The Parallel Ray Propagation Fast Multipole Algorithm with Curve Asymptotic Phase Basis Function for Large-Scale EM Scatterings

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Abstract **—** The curve asymptotic phase basis functions (AP-CRWG) are introduced to reduce the number of unknowns. Moreover, the parallel ray-propagation fast multipole algorithm (RPFMA) is used to accelerate the far-interaction calculation. The translation between any two groups in the multilevel fast multipole algorithm (MLFMA) is expensive and the translator is defined on an Ewald sphere with many $\hat{k}$ directions. When two groups are well separated, the translation can be simplified by using RPFMA, where only a few sampling $\hat{k}$ directions are required within a cone zone on the Ewald sphere. As a result, both the memory requirement and the CPU time can be saved significantly. Numerical examples are given to demonstrate that the proposed method is more efficient than both the conventional MLFMA and the RPFMA-MLFMA.

Index Terms **—** Curve asymptotic phase basis function, electromagnetic scattering, method of moments (MoM), multilevel fast multipole algorithm (MLFMA), parallization, ray-propagation fast multipole algorithm (RPFMA).

I. INTRODUCTION

The method of moments (MoM) [1-4] has been widely applied in a variety of electromagnetic (EM) radiation and scattering problems. The multilevel fast multipole algorithm (MLFMA) which is one of the most efficient approaches to solve large scale scattering problems can reduce both the memory requirement and the computational complexity. However, MLFMA is still expensive in solving the EM scattering problems for very large objects. The translation process is time consuming even though the interpolation and anterpolation are used. For very large-scale problems, the exact translation is used when two groups are close to each other. When groups are well separated, however, the translation can be simplified using a ray-propagation fast multipole algorithm (RPFMA) [5]-[7], where only a few sampling $\hat{k}$ directions are required within a cone zone on the Ewald sphere. Combining AP-CRWG and RPFMA with MLFMA, the algorithm AP-RPFMA-MLFMA is developed in this paper. It can be seen from the numerical results that the proposed AP-RPFMA-MLFMA is more efficient than both the conventional MLFMA and the RPFMA-MLFMA in 3-D electromagnetic scattering and radiation for very large structures.

In this paper, an efficient approach to accelerating the parallel curve asymptotic phase basis function (AP-CRWG) with the RPFMA is proposed for large scale scattering problems. The remainder of this paper was organized as follows. The introduction of the AP-CRWG, the RPFMA and the parallization are given in the Section II. Section III presents the numerical results to demonstrate the accuracy and efficiency of the proposed method. Finally, some conclusions are given in section IV.

II. THEORY

A. Curve asymptotic phase basis function

According to the Maxwell's equations, the surface equivalence principle and the constitutive relation, we can get:

$$\nabla \times \vec{E} = j\omega\mu\vec{H}, \tag{1}$$

$$\vec{J} = \hat{n} \times \vec{H}, \tag{2}$$

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$$\vec{D} = \varepsilon \vec{E}, \tag{3}$$

where $\vec{E}$ stands for the electric field, $\vec{H}$ is the magnetic field, $\vec{J}$ is the electric current and $\vec{D}$ denotes the electric flux.

Therefore, the relationship between $\vec{J}$ and $\vec{D}$ can be written as:

$$\vec{J} = \frac{1}{j\omega\mu\varepsilon} \hat{n} \times \nabla \times \vec{D}, \tag{4}$$

where μ, ε are permittivity and permeability respectively. The curl of $\vec{D}$ can be written as:

$$\begin{aligned} \nabla \times \vec{D} &= (\nabla_t + \hat{n}\frac{\partial}{\partial n}) \times (\vec{D}_t + \hat{n}D_n) \\ &= \nabla_t \times \vec{D}_t + \nabla_t \times \hat{n}D_n + \hat{n} \times \frac{\partial \vec{D}_t}{\partial n}, \end{aligned} \tag{5}$$

where $\hat{n}$ stands for the normal unit vector, D_n is the normal component of $\vec{D}$, $\vec{D}_t$ is the tangential component of $\vec{D}$. From (4) and (5), we can get:

$$\vec{J} = \frac{1}{j\omega\mu\varepsilon} (\nabla D_n - \frac{\partial D_t}{\partial n}). \tag{6}$$

