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A nonconformal scheme for scattering analysis from PEC objects

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ABSTRACT

A novel nonconformal scheme for electromagnetic scattering analysis from perfect electric conducting (PEC) objects is presented in this paper. In this nonconformal scheme, the constant vector basis functions defined on a single triangle element are used as basis functions to solve the magnetic field integral equation (MFIE). Several commonly used basis functions for the MFIE are discussed and it is shown that the use of the new basis functions for the MFIE is reasonable. The construction of constant vector basis function as well as details for the calculation of the admittance matrix elements resulted from the use of method of moments (MoM) to the MFIE are given. It is shown that the use of the constant vector basis functions to the MFIE results in an efficient nonconformal scheme. Numerical results further validate the effectivity and efficiency of the proposed nonconformal scheme.

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1. Introduction

Finite-difference time domain (FDTD) method [1], finite element method (FEM) [2] and method of moments (MoM) [3] are three commonly used full-wave numerical methods for the analysis of electromagnetic problems. Features of these three methods are quite different. The FDTD method is quite effective for time-domain and wide-band problems. However, it is not as accurate as the other two methods. The FEM is usually used for problems associated with inhomogeneous medium. But, it needs the whole volume of the object to be meshed which results in too many number of unknowns. Besides, condition number of the corresponding matrix system resulted from the FEM are usually poor. This makes the solution time relatively long when iterative method are used to solve the resultant linear system. Compared with the FDTD and the FEM, the MoM combined with the integral equation method is particularly attractive for electromagnetic scattering and radiation problems. This is because the radiation boundary condition has already been included in the Green's function used in this scheme. Thus, only the surface or the volume of the object to be analyzed needs to be meshed. While both the FDTD and the FEM needs some suitable absorption boundary conditions for the analysis of electromagnetic scattering and radiation problems which results in a larger solution domain.

For the analysis of electromagnetic scattering from perfect electric conducting (PEC) objects, since the unknown equivalent currents only exists on the surface of a PEC object, the surface integral equation (SIE) can be used to model the corresponding problem. Then the MoM can be used to solve the corresponding SIE. In this process, firstly the surfaces of the corresponding PEC scatterer have to be meshed with suitable discretized elements. Since triangular meshes can model arbitrarily shaped scatterer, they are used widely for solution of integral equation by MoM [4–6]. Secondly, suitable basis functions should be defined on the corresponding discretized surface of the corresponding scatterer. Then through the use of the Galerkin's method, we get the resulted linear system. When the linear system is solved, we can get the corresponding equivalent surface currents and other interesting results such as radar cross section (RCS) data.

Basis functions defined on triangular meshes are usually designed to invoke special properties across internal boundaries of the discretized meshes. The most frequently used characters of basis functions are their continuity properties across the common edge between two neighboring patches. For example, the normal components of the popularly used Rao–Wilton–Glisson (RWG) [4] basis functions are continuous across the common edge of two neighboring triangular patches while the tangential components of the $\boldsymbol{n} \times \boldsymbol{RWG}$ [7,8] basis functions are continuous across the common boundaries of the corresponding meshes. Since the continuity condition are required for these basis functions, quality of the discretized meshes are very important for successful implementation of the MoM. This means that the discretization is required to be conformal in order to enforce the continuity condition of basis functions. However, it has been found that generating a conformal discretization of high-definition targets is a tedious and time consuming work. Besides, in some cases we may need to mix different classes of basis functions together for the same discretized meshes to fully incorporating the known physics of the

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problem. Unfortunately, the requirement of the continuity conditions for basis functions on discretized meshes makes this process very complicated if not possible. On the other hand, it has been found that explicit enforcement of the continuity conditions for basis functions are not needed in some cases. In two dimensions, it is reported in [9] that the use of the high order basis function sets eliminates the explicit enforcement of continuity conditions. In [10], it has also been found that the continuity constraints can be replaced by a partition of unity function to maintain the h and p convergence. For three dimension cases, it has already been proposed in [11] that the monopolar RWG basis function set which does not enforce any continuity conditions between neighboring patches can be used directly to the MFIE for the analysis of electromagnetic scattering problems of PEC objects. This kind of basis function set is then used in the discontinuous Galerkin's method in [12] for electromagnetic wave scattering problems in [12]. In [13], a novel method which use RWG basis functions but with a volume testing of the EFIE has also been proposed for a nonconformal discretization of the EFIE.

