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Solving electromagnetic scattering from complex composite objects with domain decomposition method based on hybrid surface integral equations☆

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ABSTRACT

A new domain decomposition method (DDM) is proposed to solve the electromagnetic scattering from microstrip antennas and arrays conformally mounted on a perfect electrically conducting (PEC) platform. Based on the local geometrical structures and material properties, the complex composite structures is first decomposed into independent sub-domains, following the philosophy of *divide and conquer*. The combined field integral equation (CFIE), the electric field integral equation (EFIE), and the Poggio–Miller–Chang–Harrington–Wu–Tsai (PMCHWT) formulation are then combined seamlessly in the framework of DDM. These equations are applied for different sub-domains: CFIE is used for the platform (closed PEC) sub-domains and EFIE–PMCHWT is employed for the microstrip (composite structure with dielectric substrate and open PEC sheet) sub-domains. To ensure the continuities of fields, the transmission conditions (TCs) are applied on the touching-faces. Compared with the traditional method, the newly developed DDM not only releases the burden of geometry preparation, but also results in a better conditioned matrix.

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1. Introduction

The microstrip structure is defined as open metallic sheets attached to grounded dielectric substrates. It is widely used in a lot of electromagnetic (EM) problems due to its attractive features such as low profile, light weight and ease of conformity to a platform. Examples include: microstrip antennas mounted on a large platform (e.g. aircraft), frequency selective surfaces (FSS) [1] loaded with dielectric structures, etc. Numerical analysis with high accuracy is of great importance to understand the EM property of the microstrip structure. As an effective full-wave method, the method of moment (MoM) based on surface integral equation (SIE) plays an important role in the EM design and analysis procedures [3–5]. Different from the finite element method (FEM) [2], finite-difference time-domain (FDTD) method [6,7], and volume integral equation (VIE) method [8,9], SIE-based MoM [10] only requires a two-dimensional surface discretization, instead of a three-dimensional volumetric discretization. Therefore, SIE-based MoM is very appealing for modeling piecewise homogeneous or composite objects.

When the traditional SIE is used for the microstrip structure, a special procedure of junction testing is usually required [11]. This junction testing can enforce the boundary condition on the interface between different materials. Unfortunately, the implementation of this testing is quite involved, especially for complex composite structures. In order to avoid the junction testing, the connect-region modeling (CRM) method [12] was proposed to enforce the boundary conditions automatically. However, CRM relies on conformal meshes on interfaces to ensure the boundary condition. To overcome this difficulty, the non-conformal, non-overlapping domain decomposition method (DDM) can be applied as an alternative solution. The non-conformal property of DDM [13] greatly releases the burden of mesh generation. At the same time, the convergence property of the DDM system is much better than that of CRM.

Originally, the non-overlapping DDM was proposed in the FEM [14], then it was extended to integral equatoin (IE) based method to solve the multi-scale EM scattering from non-penetrable objects [15–18]. It was then extended for dielectric objects, material coating, and composite structures [19–21]. Recently, the idea of EFIE–PMCHWT [22] has been successfully applied to DDM (named as EFIE–PMCHWT–DDM) in [23] to model a single microstrip with multiple layers of substrates. In this paper, we extend the previous work to model a microstrip mounted on a large platform, which is usually the case for real engineering problems. Based on the idea of *divide and conquer*, this complex structure can be decomposed into micirostrip sub-domains and the platform (usually non-penetrable with closed surface) sub-domains. Consequently,

☆ Fully documented templates are available in the elsarticle package on CTAN.

