Hybrid MLFMA/MLACA for Analysis of Electromagnetic Scattering from Inhomogeneous High-Contrast Objects

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Abstract ─ An efficient hybrid method is proposed to analyze the electromagnetic scattering from the composite structures comprising PEC and inhomogeneous high-contrast dielectric materials with the volume-surface integral equation (VSIE) approach, which uses the main framework of the multilevel fast multipole algorithm (MLFMA) but adopts the multilevel adaptive cross approximation algorithm (MLACA) and the equivalent dipole-moment (EDM) to deal with part of the "strong" interaction of MLFMA. Numerical results are presented to demonstrate the accuracy and efficiency of the proposed scheme.

Index Terms ─ Equivalent dipole-moment, multilevel adaptive cross approximation algorithm, multilevel fast multipole algorithm, volume-surface integral equation.

I. INTRODUCTION

A lot of attentions have been paid for the analysis of electromagnetic scattering from the composite structures comprising PEC and inhomogeneous high-contrast dielectric materials for its wide range of applications, such as PEC targets coated with multilevel dielectric radar absorbing materials, the near space hypersonic vehicle coated with inhomogeneous plasma and so on. Some numerical methods can be used to deal with inhomogeneous composite objects, such as PMCHWT [1-2], Müller [3], JMCFIE [4-5], etc.; but they are effective only for the piecewise inhomogeneous dielectric and the efficiency will be decreased with the number of the subdomains increasing.

VSIE [6-7] can handle composite structures with arbitrarily inhomogeneous dielectric materials conveniently. However the number of unknowns N is large for an electrically large size problem, which brings the difficulty for solving matrix equation due to the computational complexity, $O(N^2)$ for iterative solver and $O(N^3)$ for direct solver.

MLFMA [8-14] is a widely used fast algorithm and it can be used to reduce the computational complexity both for memory and CPU time. However the computational resources of the "strong" interactions are still large for the composite objects comprising high-contrast dielectric since the finest level size should be larger than 0.2 λ_0, where λ_0 is the free space wavelength. MLACA [15-18] is another popular fast technique to analyze the electromagnetic problems. Compared with MLFMA, MLACA is purely algebraic and not limited by the forms of Green's function.

Although MLFMA and MLACA can be applied to accelerate the solving progress, the process of matrix filling is still time-consuming, especially for the dielectric part with high-contrast. EDM [19-21] is an arising method which can accelerate the computation of impedance matrix. In this paper, MLACA and EDM are used to speed up the computation for the "strong" interactions, and the threshold values for different parts of VSIE matrix are analyzed. Several numerical tests are given to validate the efficiency to analyze the electromagnetic scattering from the composite structures comprising PEC and inhomogeneous high-contrast dielectric materials.

It is well known that MLFMA, MLACA, EDM and some kinds of their combinations have been used in scattering analysis for several years, while they are first used together on VSIE. The hybrid scheme is a very useful and efficient method for the analysis of electromagnetic scattering from these composite objects. We find a special application area to make the three algorithms play better roles. In our proposed hybrid method, the respective advantages of three fast algorithms are played to remedy above problems tactfully. These advantages are verified in numerical results accordingly.

This paper is organized as follows. The theory and formulations of VSIE are demonstrated in part A of Section II, and the introductions of hybrid fast algorithms are mentioned in part B. Numerical results are shown and analyzed in Section III, and the conclusions are included in Section IV.

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II. THEROY AND FORMULATIONS

A. Volume-surface electric field integral equations

Consider an arbitrarily shaped composite structure illuminated by a plane wave $\mathbf{E}^{inc}$ in free space, the geometry of composite structures is shown in Fig. 1.

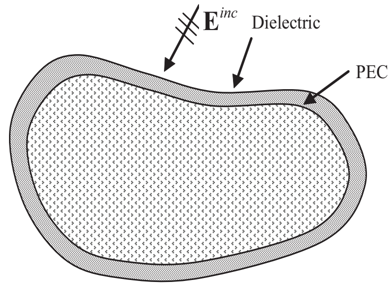

Fig. 1. Geometry of composite structure.

