Parallel Computation of Complex Antennas Around the Coated Object Using Hybrid Higher-Order MoM and PO Technique

Ying Yan, Xunwang Zhao, Yu Zhang, Changhong Liang
Science and Technology on Antenna and Microwave Laboratory
Xidian University, Xi'an, Shaanxi, 710071, People's Republic of China

Jingyan Mo
School of Communication and Information Engineering
Shanghai University, Shanghai, 200021, People's Republic of China

Zhewang Ma
Graduate School of Science and Engineering, Saitama University
255 Shimo-Okubo, Sakura-ku, Saitama-shi, Saitama 338-8570, Japan

Abstract- **This paper presents a novel hybrid technique for analyzing complex antennas around the coated object, which is termed the iterative vector fields with Physical Optics (PO). A closed box is used to enclose the antenna and then the complex field vector components on the box' surfaces can be obtained using Huygens principle. The equivalent electromagnetic currents on Huygens surface are computed by Higher-order Method of Moments (HOB-MoM) and the fields scattered from the coated platform are calculated by PO method. Moreover, the parallel technique based on Message Passing Interface (MPI) and Scalable Linear Algebra Package (ScaLAPACK) is employed to accelerate the computation, and good load balance and parallel efficiency are obtained under the proposed parallel scheme. Finally, some numerical examples are presented to validate and to show the effectiveness of the proposed method on solving the practical engineering problems.**

I. INTRODUCTION

In recent years, many researches on hybrid methods emerged. Hybrid FDTD-UTD, MoM-UTD was applied to analyze phased array antennas mounted on airborne platform in [1, 2, 3], but most of them focus on the PEC problem. The iterative MOM-NURBS PO technique was reported to analyze the antenna around NURBS surface [3], while the antenna in this report is limited to the type of line, and the model in PO region is of PEC material. As we know, the platform, such as aircraft, ship or car rarely has pure PEC surface in real-life. Generally, there are several kinds of dielectric materials coated on their surface to achieve different goals, especially for military application. Coating has become a more and more significant method on reducing RCS to make vehicles hidden. In this case, the performance of antenna near the platform will be deteriorated. Thus, it is necessary to study the characteristics of the antenna near an object with dielectric materials. Furthermore, various kinds of complex antennas should be considered in order to make the simulation more realistic. Commercial software *HOBBIES* [4] (Higher-order Basis Functions Based Integral Equation Solver), is a general purpose frequency domain electromagnetic integral equation solver which provides the reasonable solutions based on Higher-order MoM. The employment of Higher-order basis can significantly reduce the number of unknowns and the memory required as well [5]. Even if the efficiency has been enhanced, the hardware requirements are also unbearable when the model simulated has electronically large dimensions. Thus, PO technique is utilized to calculate the scattered field from the platform.

In addition, parallel technique based on MPI [6] and ScaLAPACK [5] libraries is employed to further speed-up the computation and to improve the computational efficiency. The block-partitioned scheme for the large dense MoM matrix combined with the process-cyclic scheme for the PO discretized triangles is designed to achieve excellent load balance and high parallel efficiency.

II. MODIFYING THE COMPLEX VECTOR FIELD OVER HUYGENS SURFACE

The whole model simulated has to be divided into two parts that antennas are considered as the MoM region; while the scatterer as the PO region. As shown in Figure 1, the antennas are enclosed by a cube box. There will be a short-lived interaction between these two regions until the electromagnetic currents on the box' surface become stable. The effect of the scatterer on the antenna can be equivalent to the action on the electric and magnetic currents on the box. The iteration process can be summarized as follows:

(1) Equivalence theorem tells us the whole computational region of electromagnetic problems can be decomposed into two separate parts-inner and outer. We could set antenna simulated in the inner area and only consider the outer part outside the antennas. In this case, the electromagnetic fields in the inner area should be set to zero. Moreover, there should be

electric and magnetic currents $\vec{J}_s, \vec{M}_s$ induced on the interface surface of inner and outer regions to maintain the radiation fields from antennas to the outside region.