Different from the work in [11,12], we propose to use the piecewise constant vector basis functions to the MFIE which results in a simple and efficient nonconformal scheme of the MFIE. The definition as well as the construction process for the constant vector basis functions are presented. Details for the calculation of the admittance matrix elements are also presented. The nonconformal discretized meshes used for several PEC scatterers are also shown. Numerical results for both RCS results and the iterative characteristics of the MFIE using nonconformal meshes show the advantage of the proposed scheme.

2. Different kinds of basis functions used for the MFIE

We consider the electromagnetic scattering problem for a conducting object with closed surface S in free space. Suppose the incident and scattered magnetic fields are denoted by $\mathbf{H}^i(\mathbf{r})$ and $\mathbf{H}^s(\mathbf{r})$ respectively and the equivalent surface electric currents are denoted as $\mathbf{J}_s(\mathbf{r})$. The boundary condition for the magnetic fields $\mathbf{H}(\mathbf{r})$ can be expressed as [5]

$$\mathbf{n}(\mathbf{r}) \times \mathbf{H}^i(\mathbf{r}) = \mathbf{J}_s(\mathbf{r}) - \mathbf{n}(\mathbf{r}) \times \mathbf{H}^s(\mathbf{r}) \tag{1}$$

with $\mathbf{n}(\mathbf{r})$ being the unit normal vector of the surface S. Then the traditional MFIE can be expressed as

$$\mathbf{n}(\mathbf{r}) \times \mathbf{H}^i(\mathbf{r}) = \frac{1}{2}\mathbf{J}_s(\mathbf{r}) - \mathbf{n}(\mathbf{r}) \times p.v.\iint_S \nabla G(\mathbf{r}, \mathbf{r}') \times \mathbf{J}_s(\mathbf{r}')ds' \tag{2}$$

In (1) and (2), $\mathbf{r}, \mathbf{r}' \in S$, $p.v.$ is the Cauchy principle value integral and the Green's function $G(\mathbf{r}, \mathbf{r}')$ can be expressed as

$$G(\mathbf{r}, \mathbf{r}') = e^{-jkR}/4\pi R \tag{3}$$

with $R = |\mathbf{r} - \mathbf{r}'|$ being the distance between the source point $\mathbf{r}'$ and the field point $\mathbf{r}$ and k being the wave number of free space.

Similarly, if the incident electric fields are denoted by $\mathbf{E}^i(\mathbf{r})$, the electric field integral equation (EFIE) can be expressed as [4]

$$-\mathbf{n}(\mathbf{r}) \times \mathbf{E}^i(\mathbf{r}) = \mathbf{n}(\mathbf{r}) \times \iint_S [j\omega\mu \mathbf{J}_s(\mathbf{r}')G(\mathbf{r}, \mathbf{r}') - \frac{j}{\omega\varepsilon}(\nabla' \cdot \mathbf{J}_s(\mathbf{r}'))\nabla' G(\mathbf{r}, \mathbf{r}')]ds' \tag{4}$$

In (4), μ and ε are respectively the permittivity and permeability of free space.

To solve the integral equations by MoM, basis functions are needed to expand the unknown surface currents. The basis functions that expand the unknown vectors are required to follow the mathematical constraints inherited from the integral equation formulation. Next, we analyze several commonly used basis functions defined on triangular patches for the MFIE. For simplicity, the basis functions and testing functions discussed in this paper are denoted respectively as $\mathbf{b}_n(\mathbf{r})$ ($n = 1, 2, \ldots N$) and $\mathbf{t}_m(\mathbf{r})$ ($m = 1, 2, \ldots N$) if the total number of unknowns is N.