In addition to the boundary conditions and the current continuity:

$$D_n = \rho_s, \tag{7}$$

$$\nabla_t \cdot \vec{J} = j\omega\rho_s. \tag{8}$$

From (6), (7) and (8), we can get:

$$\nabla_t^2 \rho_s + k^2 \rho_s = \nabla_t \bullet \frac{\partial D_t}{\partial n}. \tag{9}$$

The solution of (9) can be written as:

$$\rho_s(\vec{r}) = \sum_{m=1}^{M} C_m e^{-j\vec{k}^i \bullet \vec{r}} + D(\vec{r}) e^{-j\vec{k}^i \bullet \vec{r}}, \tag{10}$$

where $\vec{k}^i$ is the incident direction of propagation.

From the above analysis, the relationship is formed as:

$$\vec{J}(\vec{r}) \sim e^{-j\vec{k}^i \bullet \vec{r}}. \tag{11}$$

The current on ideal conductive surfaces has the phase characteristic, so the basis function which is used to approximate surface current also has amplitude and phase. Curved triangles are used to subdivide the surface of the target. Surface current can be expressed as follows:

$$\vec{J}(\vec{r}) = \sum_{n=1}^{N} a_n \vec{F}_n(\vec{r}) = \sum_{n=1}^{N} a_n \vec{f}_n(\vec{r}) e^{-j\vec{k}^i \cdot \vec{r}}, \tag{12}$$

where $\vec{f}_n(\vec{r})$ is CRWG basis function.

By using this basic function, the number of unknowns can be reduced greatly with encouraging accurate results when compared with the RWG basis functions.

B. Ray propagation fast multipole algorithm (RPFMA)

The scalar Green's function for 3-D problems can be expanded:

$$\frac{e^{ik|\vec{r}_i - \vec{r}_j|}}{|\vec{r}_i - \vec{r}_j|} = \frac{ik}{4\pi} \int d^2\hat{k} e^{i\vec{k}\cdot(\vec{r}_{im} + \vec{r}_{nj})} \alpha_{mn}\left(\hat{k} \cdot \hat{r}_{mn}\right), \tag{13}$$

where the integral is defined on a unit sphere S_E, the Ewald sphere, and $\vec{r}_i, \vec{r}_j$ are the observation point vector and the source point vector respectively, and $\vec{r}_{im}, \vec{r}_{nj}$ are the spatial vector from the center of the observation group to the observation point and the spatial vector from the center of the source group to the source point respectively, and α_{mn} is called a translator between the two groups which is defined as:

$$\alpha_{mn}\left(\hat{k} \cdot \hat{r}_{mn}\right) = \sum_{j=0}^{L} i^j (2j+1) h_j^{(1)}(kr_{mn}) P_j(\hat{k} \cdot \hat{r}_{mn}), \tag{14}$$

where L is the truncation number of an infinite series, and related to the group size.

In the conventional MLFMA based on (14), all $\hat{k}$ directions on the Ewald sphere are involved in the translation. Hence, a large number of sampling $\hat{k}$ directions have to be used in the numerical implementation for large-scale problems [8]. As a result, it is very time consuming to perform the exact translation. It should be noted that the truncation of an infinite summation is required for the translator. Such truncation is equivalent to the use of a square window. However, it is equally valid to use another window function which makes a smooth transition from one to zero. (14) can be rewritten as:

$$\alpha_{mn}\left(\hat{k} \cdot \hat{r}_{mn}\right) = \sum_{j=0}^{L} i^j (2j+1) h_j^{(1)}(kr_{mn}) P_j(\hat{k} \cdot \hat{r}_{mn}) w_j, \tag{15}$$

where $w_l = \begin{cases} 1 & l \le J \\ \frac{1}{2}\left[1 + \cos(\frac{l-J}{L-J}\pi)\right] & l > J \end{cases}$ is the window function. The advantage of such window function in (15) is to make the main beam of the translator pattern sharper and sidelobes lower. This is the main idea of RPFMA. Physically speaking, as shown in Fig. 1, the effective beamwidth forms a cone region around the ray direction $\hat{r}_{mn}$ on the Ewald sphere, whose solid angle is $\hat{\theta}_e$. Hence, only the $\hat{k}$ directions within the cone region have strong contribution to the translator, and all the $\hat{k}$ directions outside the region will be discarded. In this case, only a small number of $\hat{k}$ directions on the Ewald sphere are used, which makes RPFMA much more efficient.