The PEC part of the composite structures is denoted by S, and the dielectric part is denoted by V. Where the relative permeability is all 1 and the permittivity $\varepsilon(\mathbf{r})$ is a position function in the space. Based on the boundary conditions of the total electric field, VSIE can be written as the following formats:

$$\begin{aligned}\mathbf{E}^{inc}(\mathbf{r}) = \mathbf{D}(\mathbf{r})/\varepsilon(\mathbf{r}) + j\omega\mathbf{A}_V(\mathbf{r}) + \nabla\Phi_V(\mathbf{r}) \\ + j\omega\mathbf{A}_S(\mathbf{r}) + \nabla\Phi_S(\mathbf{r}) \quad \mathbf{r} \in V,\end{aligned} \tag{1}$$

$$\begin{aligned}\mathbf{E}^{inc}_{\tan}(\mathbf{r}) = [j\omega\mathbf{A}_V(\mathbf{r}) + \nabla\Phi_V(\mathbf{r}) \\ + j\omega\mathbf{A}_S(\mathbf{r}) + \nabla\Phi_S(\mathbf{r})]_{\tan} \quad \mathbf{r} \in S.\end{aligned} \tag{2}$$

In equations (1) and (2), $\mathbf{E}^{inc}$ is the incident electric field, “tan” represents the tangential component, $\mathbf{D}(\mathbf{r})$ is the electric flux density. $\mathbf{A}_V(\mathbf{r})$, $\Phi_V(\mathbf{r})$, $\mathbf{A}_S(\mathbf{r})$ and $\Phi_S(\mathbf{r})$ are the vector magnetic potentials and scalar electric potentials produced by the volume and surface currents, respectively. The electric flux densities $\mathbf{D}(\mathbf{r})$ are represented by the SWG [22] basis functions. At the same time, the surface currents $\mathbf{J}_S(\mathbf{r})$ are represented by the RWG [23] basis functions. After the Galerkin’s test, equations (1) and (2) can be converted to the following matrix equations:

$$\begin{bmatrix}\mathbf{Z}^{DD} & \mathbf{Z}^{DM} \\ \mathbf{Z}^{MD} & \mathbf{Z}^{MM}\end{bmatrix}\begin{bmatrix}\mathbf{I}^{D} \\ \mathbf{I}^{M}\end{bmatrix} = \begin{bmatrix}\mathbf{V}^{D} \\ \mathbf{V}^{M}\end{bmatrix}. \tag{3}$$

The four parts of impedance matrix $\mathbf{Z}^{DD}$, $\mathbf{Z}^{DM}$, $\mathbf{Z}^{MD}$ and $\mathbf{Z}^{MM}$ are represent volume basis test volume integral equation, volume basis test surface integral equation, surface basis test volume integral equation and surface basis test surface integral equation, respectively.

B. Hybrid fast algorithm applied for VSIE

In order to reduce the filling time of MoM, EDM is introduced for impedance matrix generation. Using EDM method, the scattered filed produced by the surface and volume currents can be relapced by the approximation of the radiated field produced by a very small diopole with equivalent moment. The interaction between the source and testing basis functions can be computed directly without double integrals when their distance is larger than the threshold value. In this paper, the threshold value in $\mathbf{Z}^{DD}$ part for dielectric is assigned as 0.15 λ_D and 0.15 λ_0 for the other parts, where λ_D is the wavelength in dielectric.

Although the time of impedance matrix evaluating is reduced, the memory consumption and time of matrix-vector product (MVP) are unchanged. MLFMA can be utilized to accelerate electromagnetic scattering calculation, which is based on the addition theorem for the scalar Green’s function. In the frame of MLFMA, the near and far interaction parts are constituted for the MVP, the near parts are still the same with MoM/EDM approach, the far parts are accelerated by MLFMA and not computed explicitly.

Though MLFMA is an efficient method for solving the 3D electrically large problems, the phenomenon of “low frequency breakdown” should be attentioned when the finest box size of MLFMA is less than 0.2 λ_0. For the high-contrast dielectric materials, the consumptions of “near” region interactions in the frame of MLFMA are still unacceptable due to the relatively fine discretization. Therefore, MLACA is used in the “near” region to remedy the shortages mentioned above. The same octal-tree structure is employed in MLACA as in MLFMA, and the finest box size can be assigned as 0.15 λ_D, which is smaller than that used in MLFMA. Therefore the pressure of the “strong” interaction portion in MLFMA can be reduced by MLACA. During the procedure of MLACA, the impedance matrix can be split into two classes sub-matrix blocks. The blocks in the first class are the diagonal blocks built by the self-group or two adjacent groups interactions, which are calculated by MoM/EDM approach. The blocks in the second class represent the interactions of well-separated groups, which are numerically rank-deficient, and they can efficiently be compressed with MLACA. Therefore the second class blocks can be written as $[\mathbf{Z}_{m\times n}] \approx [\mathbf{U}_{m\times r}]\times[\mathbf{V}_{n\times r}]^H$ to approximate the interactions of two well-separated groups in MLACA, where r is its rank, m and n represent the number of the basis functions in the observation and source boxes, respectively. With moderately grouping in the scheme, r is often much smaller than m and n. The singular value decomposition (SVD) algorithm can be used to further remove the redundancies in the matrices generated by MLACA.

