PSO Algorithm Combined with Parallel Higher-Order MoM to Compensate the Influence of Radome on Antennas

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Abstract ─ For the design and optimization of radome-enclosed antenna arrays, a fast numerical optimization algorithm is proposed to compensate the distortion error of radome-enclosed antenna arrays by correcting amplitude and phase of the excitations. Higher-order method of moments (MoM) is used to extract the eigen solution for each antenna element. In combination with the particle swarm optimization (PSO) algorithm, the antenna radiation characteristics can be quickly obtained by updating feeds, which avoid the repeated solution of the MoM matrix equation in the optimization process. Meanwhile, in the process of the eigen solution extraction, the use of the parallel technique significantly accelerates the solving of matrix equation. Finally, a radome-enclosed antenna array with 247,438 unknowns was optimized as an example, and the numerical results demonstrate effectiveness of the method.

Index Terms ─ Parallel algorithms, particle swarm optimization, radome-enclosed antenna array, the eigen solution.

I. INTRODUCTION

Due to good protectiveness and penetrability of electromagnetic wave, radome-enclosed antennas are widely used in many fields, such as aviation, ship-borne radars and base-station antennas. However, there exists distortion of radiation patterns of antennas when electromagnetic wave gets through the radome, producing error relative to the sighting axis (called as bore sight error (BSE)) [1]. Meanwhile the radiating wave of an antenna can be absorbed and reflected by the radome, which changes the energy distribution of the antenna in free space and destroy its electrical properties. Aiming at BSE and pattern aberrance, a lot of methods have been used to regulate patterns in the design, such as processing antennas, grinding the radome, and adjusting the downtilt. The fundamental method remains making rational optimization and adjustment of the antenna characteristics at the initial stage of the design. The mainly used approach is to optimize and adjust physical properties like materials, sizes and so on, to get the desired results [2, 3]. However, the sizes and materials of most radome-enclosed antennas are relatively fixed due to its practical purposes. Therefore, an alternative optimization method, optimizing amplitude and phase of feeds, gradually becomes popular [4]. With antenna structures and materials becoming more and more complex, it is very difficult for commercial software to compute and analyze antennas. Although fast methods such as fast multipole method (FMM) can be used, the computing time may be extremely long. It is well known that optimization algorithms need plenty of iterations, in which FMM needs repeated solution of matrix equations due to its iterative nature, and thus the use of FMM may take a very long time and is hard to optimize large radome-enclosed antennas.

To solve the problem, this paper adopts the eigen solution extraction technique, utilizing method of moments (MoM) to extract the eigen solution for each antenna array element and computing radiation patterns of the antenna array by using linear combination of the eigen solution. The LU (lower/upper) decomposition based direct solver is used to solve MoM matrix equations. The matrix needs to be factorized only once, and is reused to extract the eigen solution. Through rapid combination of the eigen solution, new radiation patterns of the antenna array is obtained. The proposed method solves the problem that the time is too long for each round of optimization and greatly enhances optimizing efficiency.

MoM is a numerically accurate method for analysis of electromagnetic field [5]. However, given a large dense matrix generated by MoM, electrically large problems can hardly be computed. To reduce the number of unknowns and matrix size, higher-order polynomial basis functions are employed in MoM, and moreover, the parallel computing technique is utilized to further

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improve the method. In the previous works, the method was used to accurately simulate large electromagnetic models [6–8].

Comparing to traditional optimizing methods, the particle swarm optimization (PSO) algorithm is widely used in the antenna design as a new evolutionary algorithm [10]. It's a kind of bionic algorithms and originates from the research of the predation of birds, with characteristics of easy implementation, high precision and fast convergence. Its main idea is to use the sharing of individual information in the population and then make the whole population orderly movement to find the optimal solution. The inertia weight factor ω in this algorithm has the feature of controlling searching ability. The larger ω is, the stronger the global searching ability is. The small ω is, the stronger the local searching ability is [9]. Based on this feature, references [11, 12] propose a self-adaptive PSO algorithm to overcome the defect that the PSO algorithm is easy to fall into local optimum.