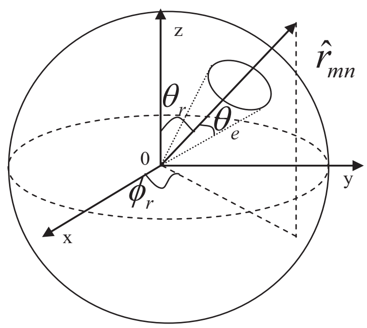

Fig. 1. Ewald sphere.

C. Parallization

Although the MLFMA reduces the complexity of MoM from $O(N^2)$ to $O(N\log N)$, allowing for the solution of large problems with limited computational resources. However, accurate solutions of large problems require discretization's with millions of unknowns, which cannot be solved with sequential implementations of MLFMA running on a single processor easily. To solve such large problems, it is helpful to increase computational resource by assembling parallel computing platforms and, at the same time, by paralleling MLFMA [9-13]. There are many studies that have been done to improve the efficiency of the parallel MLFMA [14-15] Thanks to these studies, problems with millions of unknowns have been solved on relatively inexpensive platforms.

Series of implementation techniques have been developed for efficiently parallelizing the MLFMA. These techniques are different, but the most important thing in those techniques in parallelizing MLFMA is load-balancing and minimizes the communications between the processors. This is achieved by using different partitioning strategies for the lower and higher levels of the tree structure. In the lower levels of the tree structure, there are many clusters with small number of samples for the radiated and incoming fields. The number of cubes is much larger than the number of processors. Therefore, it is natural to distribute the cubes equally among processors. However, it is difficult to achieve good load-balancing in higher levels with this parallel approach, since the number of cubes in the coarse levels is small and the electric size of the cube is large, the far-field patterns is large. Therefore, in the coarse level, we adopt another parallel approach in the coarse levels; we partition the far-field patterns equally among all processors and send the needed messages to each processor. Using this approach for the parallel MLFMA in the far-field, good load balancing can be achieved.

III. NUMERICAL RESULTS

In this section, three examples are presented to demonstrate the benefits of the proposed method. In our experiments, the restarted version of GMRES [16] algorithm is used to solve the linear systems. All cases are tested on HP server with Intel Xeon CPU X5550 (2.67 GHz). The operating system is Red Hat Enterprise Linux Server release 5.3. The environment of compiling is Intel Visual Fortran 9. Additional details and comments on the implementation are given as follows:

- The terminating tolerances of the RPFMA are set as 0.001.
- The resulting linear systems are solved iteratively by the GMRES (30) solver with a relative residual of 10^{-3}.
- Zero vector is taken as initial approximate solution for all examples.
- The maximum number of iterations is limited to be 5000.
- The second and third examples are performed on 10-node cluster connected with an Infiniband network. Each node includes 8 cores and 48 GB of RAM. One node is used in the first examples with 8 cores.
- The mesh size for both the conventional MLFMA and the RPFMA-MLFMA is 0.15λ, while the mesh size for the proposed AP-RPFMA-MLFMA is 1.0λ.

We first consider the scattering from a strip of $9m\times3m$ at the frequency of 3 GHz. When the incident plane wave is fixed at $\theta_{inc}=60^\circ$ $\phi_{inc}=0^\circ$, the bistatic RCS results for VV polarization computed by the conventional MLFMA, AP-RPFMA-MLFMA are shown in Fig. 2. Four-level algorithms have been used in the AP-RPFMA-MLFMA algorithm while seven-level algorithms have been used in the conventional MLFMA. Figure 2 illustrates the validation of numerical results from the AP-RPFMA-MLFMA against the conventional MLFMA. The comparison of the translator numbers between the MLFMA and the RPFMA is listed in Table 1. The comparisons of the number of unknowns, the iteration number, the translator pattern memory and the total time of the conventional MLFMA, RPFMA-MLFMA and the AP-RPFMA-MLFMA are shown in Table 2.