In this paper, the hybrid MLFMA/MLACA algorithm is proposed to analyze the electromagnetic scattering from composite structures comprising PEC and inhomogeneous high-contrast dielectric materials. The impedance matrix can be written as:

$$[\mathbf{Z}]=[\mathbf{Z}_0]+[\mathbf{Z}_1]+[\mathbf{Z}_2]. \tag{4}$$

$[\mathbf{Z}_0]$ is the "near" part computed by MoM/EDM, $[\mathbf{Z}_1]$ is the "middle" part compressed by MLACA, and $[\mathbf{Z}_2]$ is the "far" part accelerated by MLFMA. In order to demonstrate our proposed scheme clearly, the impedance matrix can be described by the figure format as shown in Fig. 2.

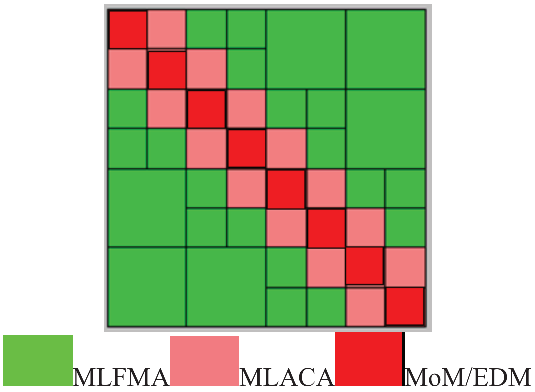

Fig. 2. The distribution of sub-matrix blocks.

III. NUMRICAL RESULTS

In this section, four numerical examples are presented to show the accuracy and efficiency of this scheme. The first and last three examples are performed on the server with same 2.67 GHz CPU, different RAM of 512 GB and 48 GB, respectively. The tolerance of MLACA in these examples is chosen as 5e-3. The multi-frontal sparse direct solver Mumps [24] is used as a preconditioner to accelerate the convergence.

Firstly, the electromagnetic scattering from a series of coated spheres are computed to test the accuracy of the proposed method and the ability to analyze the object with the increasing unknowns. The radius of PEC sphere is 0.8 m, and the thickness of coated layer is 0.1 m. The relative permittivity of dielectric layer is 4. It is illuminated by the vertical polarization plane wave traveling along Z direction at four kinds of incident frequencies 150 MHz, 300 MHz, 600 MHz and 1.2 GHz. The unknown numbers are 16768, 115616, 850816 and 6510080 for the different cases, respectively. 40 cores are used for the parallel computation. The curves of the bistatic RCS for different cases are shown in Fig. 3. It is observed that there are good agreements between the proposed method and Mie series results. The requirements of memory and CPU time are shown in Table 1.

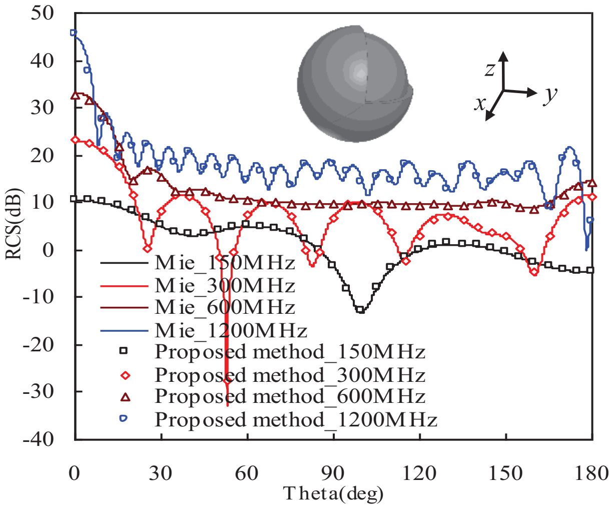

Fig. 3. The bistatic RCS of coated sphere with different frequencies (phi=0).