This paper presents a method of using the eigen solution extraction technique to accelerate optimization, adopts self-adaption PSO and parallel higher-order MoM to optimize the performance of radome-enclosed antennas. This method realizes efficient optimization by using the eigen solution extraction technique to avoid repeated solution of MoM matrix equations, obtaining accurate results compared with the traditional optimized patterns. The effectiveness of the proposed method is verified by using the Tianhe-2 supercomputer to optimize a radome-enclosed antenna array with 247,438 unknowns.

II. ANALYSIS OF THE OPTIMIZATION METHOD FOR COMPENSATING RADOME

A. Influence of radome on the electrical performance of antennas

The influence of radome on the system of radome-enclosed antennas can be divided into two categories: the first-order influence and the second-order influence. The first-order influence factors include the uneven insert transmission coefficient, the field strength transmission coefficient and the surface wave generated by the incident wave on the surface of radome. These changes mainly affect the variation of antenna pattern, and lead to the reduction of maximum gain, the null depth of difference beam increase, the side lobe level rise, the main beam deformation and so on. The main cause of the second-order influence is the second-reflected wave and the reflection wave generated by the radome wall. This mainly results in the generation of BSE and the change of VSWR.

There are two main factors caused the error of radome-enclosed antenna systems. On the one hand, it is due to the shape of radome, the material (such as dielectric constant, conductivity), and the relative position of radome and antenna. On the other hand, it is caused by the non-uniformity of the feed's phase and amplitude, which is the object of main analysis in the design of radome-enclosed antennas. It is assumed that radome-enclosed antennas have N performance parameters to optimize. The n-th can be expressed as follow:

$$F_n = F_n(S, E, \theta, f) \qquad n = 1, 2, \ldots, N, \tag{1}$$

where S is radome material and structural parameters, in most cases, it has been determined in practical design. E is excitation parameters of array antenna. $\theta \in \Theta$ is antenna pointing and $\Theta=[\theta_{\min}, \theta_{\max}]$. $f \in \Gamma$ is the working frequency.

When θ, f and S are determined, it can be optimized by E that further enhances the performance of radome-enclosed antennas. Such problems can be summarized in the following form:

$$\begin{cases} \min\ Z = \sum_{i=1}^{N} F_i(E)\omega_i \\ \text{Subject to } A_i \le F_i(E) \le B_i \qquad i = 1, 2, \ldots, N, \\ E = [e_1\ e_2\ \ldots\ e_m]^T \end{cases} \tag{2}$$

where A_i, B_i are the upper and lower limits of the range of performance parameter F_i. e_m represents the amplitude and phase characteristics of each feed. ω_i is the weight factor that can eliminate radome affect by selecting appropriate value.

In this paper, a linear decreasing inertia weight PSO algorithm, which is proposed by Eberhart [13], is used to optimize the radome-enclosed antennas. This method not only has the advantages of standard PSO algorithm with easy realization, high accuracy, fast convergence properties and other characteristics, but also overcome the problems of premature convergence and slow convergence rate in the later period of the optimization. Meanwhile it makes good effect on the multidimensional discrete problem such as antenna design.

B. Extracting the eigen solution by MoM

The MoM matrix equation can be written as follows:

$$\begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix} \cdot [I] = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix}. \tag{3}$$

For the antenna radiation problem, the excitation V_i on the right side of the matrix equation is the ith feed. When all the units are fed, radiation characteristics of the antenna can be quickly obtained after solving the current coefficient I in the (3). Since the matrix equation is a linear equation, the excitation vector on the right side of the equation can be divided into the superposition of n units:

$$\begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix} \cdot \left([I_1] + [I_2] + \cdots + [I_n] \right) = \left(\begin{bmatrix} V_1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ V_2 \\ \vdots \\ 0 \end{bmatrix} + \cdots + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ V_n \end{bmatrix} \right), \quad (4)$$

where I_i is the current coefficient corresponding to the i-th unit feed in (4). Then it can be written as a matrix equation when an arbitrary unit is excited, the form is as follows:

$$\begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix} \cdot [I_i] = \begin{bmatrix} 0 \\ V_i \\ \vdots \\ 0 \end{bmatrix}. \quad (5)$$

