(\mathbf{r}, \mathbf{r}') = \frac{e^{-jk_0|\mathbf{r}-\mathbf{r}'|}}{4\pi |\mathbf{r}-\mathbf{r}'|}
\]

with \( \mathbf{I} \) being the unit dyad. Also, \( \mathbf{J}(\mathbf{r}) \) denotes the unknown surface current, \( k_0 \) is the free-space wavenumber, and \( \eta_0 \) is the free-space wave impedance. For a closed conducting object, the MFIE is given by

\[
\frac{1}{2} \mathbf{J}(\mathbf{r}) - \hat{n} \times \nabla \times \int \int_{S} g(\mathbf{r}, \mathbf{r}') \mathbf{J}(\mathbf{r}') d\mathbf{r}' = \hat{n} \times \mathbf{H}^{inc}(\mathbf{r}) \quad \text{on} \quad S
\]

where \( \mathbf{r} \) approaches \( S \) from the outside. The CFIE for a closed conducting object is simply a linear combination of EFIE and MFIE
and is of the form:

$$\alpha \text{EFIE} + (1 - \alpha) \frac{1}{jk_0} \text{MFIE}$$

(4)

where $\alpha$ is the combination parameter ranging from 0 to 1 and can be chosen to be any value within this range. It is found that $\alpha = 0.8$ is an overall good choice.

The EFIE, MFIE, and CFIE can be solved by MoM. Since both EFIE and MFIE can be considered as special cases of CFIE, we consider the MoM solution of CFIE here. For this, the conducting surface $S$ is subdivided into small triangular elements and the current on the surface is expanded using the Rao-Wilton-Glisson (RWG) basis function $f_n(r)$: $J(r) = \sum_{n=1}^{N} I_n f_n(r)$, where $N$ is the number of unknowns. Applying Galerkin’s method results in a matrix equation

$$ZI = V$$

(5)

in which the impedance matrix $Z = [Z_{mn}]$ and the vector $V = [V_m]$ can be obtained by the standard Galerkin’s procedure.

To develop a fast algorithm to solve the MoM equation (5), it is necessary to combine an iterative method with a fast approach to compute the matrix-vector products of the form $ZI$. In fact, computing $ZI$ is equivalent to computing the interactions between $N$ sources. The interactions between the sources can be divided into the near and far interactions. The near interactions correspond to a sparse matrix $Z^\text{near}$ and $Z^\text{near}I$ is easy to compute. The far interactions correspond to a dense matrix $Z^\text{far}$ and the computation of the matrix-vector product $Z^\text{far}I$ has to be accelerated for an efficient solution. To achieve this acceleration using FFT, the whole structure is enclosed in a rectangular domain known as an auxiliary domain. After discretizing the surface $S$ into triangular elements, the auxiliary domain is recursively subdivided into a regular Cartesian grid, so that each small cube contains a few triangular elements at most. In order to perform the matrix-vector product using FFT, we have to translate the original triangular basis functions to the Cartesian grid, which can be done using the basis transformation technique. Based on this idea, the matrix-vector product can be expressed as

$$ZI = Z^\text{near}I + Z^\text{far}I$$

$$= Z^\text{near}I + \alpha \sum_{k=1}^{3} T_k \mathcal{F}^{-1}\{\mathcal{F}\{[g]\} \cdot \mathcal{F}\{T_k^T I\}\}$$

$$+ \frac{\alpha}{k_0^2} T_d \mathcal{F}^{-1}\{\mathcal{F}\{[g]\} \cdot \mathcal{F}\{T_d^T I\}\}$$
Simulation of EM scattering using AIM

The monostatic scattering patterns of the dihedral corner reflector with $2\beta = 90^\circ$.

\[ + (1 - \alpha) \frac{1}{jk_0} \sum_{k=1}^{3} \tilde{T}_k \mathcal{F}^{-1}\{\mathcal{F}\{g\} \cdot \mathcal{F}\{T_k^T I\}\} \]  

in which $[Z^\text{near}] = [Z_{mn}] - [Z^\text{far}_{mn}]$, $T_k$, $T_d$, and $\tilde{T}_k$ are called the basis transformation matrices. The $T_k$, $T_d$, and $\tilde{T}_k$ can be determined by using the multipole moment approximation criteria or the far field approximation criteria [7, 8]. $Z^\text{far}$ can be given as following

\[ Z^\text{far} = \alpha \sum_{k=1}^{3} T_k [g(r_m, r'_n)] T_k^T \]

\[ + \frac{\alpha}{k_0^2} T_d [g(r_m, r'_n)] T_d^T + (1 - \alpha) \frac{1}{jk_0} \sum_{k=1}^{3} \tilde{T}_k [g(r_m, r'_n)] T_k^T \]

This is the basic idea of AIM. More detail on the implementation of AIM for CFIE is available in [9].

3. NUMERICAL RESULTS

The first problem that we have investigated is the scattering from the dihedral corner reflector, assumed to be comprised of two square plates measuring 5.6088\,\lambda on each side at 9.4 GHz [18]. Several dihedral...
Figure 2. The monostatic scattering patterns of the dihedral corner reflector with $2\beta = 77^\circ$.