The equivalent currents can be determined by the electric and magnetic fields $\vec{E}$ and $\vec{H}$, which can be expressed as

$$\vec{J}_s = \hat{n} \times \vec{H}, \vec{M}_s = \vec{E} \times \hat{n} \tag{1}$$

Where $\hat{n}$ is the outward unit normal vector of the equivalent surface, and $\vec{E}$, $\vec{H}$ are the radiation fields of antennas on the equivalent surfaces without platform in PO region. The interaction between MoM region and PO region can be transformed into the one between the equivalent surface and the PO region, and the antennas in the box can be considered as non-existed.

In this paper, a cube shaped box is selected as the equivalent surfaces, whose six surfaces are all uniformly divided into some small square patches. The side length of a square is selected as $\lambda/10$ to guarantee the computational precision. To each square patch, its center point is regarded as the sampling point, at which the radiation fields of antennas without platform $\vec{E}^i, \vec{H}^i$ can be obtained by the EM solver *HOBBIES* so that the initial electromagnetic currents $\vec{J}_s(0)$ and $\vec{M}_s(0)$ can be calculated as

$$\vec{J}_s(0) = \hat{n} \times \vec{H}^i, \vec{M}_s(0) = \vec{E}^i \times \hat{n} \tag{2}$$

(2) According to the dual theorem, the electric field produced by the electric and magnetic currents can be expressed as

$$\vec{E}(\vec{r}) = (je^{-jkR}\Delta s/4\pi\omega\varepsilon)\left\{\frac{k^2R^2-3jkR-3}{R^5}\left\{\vec{R}\times\left[\vec{J}_s\times\vec{R}\right]\right\}-\frac{1+jkR}{R^3}\cdot 2\vec{J}_s\right\} \\ -\frac{\Delta s}{4\pi}\left\{\frac{1+jkR}{R^3}e^{-jkR}\cdot\left[\vec{M}_s\times\vec{R}\right]\right\} \tag{3}$$

In equation (3), $\vec{R}$ is the vector from source point $\vec{r}'$ to the observation point $\vec{r}$. The square patch is considered small enough that the currents on it can be uniform and are equal to those at the center. The notation Δs stands for the area of each square patch.

(3) The electromagnetic currents on the equivalent surface are considered as source points; they will radiate electric and magnetic fields to the PO model, and then all the illuminated PO triangles radiate fields back to the equivalent source points so as to modify the electromagnetic currents as follows:

$$\Delta\vec{J}_s = (-\hat{n}) \times \vec{H}, \Delta\vec{M}_s = \vec{E} \times (-\hat{n}) \tag{4}$$

Let $\vec{J}_s(k)$ and $\vec{M}_s(k)$ to be the currents after the *k*th iteration, the ones after *k+1*th can be expressed as

$$\vec{J}_s(k+1) = \vec{J}_s(0) + \Delta\vec{J}_s \\ \vec{M}_s(k+1) = \vec{M}_s(0) + \Delta\vec{M}_s \tag{5}$$

This process should be repeated until the convergence condition is satisfied

$$\frac{\left\|\vec{J}_s(k+1) - \vec{J}_s(k)\right\|}{\left\|\vec{J}_s(k)\right\|} \le \varepsilon, \frac{\left\|\vec{M}_s(k+1) - \vec{M}_s(k)\right\|}{\left\|\vec{M}_s(k)\right\|} \le \varepsilon \tag{6}$$

Where ε is the threshold of the iteration and is set to be 10^{-5} in this paper, $\|\cdot\|$ denotes the 2-norm of complex vector.

(4) After the currents on equivalent surface become stable, it will radiate fields directly to the observation points in free space, adding the scattered fields from PO region we can obtain the total fields.