In (5), if V_i=1, the eigen solution $\tilde{I}_i$ of the ith unit can be obtained:

$$[\tilde{I}_i] = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix}^{-1} \cdot \begin{bmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{bmatrix}. \quad (6)$$

Since the matrix equation is linear, the solution of MoM with any excitation can be obtained by the linear combination of the eigen solution as long as the eigen solution for each unit is obtained. It can be seen that the impedance matrix is constant when the eigen solution is solved in (6), that is to say, it only needs to solve the inverse matrix at once. Accordingly, the calculation of the eigen solution does not significantly increase the computation. For any combination of feed (V_1, V_2, …, V_n), the corresponding MoM solution is as follow:

$$[I] = \sum_{i=1}^{n} V_i [\tilde{I}_i]. \quad (7)$$

The extraction of the eigen solution brings great convenience for optimizing of the feed. The optimize algorithm only need to update the feed (V_1, V_2, …, V_n) and to quickly combine the response of this feed, and then the radiation characteristics of the antenna with this feed can be calculated.

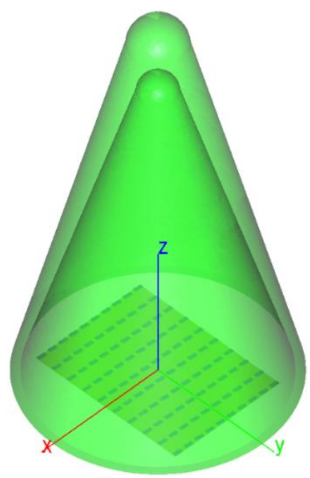
III. INTRODUCTION OF THE COMPUTING PLATFORM

The computing platform used in this paper is Tianhe-2 supercomputer at the National Super Computer Center in Guangzhou, which was ranked No. 1 among the World's TOP500 Supercomputers with 33.86 PFlop/s Linpack performance. It has 16,000 nodes, each of which contains two 12-core Xeon E5 CPU and 64 GB memory. In the following section, 20 nodes with 480 cores are used.

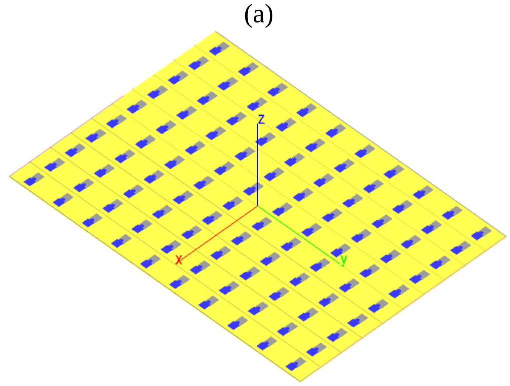
IV. OPTIMIZATION EXAMPLE AND ANALYSIS

The reliability and accuracy of the higher-order MoM has been verified in the literature [6–8, 14], and the literature [2, 3] has verified the feasibility of the PSO algorithm to optimize the two-dimensional radome-enclosed antennas.

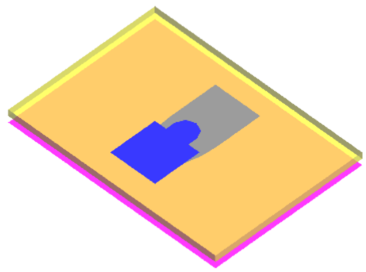
To illustrate the validity of the proposed method, a radome-enclosed antenna array is optimized, as shown in Fig. 1. The height of the radome is 1500 mm, the bottom radius is 450 mm, and the thickness is 32.275 mm. The dielectric constant of the radome is 2.4, and the loss tangent is 0.015. The microstrip antenna array has 10×10 elements and works at 3.0 GHz. The distance between neighboring elements along x direction and y direction are 0.46 λ and 0.65 λ, respectively, as shown in Fig. 1 (b). Each microstrip element consists of a pair of patches with the sizes of 0.33 λ×0.14 λ×0.02 λ, as shown in Fig. 1 (c). Parallel higher-order MoM running on 480 CPU cores is used to simulate the model, which generates 247,438 unknowns.