Table 1: Requirements of memory and CPU time

Frequency (MHz)	150	300	600	1200
Memory (GB)	0.28	3.9	47.9	459.6
CPU time (s)	82	1292	7998	45989

Next, in order to demonstrate the effect of the proposed method with different relative permittivities, three PEC cylinders with different coating materials are considered. Here, all of the coated PEC cylinder have same dimensions with the height 1.6 m and radius 0.1 m, the thickness of coating material is 0.07 m. They are illuminated by a vertical polarization plane wave traveling along Z direction at the frequency of 0.3 GHz. The relative permittivity of them are $\varepsilon_r = 2, 4, 16$, and the unknowns are 5787, 12726, 96404 for the three cases, respectively. Here, the choices of EDM threshold value are discussed in detail according to the results of second model. The parameters of MLFMA and MLACA are unchanged. The value of relative root mean square (RRMS) error is defined as $\sqrt{(1/n)\sum_{i=1}^{n}|a_i-b_i|^2/|b_i|^2}$, where a_i and b_i are the values of bistatic RCS for the test results and VSIE method with only MLFAM and MLACA, n denotes the number of observation. Now, except for $\mathbf{Z}^{DD}$ part, the calculations of impedance matrix for the other three parts are accelerated by EDM with different threshold values. Then only the calculation of $\mathbf{Z}^{DD}$ part is combined with EDM, the curves of RRMS error are shown in Fig. 4. From the curves, it can be found that the RRMS error is acceptable when the threshold value in $\mathbf{Z}^{DD}$ part is assigned as $0.15\lambda_D$ and $0.15\lambda_0$ for the other parts. The curves of the bistatic RCS for three different relative permittivities are shown in Fig. 5. It is observed that there are good agreements between them when compared with FEKO results (based on MoM/MLFMA with surface equivalence principle). As listed in Table 2, their memory requirement and CPU time are compared to show the efficiency of the proposed method, when 8 cores are used for the parallel computation. It can be found that memory requirement of "strong" interaction portion and CPU time can be reduced as high as 75% and 88% for the proposed method.

In the third example, the effect comparisons of proposed hybrid method with dielectric materials and PEC are demonstrated. A X33 scale model is considered, which is shown as Fig. 6. It is illuminated by a vertical polarization plane wave traveling along $-X$ direction at the frequency of 0.3 GHz. The PEC and high-contrast carbon fiber medium are considered to use as the fuselage material, respectively. Their unknowns are 12948, 235940, respectively. The thickness of carbon fiber is 0.01 m, the relative permittivity is 40 and the conductivity is 1e-3. The curves of the bistatic RCS are shown in Fig. 7 for both MLFMA+MLACA+EDM and MLFMA. It can be found the accuracy of the hybrid method is acceptable when compared with MLFMA. As listed in Table 3, their memory requirement and CPU time are compared to show the efficiency of the proposed method, when 40 cores are used for the parallel computation. For the high-contrast material, there are bigger advantages for memory requirement of "strong" interaction portion and CPU time than PEC material.

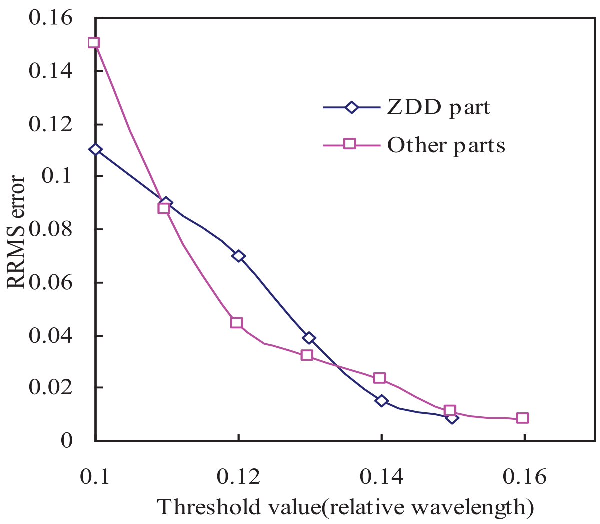

Fig. 4. The analysis of EDM threshold values with different relative wavelengths (λ_D for $\mathbf{Z}^{DD}$ part, λ_0 for the other parts).