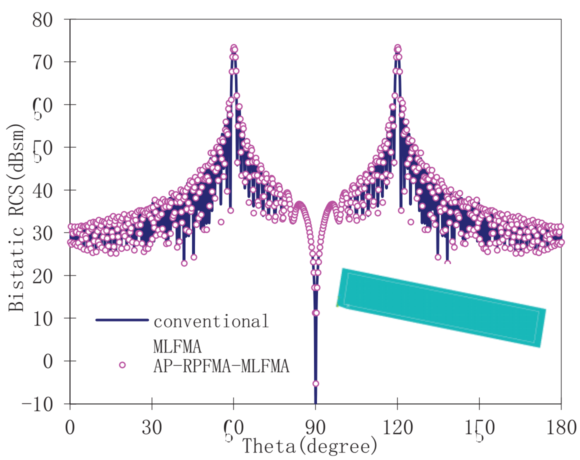

Fig. 2. Bistatic RCS of a strip of $90\lambda \times 30\lambda$ (V-V polarization).

Table 1: Comparison of the translator numbers between the MLFMA and the RPFMA for the strip

Nlevel	$\hat{\theta}_e$	Number of Translator for MLFMA	Number of Translator for RPFMA
1	1.0π	2738	2738
2	0.6π	9522	6881
3	0.3π	34848	10296
4	0.2π	130050	50090

Next, we consider the scattering from a PEC sphere with the radius of 80 m at the frequency of 0.6 GHz. The incident plane wave is fixed at $\theta_{inc} = 0^\circ$ $\phi_{inc} = 0^\circ$, the scattering angle is fixed at $\theta_s = 0^\circ \sim 180^\circ$ $\phi_s = 0^\circ$. As shown in Fig. 3, there is a good agreement between the AP-RPFMA-MLFMA and the conventional MLFMA. Six-level algorithms have been used in the AP-RPFMA-MLFMA while nine-level algorithms have been used in the conventional MLFMA. The comparison of the translator numbers between the MLFMA and the RPFMA is listed in Table 3. The comparisons of the number of unknowns, the iteration number, the translator pattern memory and the total time of the conventional MLFMA, RPFMA-MLFMA and the AP-RPFMA-MLFMA are illustrated in Table 4. Clearly, both the memory requirement and the total CPU time in AP-RPFMA-MLFMA have been reduced.

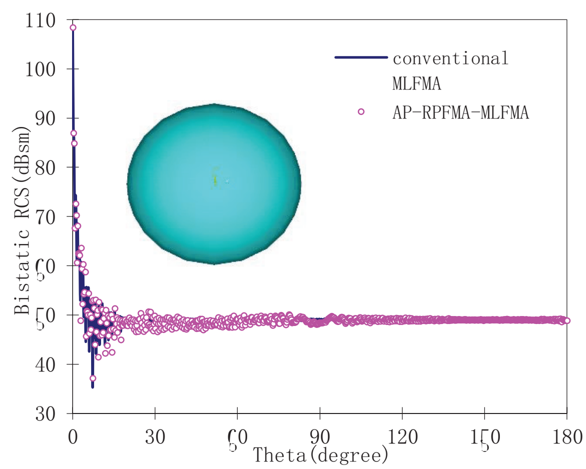

Fig. 3. Bistatic RCS of a PEC sphere of radius 80 m at 0.6 GHz (V-V polarization).

Table 3: Comparison of the translator numbers between the MLFMA and the RPFMA for the PEC sphere

Nlevel	$\hat{\theta}_e$	Number of Translator for MLFMA	Number of Translator for RPFMA
1	1.0π	2312	2312
2	0.6π	7688	5550
3	0.3π	27848	8260
4	0.2π	103968	41195
5	0.15π	399618	117785
6	0.1π	1562912	303751

At last, the proposed method is used to analysis scattering from a satellite with longest length of 22 m at 13 GHz. Seven-level algorithms have been used in the AP-RPFMA-MLFMA while eleven-level algorithms have been used in the conventional

MLFMA. The incident plane wave direction is fixed at $\theta_{inc} = 0^\circ \quad \phi_{inc} = 0^\circ$, the scattering angle is fixed at $\theta_s = 0^\circ \sim 180^\circ \quad \phi_s = 0^\circ$. Figure 4 shows the bistatic RCS results for VV polarization computed by the conventional MLFMA and the AP-RPFMA-MLFMA. The comparison of the translator numbers between the MLFMA and the RPFMA is listed in Table 5. The comparisons of the number of unknowns, the iteration number, the translator pattern memory and the total time of the conventional MLFMA, RPFMA-MLFMA and the AP-RPFMA-MLFMA are shown in Table 6.