2.1. Basis functions imposing normal component continuity condition

It can be seen clearly from (4) that the divergence operator is imposed on the surface currents. In this case, the divergence-conforming Rao–Wilton–Glisson (RWG) functions which keep the continuity of the normal component of the surface currents between neighboring elements are firstly used in [4] to solve the EFIE. Afterwards, this kind of basis function is also used to solve the MFIE in [5]. Since $\mathbf{J}(\mathbf{r})$ is associated with the tangential component of the magnetic fields $\mathbf{H}(\mathbf{r})$ in (1), the continuity condition for the surface currents $\mathbf{J}_s(\mathbf{r})$ is in fact that for the magnetic fields $\mathbf{H}(\mathbf{r})$.

Let us consider two neighboring triangular elements shown in Fig. 1. The three unit vectors $\mathbf{u}(\mathbf{r})$, $\boldsymbol{\tau}(\mathbf{r})$ and $\mathbf{n}(\mathbf{r})$ which are orthogonal with each other are shown in this figure. If the basis function imposing normal component continuity conditions between neighboring elements, then we have the following equation:

$$\mathbf{u}_1(\mathbf{r}) \cdot \mathbf{b}_{n_1}(\mathbf{r}) = \mathbf{u}_2(\mathbf{r}) \cdot \mathbf{b}_{n_2}(\mathbf{r}) \tag{5}$$

Since the basis functions are used to expand the surface currents which is associated with the tangential magnetic fields, then from (5), we get

$$\mathbf{u}_1(\mathbf{r}) \cdot (\mathbf{n}_1(\mathbf{r}) \times \mathbf{H}_1(\mathbf{r})) = \mathbf{u}_2(\mathbf{r}) \cdot (\mathbf{n}_2(\mathbf{r}) \times \mathbf{H}_2(\mathbf{r})) \tag{6}$$

which can be further written as

$$(\mathbf{u}_1(\mathbf{r}) \times \mathbf{n}_1(\mathbf{r})) \cdot \mathbf{H}_1(\mathbf{r}) = (\mathbf{u}_2(\mathbf{r}) \times (\mathbf{n}_2(\mathbf{r})) \cdot \mathbf{H}_2(\mathbf{r}) \tag{7}$$

$$\boldsymbol{\tau}_1(\mathbf{r}) \cdot \mathbf{H}_1(\mathbf{r}) = \boldsymbol{\tau}_2(\mathbf{r}) \cdot \mathbf{H}_2(\mathbf{r}) \tag{8}$$

That is, from the normal continuity condition (5) for the basis function, we have derived the tangential continuity condition for the magnetic fields $\mathbf{H}(\mathbf{r})$. Therefore, the normal component continuity condition for the surface currents $\mathbf{J}(\mathbf{r})$ is in fact the tangential component continuity condition for the magnetic fields $\mathbf{H}(\mathbf{r})$.

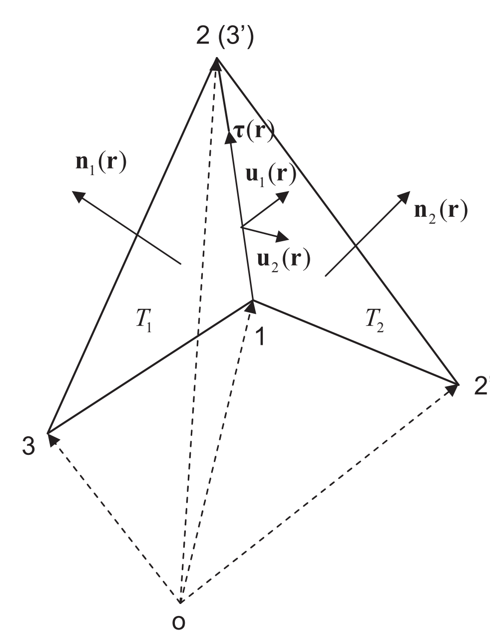

Fig. 1. Two neighboring triangles.

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