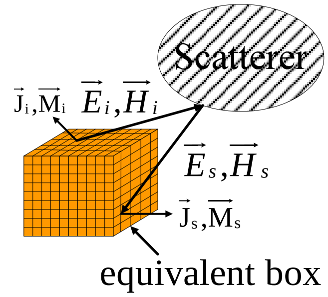


Figure 1. Model illustrating

III. Parallel Strategy Based on MPI and ScaLAPACK

A. PO part

Distributing to processes the computation of PO currents at all points over the illuminated triangles is the main task to parallelize the PO method. We use the same number of points over each triangle; hence we can partition triangles rather than points among processes. What is necessary is to ensure that the triangles in the lit PO region are partitioned equally to each process. This can be realized by distributing the triangles in neighboring regions, either lit or shadowed, to different processes.

B. MoM part

To parallelize the solution of the large dense matrix in a MoM problem, typically one needs to divide the matrix between processes in such a way that two important conditions are fulfilled: each process should store approximately the same amount of data, and the computational load should be equally distributed among the processes that run on different nodes.

The parallel LU decomposition based on the ScaLAPACK library package [5] is employed as the solver and the block storage scheme is designed accordingly. For explanation purpose, the MoM matrix equation is rewritten in a general form as

$$AX = B \tag{7}$$

where *A* denotes the complex dense matrix, *X* is the unknown vector to be determined and *B* denotes the given source vector.

For example, we assume that the matrix *A* is divided into 6×6 blocks, which are distributed to 6 processes in a 2×3 process grid. Figure 2 (a) and (b) show to which process the blocks of *A* are distributed using the ScaLAPACK's distribution methodology [5].

Process unit index

	0	1	2	0	1	2
0	11	12	13	14	15	16
1	21	22	23	24	25	26
0	31	32	33	34	35	36
1	41	42	43	44	45	46
0	51	52	53	54	55	56
1	61	62	63	64	65	66

0 (0,0)	2 (0,1)	4 (0,2)	0 (0,0)	2 (0,1)	4 (0,2)
1 (1,0)	3 (1,1)	5 (1,2)	1 (1,0)	3 (1,1)	5 (1,2)
0 (0,0)	2 (0,1)	4 (0,2)	0 (0,0)	2 (0,1)	4 (0,2)
1 (1,0)	3 (1,1)	5 (1,2)	1 (1,0)	3 (1,1)	5 (1,2)
0 (0,0)	2 (0,1)	4 (0,2)	0 (0,0)	2 (0,1)	4 (0,2)
1 (1,0)	3 (1,1)	5 (1,2)	1 (1,0)	3 (1,1)	5 (1,2)

(a) a matrix consisting of 6×6 blocks (b) rank and coordinates of each process owning the corresponding blocks in (a)

Figure 2. Block-cyclic distribution of a matrix

By varying the dimensions of the blocks of *A* and those of the process grid, different mappings can be obtained. This scheme can be referred to as a "block-cyclic" distribution procedure.

Note that the storage required for the vectors *X* and *B* is negligible compared with that of the large dense matrix *A*. Therefore, the entire vectors can be stored in each process.

Load balance is critical to obtain an efficient operation of a parallel code. This parallel scheme of matrix filling is able to achieve the good load balance. Little communication between processes is necessary during the matrix filling [5].

IV. NUMERICAL EXAMPLES

1. Simulation of a patch antenna near a coated cube

In this example, the model of a patch antenna near a coated cube has been simulated. Besides the comparison of field results with Higher-order MoM, the times consumed are also compared and the parallel efficiency is drawn as well.

The simulation frequency is 440 MHz. A closed box centered at (0, 0, 8) encloses the antenna, whose edge length is 0.55m. Through the discretization, all the six surfaces of the box have been meshed into 8×8 squares, at whose center are the equivalent electromagnetic sources. The model in PO region is a cube with edge length 4.0m, whose surfaces are coated with one layer of dielectric material. The parameters of the coating can be referenced from the 1st material in Table I. The cube has been discretized into 47204 small triangles.