(a)



(b)



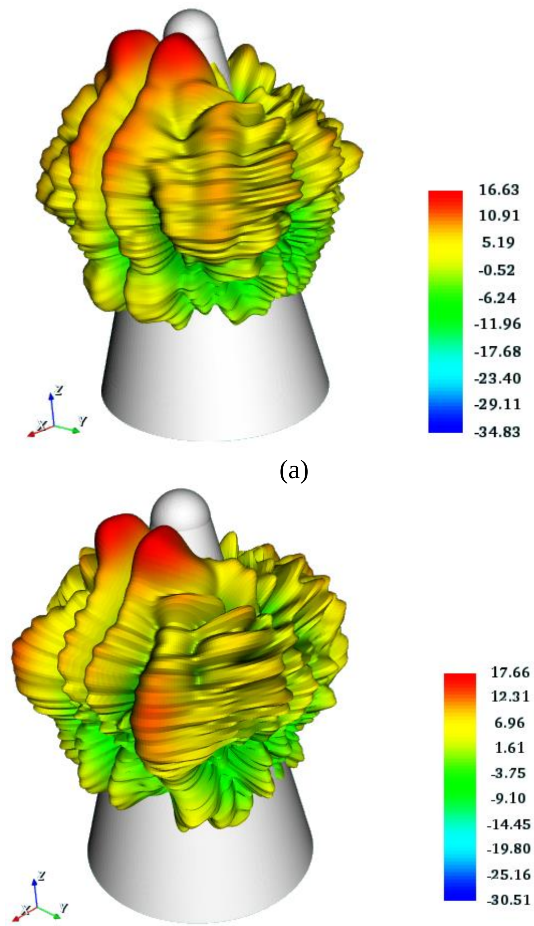
(c)

Fig. 1. Radome-enclosed microstrip antenna array: (a) the whole model, (b) the 10×10 microstrip antenna array, and (c) the microstrip element.

The excitation of the antenna array is in the form of –30 dB Taylor distribution with a phase shift that makes the mainlobe point to the direction of $\phi = 0^\circ$ and $\theta = 20^\circ$, as listed in Table 1. Figure 2 (a) shows the three-dimensional (3D) difference-beam patterns of the radome-enclosed antenna array before optimization and Fig. 3 shows the patterns in the mainlobe cut plane. It can be seen that, the maximum gain of the radome-enclosed antenna array before optimization is 16.63 dB and the null depth of difference beam is 15.205 dB, which deteriorates compared with the pattern of the original antenna array without the radome.

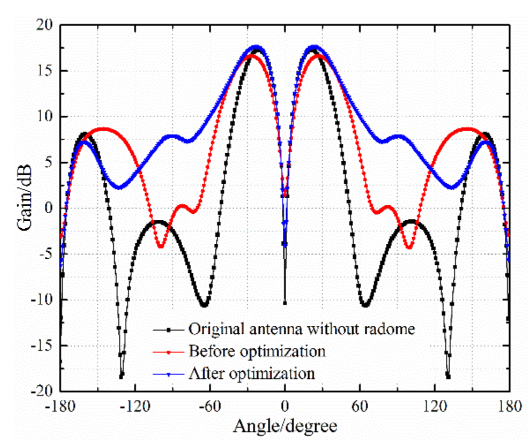
Then the influence of the radome on the pattern is compensated through optimizing the excitation amplitude and phase. The optimized design specifications are as follows: the maximum gain is greater than 17 dB, and the null depth of difference beam is larger than 20 dB. Set the particle number to 5, the iterations number to 1000, c_1 and c_2 to 2.0, and the weight factor range to [0.4, 0.8]. The optimized excitation is also listed in Table 1. The pattern after optimization is shown in Fig. 2 (b) and Fig. 3. It is obvious that, the maximum gain of the radome-enclosed antenna array after optimization is 17.66 dB and the null depth of difference beam is 21.76 dB, which meet the design requirements. The computation time is given in Table 2, and the matrix equation solving procedure involves the matrix factorization and the extraction of the eigen solution. During extracting the eigen solution for each array element, the factored matrix is reused and thus the method significantly saves time compared with iterative based methods, such as FMM. When the eigen solution is obtained, the PSO algorithm is carried out on an ordinary desktop computer, because it needs much fewer computational resources than the matrix equation solving procedure.