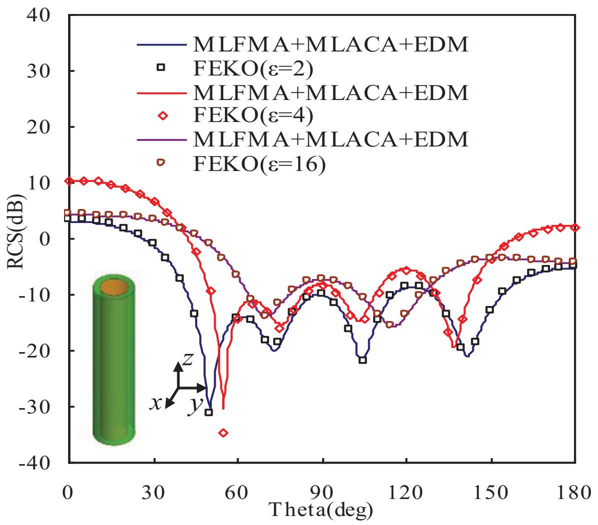

Fig. 5. The bistatic RCS of coated cylinder with different cases (phi=0).

Table 2: Comparison of the cost and performance

	MLFMA			MLFMA+MLACA		
Relative permittivity	2	4	16	2	4	16
Number of levels	2			2+1	2+2	2+3
CPU time for each MVP (s)	1.8	5.9	109	0.7	1.5	9
Total time (s) (MoM)	45	539	17984	28	121	2436
Total time (s) (MoM/EDM)	41	505	15237	25	96	2208
Near part cost (MB)	116	545	13239	80	211	3245
Memory saving ratio (%)				31	61	75
Time saving ratio (%)				44	82	88

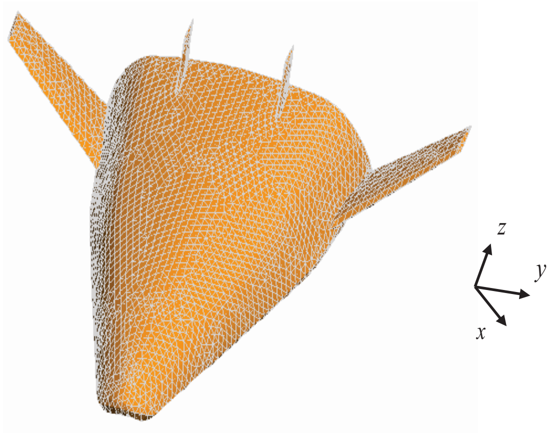

Fig. 6. The geometry of the X33.

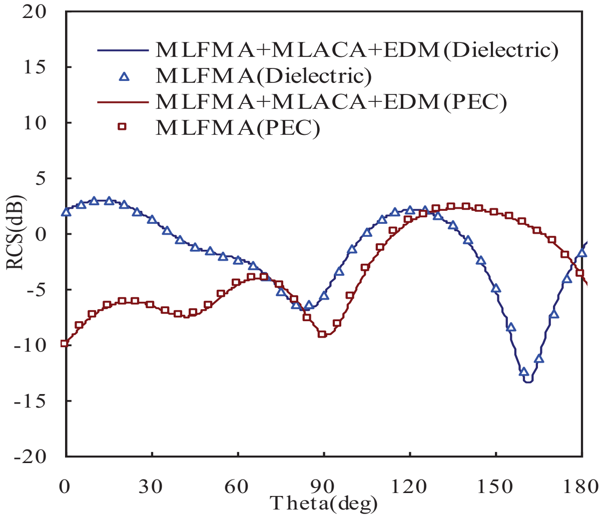

Fig. 7. The bistatic RCS of different materials (phi=0).