This simulation employs the "magic cube" supercomputer in SSC [7]. Let us take 4 CPUs as a base, 8, 16, 32, 64, 128 CPUs are tested respectively to draw the parallel efficiency curve, as shown in Figure 4. From which we can find the good parallel effect of this paper's method, even though the efficiency drops at 128 CPUs, which is due to the reason that the problem simulated is not big enough, the more CPUs used, the longer communication times required. Moreover, the computational time comparison between this method and Higher-order MoM has been presented in Table II and we can easily find this method's superiority in time requirement.

Finally, the field results' comparison is presented in Figure 5. The pattern on *XOY* is of omnidirectional characteristic; while there are some disagreements near $\theta = 0^\circ, 180^\circ$ on *YOZ*, which is due to the edge diffraction effect from the cube.

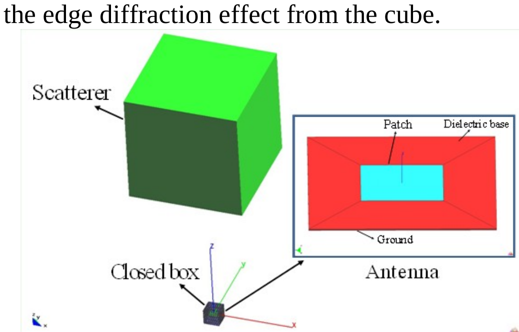


Figure 3. A patch antenna near a coated cube

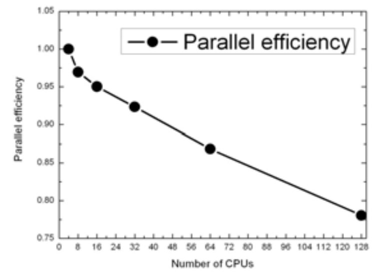


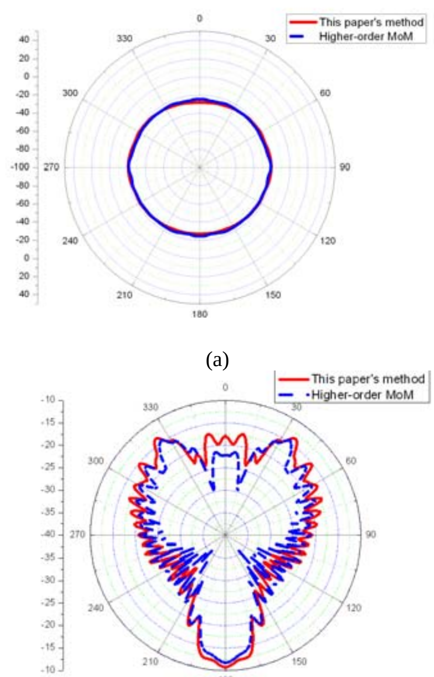
Figure 4. Parallel efficiency

TABLE I
INFORMATION OF THE COATING

	Relative Electric Permittivity	Loss Tangent	Relative Magnetic Permeability	Thickness (mm)
1st material	16	0.275	1.0	5
2nd material	2.5	0.00045	1.0	5

TABLE II
TIME COMPARISON

	Number of CPUs	Total time (Second)
This paper's method	128	84
Higher-order MoM	128	1007



(b)

Figure 5. Results comparison. (a) XOY plane; (b) YOZ plane.

2. Phased antenna array near a coated aircraft

In this example, the disturbed radiation pattern of a phased patch antenna array located near a coated aircraft has been analyzed. The simulation frequency is 440MHz. The aircraft is of the dimensions 26.4λ ×32.3λ ×7.0λ and is coated with two layers of dielectric materials, whose parameters can be referenced in Table I. The patch array, whose 11×11 elements radiates beam maximum in the direction of $\theta = 30^\circ, \phi = 90^\circ$, is excited by a Taylor shaped drive distribution and located along *XOY* coordinate plane. It is worth describing here the angle θ is started from *XOY* plane, while ϕ is still from *X*-axis. A cube whose edge length is 3.14m is chosen as the closed box to surround the antenna array, the center of the box is located at (1.434, 1.28, 0.0175) and all of the surfaces has been partitioned into 46×46 small squares.