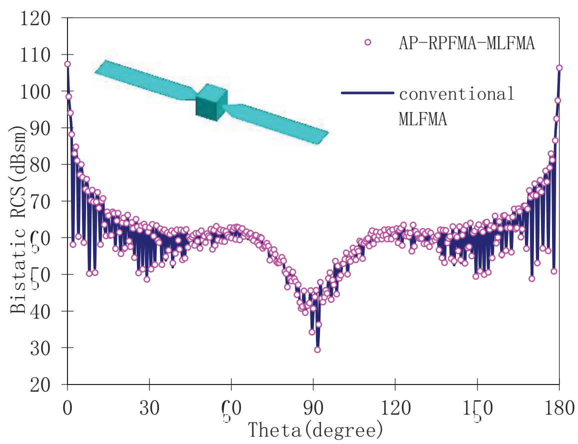

Fig. 4. Bistatic RCS of a satellite at 13 GHz (V-V polarization).

From the above figures, we clearly see that the numerical results from the AP-RPFMA-MLFMA are very accurate in both cases while the tolerance is set as 0.001. This is because the near neighbor groups have been treated using MLFMA exactly. $\hat{\theta}_e$ is an experiential number, which is related to the distance between the observation group and the source group. The corresponding $\hat{\theta}_e$ can be chosen smaller when the observation group is far away from the observation group.

Table 5: Comparison of the number of translator between the MLFMA and the RPFMA algorithm for the satellite

Nlevel	$\hat{\theta}_e$	Number of Translator for MLFMA	Number of Translator for RPFMA
1	1.0π	4418	4418
2	0.6π	15488	11190
3	0.3π	57800	17340
4	0.2π	219122	87691
5	0.15π	852818	254895
6	0.1π	3348872	665146
7	0.08π	13271552	2099288

Table 2: Comparisons of the number of unknowns, the iteration number, the translator pattern memory and the total time of the conventional MLFMA, RPFMA-MLFMA and the AP-RPFMA-MLFMA for the strip

Method	Unknowns	Iteration Number	Translator Pattern Memory (MB)	Total Time (s)	Saving in Memory (%)
Conventional MLFMA	415,692	1788	415.91	13919	*
RPFMA-MLFMA	415,692	1790	276.34	9561	33.56
AP-RPFMA-MLFMA	12,750	278	34.18	785	91.78

Table 4: Comparisons of the number of unknowns, the iteration number, the translator pattern memory and the total time of the conventional MLFMA, RPFMA-MLFMA and the AP-RPFMA-MLFMA for the PEC sphere

Method	Unknowns	Iteration Number	Translator Pattern Memory (MB)	Total Time (s)	Saving in Memory (%)
Conventional MLFMA	12,275,926	168	6519.06	19370	*
RPFMA-MLFMA	12,275,926	169	1741.97	12291	73.27
AP-RPFMA-MLFMA	478,776	30	223.29	3984	96.57

Table 6: Comparisons of the number of unknowns, the iteration number, the translator pattern memory and the total time of the conventional MLFMA, RPFMA-MLFMA and the AP-RPFMA-MLFMA for the satellite

Method	Unknowns	Iteration Number	Translator Pattern Memory (MB)	Total Time (s)	Saving in Memory (%)
Conventional MLFMA	18,502,579	5000	94080.48	57156	*
RPFMA-MLFMA	18,502,579	5000	8941.63	34209	90.49
AP-RPFMA-MLFMA	596,696	1534	1533.31	23652	98.37

IV. CONCLUSION

This paper presents the parallel ray propagation fast multipole algorithm with curve asymptotic phase basis function for large scale scattering problems. Numerical results show the efficiency of the presented technique for analyzing large-scale EM scattering problems. AP-CRWG is more efficient in reducing the number of unknowns, memory requirement and calculation time than the conventional RWG. Based on the conventional MLFMA, we introduce RPFMA to accelerate far interactions. Compared with both the conventional MLFMA and the RPFMA-MLFMA, both the memory requirement and the CPU time can be reduced by using the proposed algorithms while assuring the precision.

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