Table 3: Comparison of the cost and performance

	MLFMA		MLFMA+MLACA	
Material	Dielectric	PEC	Dielectric	PEC
Number of levels	2	2	2+3	2+1
CPU time for each MVP (s)	102	0.7	12.1	0.61
Total time (s) (MoM)	11457	37.5	5275	78.5
Total time (s) (MoM/EDM)	9897	29.6	4519	70.9
Near part cost (GB)	26.8	0.27	4.9	0.19
Memory saving ratio (%)			82%	29%
Time saving ratio (%)			61%	--

In order to demonstrate the advantage of VSIE to analyze the inhomogeneous composite object, an inhomogeneous composite body of revolution is considered as the last example, which is illuminated by a vertical polarization plane wave traveling along $-X$ direction at the frequency of 2 GHz and the unknown is 221621. Its relative permittivity in XoY plane is shown in Fig. 8. The curves of the bistatic RCS are shown in Fig. 9 for MLACA+MLFMA+EDM and the MLFMA. It can be found that there is a good agreement between them when compared with the MLFMA. As listed in Table 4, their memory requirement and CPU time are compared to show the efficiency of the proposed method, when 40 cores are used for the parallel computation. It can be found that memory requirement of "strong" interaction portion and CPU time can be reduced 59% and 57% for the proposed method.

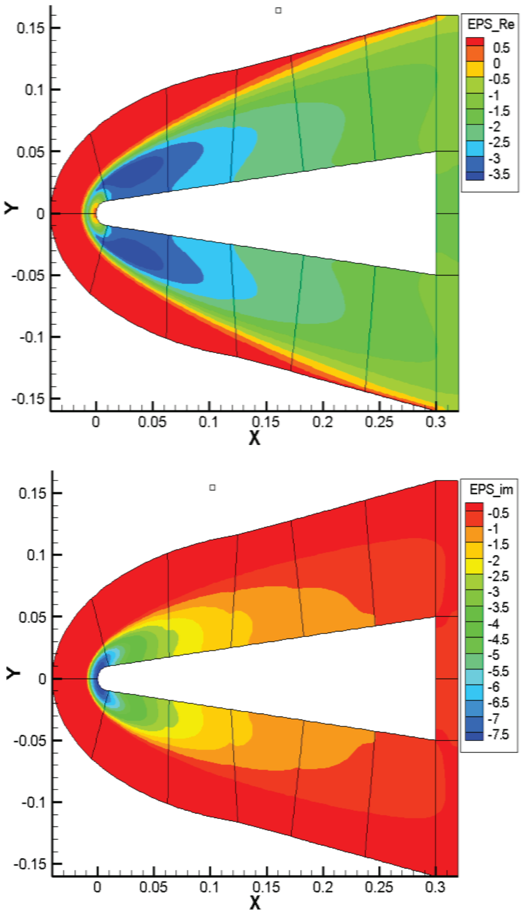

Fig. 8. The distribution of relative permittivity (real and imagine part).

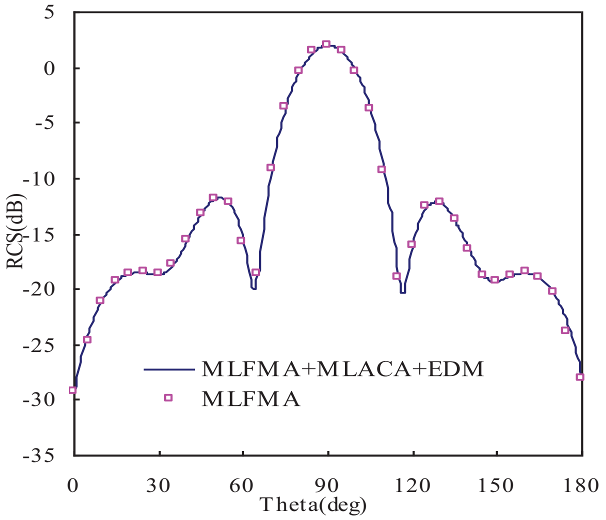

Fig. 9. The bistatic RCS of the inhomogeneous composite body (phi=0).

Table 4: Comparison of the cost and performance

	MLFMA	MLFMA+MLACA
Number of levels	2	2+2
CPU time for each MVP (s)	27.3	9.9
Total time (s) (MoM)	3115	1578
Total time (s) (MoM/EDM)	2691	1325
Near part cost (GB)	31.6	12.9
Memory saving ratio (%)		59%
Time saving ratio (%)		57%

IV. CONCLUSION

In this paper, the combination of MLACA and EDM is introduced to further accelerate MLFMA in the VSIE to efficiently analyze the electromagnetic scattering from composite structures comprising PEC and inhomogeneous high-contrast dielectric materials. Its memory requirements of "strong" interaction portion and CPU time have been reduced effectively when compared with MLFMA.

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