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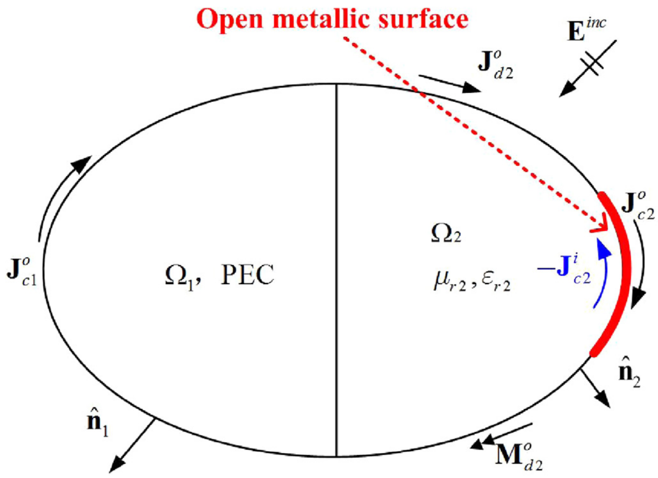

Fig. 1. EM scattering from an closed/open composite dielectric/metallic object illuminated by a plane wave.

EFIE–PMCHWT and CFIE can be used in the microstrip sub-domains and non-penetrable platform sub-domains, respectively. In the following discussion, the new DDM will be named as the hybrid surface integral equations domain decomposition method (HSIE–DDM). Compared with the traditional method such as CRM, the newly developed HSIE–DDM significantly improves the convergence of the iterative solution, and hence drastically reduces the computation time. More importantly, because the microstrip sub-domains and the platform sub-domains can be modeled independently with non-conformal meshes, the geometrical preparation can be much simplified.

The rest of the paper is organized as follows. In Section 2, the detailed derivation and Galerkin test procedure of the HSIE–DDM are derived. In Section 3, three examples are presented to validate the accuracy and demonstrate the capability of HSIE–DDM. Conclusions are summarized in Section 4.

2. Formulations and equations

Consider the electromagnetic (EM) scattering problem as shown in Fig. 1, where a composite object $\Omega = \Omega_1 \cup \Omega_2$ is illuminated by an incident plane wave. The Ω_1 is PEC object and the Ω_2 is a composite object. The $\partial\Omega_1$ and $\partial\Omega_2$ are the surface of Ω_1 and Ω_2. The $\overline{\Gamma}_m$ and $\Gamma^+_m, m = 1, 2$ are the exterior face and touching face of $\Omega_m, m = 1, 2$. They have this relationship, $\partial\Omega_1 = \overline{\Gamma}_1 \cup \Gamma^+_1$, $\partial\Omega_2 = \overline{\Gamma}_2 \cup \Gamma^+_2$. The Ω_2 is the simplification of a typical microstrip structure. The red thick line is open metallic surface printed on the surface of homogeneous dielectric object. The ε_{r2}, μ_{r2} are relative permeability and permittivity of the sub-region Ω_2. The exterior surface can be further decomposed into two parts and they satisfy $\overline{\Gamma}_2 = \overline{\Gamma}_{d2} \cup \overline{\Gamma}_{c2}$. The $\overline{\Gamma}_{d2}, \overline{\Gamma}_{c2}$ stand for the surface of dielectric and metallic, respectively. As shown in Fig. 2, the original object can be decomposed into two independent sub-domains.

The $\mathbf{J}^o_{c1}$ is the current of the first sub-domain. The $\mathbf{J}^o_{d2}, \mathbf{M}^o_{d2}$ are the electric and magnetic currents of dielectric surface of Ω_2, The $\mathbf{J}^o_{c2}, -\mathbf{J}^i_{c2}$, are the equivalent electric currents on the exterior and interior surface of $\overline{\Gamma}_{c2}$.

The combined field integral equation (CFIE) is chosen as the governing equation of sub-domain Ω_1, and the EFIE–PMCHWT is taken as the governing equation of sub-domain Ω_2.

When the field point $\mathbf{r} \in \overline{\Gamma}_1$, the combined field integral equation is expressed as,

$$\beta\eta_0\mathbf{J}_{c1}(\mathbf{r}) - C_{\alpha,\beta}\left(\mathbf{J}_{c1}, \partial\Omega_1\right)(\mathbf{r}) = \alpha\mathbf{E}^{inc}(\mathbf{r}) + \beta\eta_0\hat{\mathbf{n}} \times \mathbf{H}^{inc}(\mathbf{r}) + C_{\alpha,\beta}(\mathbf{J}_2; \partial\Omega_2) + \hat{\mathbf{n}}_2 \times C_{\beta,\alpha}(\mathbf{M}_{d2}; \partial\Omega_2 \setminus \overline{\Gamma}_{c2}), \mathbf{r} \in \overline{\Gamma}_1 \tag{1}$$