This simulation employs 256 CPUs in SSC and requires 3 iterations, 21164 seconds to finish the calculation, in which 10229 seconds for sheltering and 9465 seconds for iteration. The disturbed pattern in 3-D is illustrated in Figure 7. We can easily find the effect of the aircraft on the characteristic of the antenna. Another main beam nearly symmetrical to the original one about *XOZ* coordinate plane appears due to the reflection of the aircraft. The side lobe has been raised about maximum 15dB, while the back lobe has been raised about 20dB.

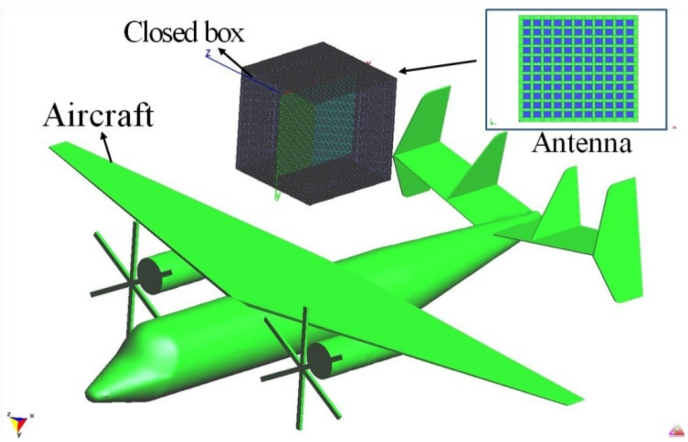
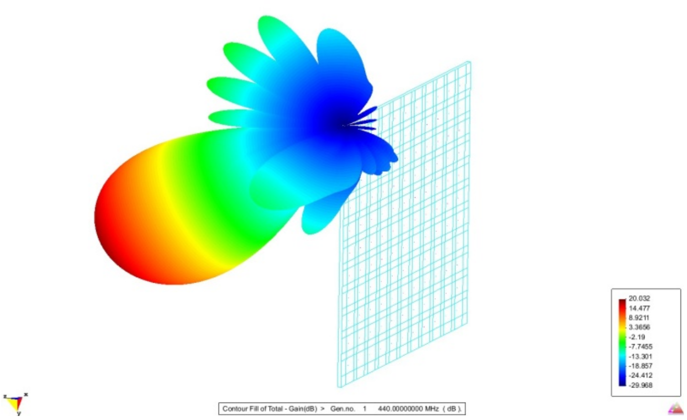
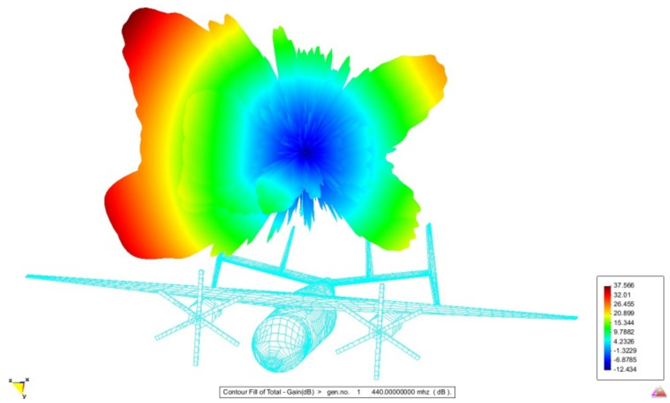


Figure 6. Phased antenna array near a coated aircraft



(a)



(b)

Figure 7. (a) The radiation pattern (dB) of the antenna array; (b) The disturbed radiation pattern (dB) after the antenna array being located near a coated aircraft.

From the examples above, we can find this paper's method needs very few iteration times to obtain the convergent solution. It is capable of solving the practical engineering problems including complex antennas and electrically large platform.

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