Figure 3. The monostatic scattering patterns of the dihedral corner reflector with $2\beta = 98^\circ$. 
corner reflectors are examined. The simulated monostatic scattering patterns are shown in Figs. 1–3. All the results for three dihedral corner reflectors obtained using AIM are in good agreement with the results obtained in [18]. Fig. 1 shows that the 90-degree dihedral corner reflector is characterized by a dominant double reflected field in the forward region and large specular lobes at the four observation directions which are normal to each of the four surfaces. Fig. 2 shows that the 77-degree dihedral corner reflector has lower monostatic scattering pattern in the forward region than the right angle case due to reduction in the double reflection. This is true for other non-right angle dihedral corner reflectors, such as the 98-degree case shown in Fig. 3. The second problem investigated is scattering from a multiplate structure comprising trapezoidal plates, which was simulated using the PO method in [17]. The dimensions of the structure are about $10\lambda \times 15\lambda \times 3\lambda$ at 0.3 GHz. Fig. 4 shows the geometry of the multiplate structure and the current distribution for fixed incident angles $\theta = 90^\circ$ and $53^\circ$, respectively. Figs. 5 and 6 show the normalized monostatic scattering patterns for fixed $\theta = 90^\circ$ and $\theta = 53^\circ$, respectively. From these two figures, we observed that the monostatic scattering pattern at $\theta = 53^\circ$ in the nose region is lower than that at $\theta = 90^\circ$. The reason is that the multireflection strongly affects the scattering pattern at $\theta = 53^\circ$. This fact is consistent with the findings of [17] and [18]. All the numerical results facilitate understanding on the contributions of multireflection and the scattering characteristics of other geometries.
Figure 5. The normalized monostatic scattering patterns of the multiplate structure constructed of trapezoidal plates for fixed incident angle $\theta = 90^\circ$.

Figure 6. The normalized monostatic scattering patterns of the multiplate structure constructed of trapezoidal plates for fixed incident angle $\theta = 53^\circ$. 
Figure 7. The geometry of a composite PEC sphere and plate structure.

Figure 8. The monostatic scattering patterns of the composite PEC sphere and plate structure for fixed incident angle $\theta = 90^\circ$ at 1 GHz.
Figure 9. The monostatic scattering pattern of the composite PEC sphere and plate structure for fixed incident angle $\theta = 90^\circ$ at 2.5 GHz: VV-Polarization.

The more complex problem investigated is the scattering from the composite PEC sphere and plate structure that was studied using the RECOTA code in [19]. The structure comprises a conducting sphere in front of a PEC plate as shown in Fig. 7. The radius of the sphere is 12". The dimensions of the PEC plate are 30" $\times$ 1" $\times$ 20". The spacing between the sphere and plate is 2". The monostatic scattering pattern of this structure is simulated using the AIM and PO methods at different frequencies. Fig. 8 shows the monostatic scattering patterns for $\theta = 90^\circ$ at 1 GHz. Figs. 9 and 10 show the monostatic scattering patterns for $\theta = 90^\circ$ at 2.5 GHz. Figs. 11 and 12 show the monostatic scattering patterns for $\theta = 90^\circ$ at 5 GHz. The AIM simulation is in good agreement with the PO simulation for frequencies higher than 2.5 GHz. The accuracy of our PO simulation was checked by comparing with the measurement result obtained in [19]. Figs. 8–12 show the shadowing and multiple scattering effects.

The last problem investigated is the scattering from an aircraft model with flat surfaces on most parts of its body. The choice is based on the ease of construction and mesh generation, due to the flat faceted surface. We consider this object as a practical model to test our AIM code and to demonstrate the performance of AIM. The aircraft model has been built for this purpose. The mesh generation has also been carried out by us. The monostatic scattering pattern
Figure 10. The monostatic scattering pattern of the composite PEC sphere and plate structure for fixed incident angle $\theta = 90^\circ$ at 2.5 GHz: HH-Polarization.

Figure 11. The monostatic scattering pattern of the composite PEC sphere and plate structure for fixed incident angle $\theta = 90^\circ$ at 5 GHz: VV-Polarization.
Figure 12. The monostatic scattering pattern of the composite PEC sphere and plate structure for fixed incident angle $\theta = 90^\circ$ at 5 GHz: HH-Polarization.

Figure 13. The memory requirement of AIM for analyzing the aircraft model.
of our aircraft model was measured in a compact range. With the mesh and measurement results of the aircraft model, the simulation was carried out using AIM. The simulated monostatic scattering pattern using AIM is in good agreement with the measurement result. Figs. 13 and 14 show the computational expense of AIM for simulation an aircraft model. From these two figures, we observed that the memory requirement is $O(N^{1.2})$ and the CPU time per iteration is $O(N^{1.2} \log N)$.

4. CONCLUSION

The AIM has been applied to simulate electromagnetic scattering from large complex PEC objects, such as a dihedral corner reflector, a multiplate structure comprising trapezoidal plates, a composite PEC sphere and plate structure, and an aircraft model. Numerical simulation shows that the AIM is an efficient method for analyzing electromagnetic scattering from large complex PEC objects.
REFERENCES


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