Besides null depth of difference beam, electromagnetic parameters of antennas, such as front-to-back ratio and the average sidelobe level, can also be optimized by using the proposed method.

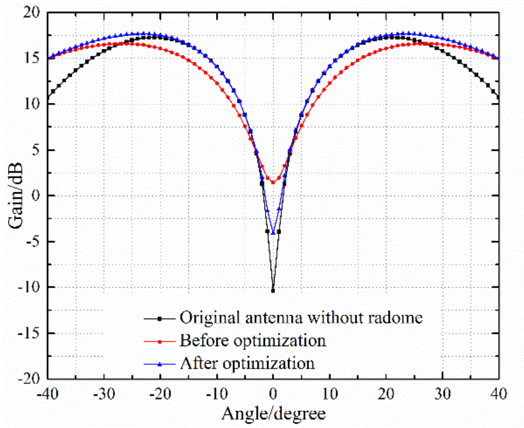


(b)

Fig. 2. 3D difference-beam patterns of the radome-enclosed antenna array: (a) before and (b) after optimization.



(a)



(b)

Fig. 3. Difference-beam patterns in the mainlobe cut plane before and after optimization: (a) angle range [–180°, 180°] and (b) angle range [–40°, 40°].

Table 1: Excitations of the radome-enclosed antenna array before and after optimization

No.	Initial Amplitude (V)	Initial Phase (°)	Optimized Amplitude (V)	Optimized Phase (°)
1	0.08936	0	0.06507	-79.97183
2	0.13349	0	0.26866	5.31126
3	0.20333	0	0.22841	3.54343
4	0.26381	0	0.04087	18.5360
5	0.29892	180	0.38811	-8.33680
6	0.29892	180	0.38811	171.66319
7	0.26381	180	0.04087	-161.46396
8	0.20333	180	0.22841	-176.45657
…	…	…	…	…
94	0.26381	-161.68642	0.34793	179.92870
95	0.29892	-161.68642	0.37986	-146.17421
96	0.29892	18.31366	0.37986	33.82578
97	0.26381	18.31369	0.34793	-0.07131
98	0.20333	18.31369	0.21166	24.92824
99	0.13349	18.31369	0.33065	7.35495
100	0.08936	18.31369	0.07010	11.13298

Table 2: Time for optimization of the radome-enclosed antenna array

Matrix Filling (s)	Matrix Equation Solving (s)	Optimization Iteration (s)	Total (s)
756.8	7619.2	4988.0	13,363.9

V. CONCLUSION

In this paper, a new method, which is based on the eigen solution extraction technique and combined with the adaptive PSO and the parallel higher-order MoM, is proposed to solve the optimization problem of large-scale radome-enclosed antennas. Compared with the traditional radome-enclosed antenna optimization method, the proposed method gives a new way to optimize radome-enclosed antennas. By using the eigen solution extraction technique, a large number of repeated computations are avoided in the process of optimization, which greatly accelerates the optimization. Moreover, the parallel higher-order MoM ensures that this method is capable of accurately solving electrically large problems and the adaptive PSO algorithm eliminates the problem of premature convergence in the optimization process. Numerical results demonstrate that the method is suitable for large-scale radome-enclosed antenna optimization problems and it provides a new research idea for the optimization of airborne antennas.

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