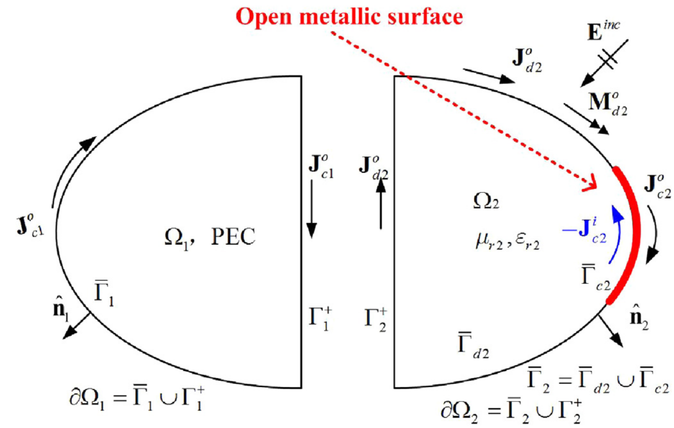

Fig. 2. The notation of the original complex composite object as shown in Fig. 1.

The detailed definition of the $C_{\alpha,\beta}$ is in the appendix, and the α, β is set as $\alpha = \beta = 0.5$.

When the field point $\mathbf{r} \in \Gamma^+_1$, the TCs are enforced directly to ensure the continuities of fields.

$$\mathbf{J}_{\Gamma^+_1}(\mathbf{r}) = -\mathbf{J}_{\Gamma^+_{d2}}(\mathbf{r}) + \hat{\mathbf{n}}_2(\mathbf{r}) \times \mathbf{M}_{\Gamma^+_{d2}}(\mathbf{r}), \mathbf{r} \in \Gamma^+_1 \tag{2}$$

When the field point $\mathbf{r} \in \overline{\Gamma}_2$, the EFIE and MFIE in the exterior region can be expressed as,

$$\left\{\begin{array}{l} \hat{\mathbf{n}}_2(\mathbf{r}) \times \mathbf{M}_2(\mathbf{r}) - \mathbf{E}^{sca}(\mathbf{r}; \partial\Omega_2) = \mathbf{E}^{inc}(\mathbf{r}) \\ \qquad + \mathbf{E}^{sca}(\mathbf{r}; \partial\Omega_1) \\ \mathbf{J}_2(\mathbf{r}) \times \hat{\mathbf{n}}_2(\mathbf{r}) - \mathbf{H}^{sca}(\mathbf{r}; \partial\Omega_2) = \mathbf{H}^{inc}(\mathbf{r}) \\ \qquad + \mathbf{H}^{sca}(\mathbf{r}; \partial\Omega_1) \end{array}\right., \quad \mathbf{r} \in \overline{\Gamma}_2 \tag{3}$$

Further more, The EFIE and MFIE can be detailed expressed as,

$$\left\{\begin{array}{l} -\eta_0\mathcal{L}_0\left(\mathbf{J}^o_2; \partial\Omega_2\right) - \frac{\eta_0}{2}\mathbf{M}^o_{d2}(\mathbf{r}) \times \hat{\mathbf{n}}_2(\mathbf{r}) \\ +\eta_0\overline{\mathcal{K}}_0(\mathbf{M}^o_{d2}; \partial\Omega_2 \setminus \Gamma^+_{c2}) = \mathbf{E}^{inc}(\mathbf{r}) + \eta_0\mathcal{L}_0\left(\mathbf{J}^o_1; \partial\Omega_1\right) \\ -\eta_0\overline{\mathcal{K}}_0\left(\mathbf{J}^o_2; \partial\Omega_2\right) - \frac{\eta_0}{2}\hat{\mathbf{n}}_2(\mathbf{r}) \times \mathbf{J}^o_2(\mathbf{r}) \\ -\eta_0\mathcal{L}_0(\mathbf{M}^o_{d2}; \partial\Omega_2 \setminus \Gamma^+_{c2}) = \eta_0\mathbf{H}^{inc}(\mathbf{r}) + \eta_0\mathcal{K}_0\left(\mathbf{J}^o_1; \partial\Omega_1\right) \end{array}\right., \quad \mathbf{r} \in \overline{\Gamma}_2 \tag{4}$$

When the field point $\mathbf{r} \in \Gamma^+_2$, The TCs can be defined in the following.

$$\left\{\begin{array}{l} \mathbf{J}_{\Gamma^+_{d2}}(\mathbf{r}) + \hat{\mathbf{n}}_2(\mathbf{r}) \times \mathbf{M}_{\Gamma^+_{d2}}(\mathbf{r}) = -\mathbf{J}_{\Gamma^+_1}(\mathbf{r}) \\ -\hat{\mathbf{n}}_2(\mathbf{r}) \times \mathbf{J}_{\Gamma^+_{d2}}(\mathbf{r}) + \mathbf{M}_{\Gamma^+_{d2}}(\mathbf{r}) = -\hat{\mathbf{n}}_1(\mathbf{r}) \times \mathbf{J}_{\Gamma^+_1}(\mathbf{r}) \end{array}\right., \quad \mathbf{r} \in \Gamma^+_2 \tag{5}$$

When the field point $\mathbf{r} \in \partial\Omega_2$, the EFIE and MFIE in the interior region can be expressed as,

$$\left\{\begin{array}{l} \frac{\eta_0}{2}\mathbf{M}^o_{d2}(\mathbf{r}) \times \hat{\mathbf{n}}_2(\mathbf{r}) - \eta_2\mathcal{L}_2(\mathbf{J}^o_{d2} + \mathbf{J}^i_{c2}; \partial\Omega_2) \\ \qquad + \eta_0\overline{\mathcal{K}}_2(\mathbf{M}^o_{d2}; \partial\Omega_2 \setminus \Gamma^+_{c2}) = 0 \\ \frac{\eta_0}{2}\hat{\mathbf{n}}_2(\mathbf{r}) \times \mathbf{J}^o_{d2}(\mathbf{r}) - \eta_0\overline{\mathcal{K}}_2(\mathbf{J}^o_{d2} + \mathbf{J}^i_{c2}; \partial\Omega_2) \\ \qquad - \frac{\eta_0}{\eta_2}\mathcal{L}_2(\mathbf{M}^o_{d2}; \partial\Omega_2 \setminus \Gamma^+_{c2}) = 0 \end{array}\right., \quad \mathbf{r} \in \partial\Omega_1 \setminus \Gamma^+_{c2} \tag{6}$$

$$-\eta_1\mathcal{L}_2(\mathbf{J}^o_{d2} + \mathbf{J}^i_{c2}; \partial\Omega_2) + \eta_0\overline{\mathcal{K}}_2(\mathbf{M}^o_{d2}; \partial\Omega_2 \setminus \Gamma^+_{c2}) = 0, \quad \mathbf{r} \in \Gamma^+_{c2} \tag{7}$$

make a weighted linear combination of (1) and (2) and (4)–(7), namely $\{(1) + \frac{\eta_0}{2}(2)\} + \{4) + \frac{\eta_0}{2}(5) + (6) + (7)\}$. Applying the Galerkin method to discrete and test this linear combination, the Eq. (8) can be got.

$$\begin{bmatrix} \mathbf{A}_{11} & \mathbf{C}_{12} \\ \mathbf{C}_{21} & \mathbf{A}_{22} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{V}_1 \\ \mathbf{V}_2 \end{bmatrix} \tag{8}$$

where

$$\mathbf{A}_{22} = \mathbf{A}^i_{22} + \mathbf{A}^o_{22} \tag{9}$$

$$\mathbf{X}_2 = \left[\mathbf{J}_{d2}, \mathbf{M}_{d2}, \mathbf{J}_{c2}, \mathbf{J}^i_{c2}\right] \tag{10}$$

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