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FAST HYBRID FEM/CRE — UTD METHOD TO COMPUTE THE RADIATION PATTERN OF ANTENNAS ON LARGE CARRIERS

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Abstract—A hybrid method is developed to compute the radiation pattern of antennas on large complex three-dimension carriers. The hybrid method involves computing the radiation fields of the antenna in free space with FEM, characterizing the reflection and diffraction of the carrier to the radiation fields with CRE (Complex Ray Expansion) and UTD (Uniform Theory of Diffraction). The ray technique of SBR using traditional hybrid method is employed by CRE. The shortcomings of the SBR, such as great number of ray trace, distortion and partly shadowing of the rays etc., are overcome by the use of CRE, and the time consuming physical-optics-type integration is replaced by the paraxial approximation of the complex rays. A dipole placed on different carriers are taken as the examples to show the validity of the hybrid method, and the radiation patterns computed by the proposed method are in good agreement with those by FEM. By using the proposed method, the computation of the three dimension radiation pattern of an antenna in a large ship is finished by a PC in 1671.20 seconds.

1. INTRODUCTION

The computation of the radiation pattern of antenna on large carrier is a difficult task for the conflict between the high analyzing precise of the complex structure of antenna and the great time and memory demands for analyzing large carrier. Low-frequency techniques, such as method of moments (MoM) [1], finite-element method (FEM) [2], and finite-difference time-domain method (FDTD) [3], are employed

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to compute the radiation pattern of antennas for their high precision. But it will be difficult or even impossible to compute the fields of antenna and its large complex three-dimension carrier by low-frequency techniques for the great time and memory demands in computation. High-frequency techniques including geometrical theory of diffraction (GTD) [4], physical theory of diffraction (PTD) [5], and uniform theory of diffraction (UTD) [6] have obvious advantages in computing speed and memory demands, but the low computing precision limits their application. Then it is necessary to combine the low- and high-frequency techniques to form hybrid methods [7–18] for analyzing the radiation fields of antenna on large carrier.

As a kind of resonant structures, the antennas' current distributions at resonance frequency are determined mainly by their internal structures such as the geometry and material of the antennas. Provided that an antenna is mounted at a distance far enough from its large carrier, the shape of the host 3D body has little effect on its current distribution. Therefore, using FEM, the radiation fields of the antenna to be analyzed can be computed approximately by assuming that it is placed in free space. Once the radiation fields are obtained, by considering the scattering effect of the carrier, one can get the radiation pattern of the antenna on large carriers. As mentioned in [19], there are two approaches to compute the radiated field by ray method. One is the backward calculation method, in which the reciprocity theorem combined with the scattering fields computing program. For example, XPATCH [19, 20] is employed to calculate the radiation fields of the antenna on the 3D host body. The other is the forward calculation method, in which the radiated field of the antenna is computed over a small sphere including the antenna. Then the field is expanded into many rays shooting in different radial directions, and each ray is traced by geometrical optics (GO) method as it bounces around the carrier. Finally the radiation field of the antenna on large carrier is computed by accumulating the contributions of all rays to the far fields. This approach has the advantage of simultaneously computing the radiated field in all directions. However, the SBR method is always used in this approach, in which a physical-optics-type integration is performed at the last hit point to determine the ray contribution to the radiated field, and the field on the sphere surrounding the antenna must be divided into a great number of rays to obtain accurate results. Besides, the distortion and partly shadowing of the rays' sections in ray tracing also give rise to many difficulties in numerical computing. All the above shortcomings can be overcome by the CRE method proposed in this article. In the CRE method, the complex rays will take the place of the GO rays in SBR with a much lower number (the number of rays can be reduced by about 95%), and the time consuming physical-optics-type integration is replaced by the paraxial approximation of the complex rays. Another advantage of complex rays is that it need not consider the distortion and partly shadowing of the rays' sections.

The theoretical development of the hybrid method is discussed in Section 2, and in Section 3 two examples are computed by the proposed hybrid method and FEM. Following which, detailed analyses of the computing precision and the speed of the proposed method are made.

2. THEORETICAL DEVELOPMENT

Take a dipole placed above a 3D structure shown in Fig. 1 as an example. The radiation fields of the dipole $\vec{E}(\theta', \varphi', r)$ in free space are calculated by FEM.

The scattering effect of the carrier on the radiation pattern of the antenna can be divided into two parts. One is the reflection of the fields by the surface of the carrier, and the other is the diffraction of the fields by the edges.

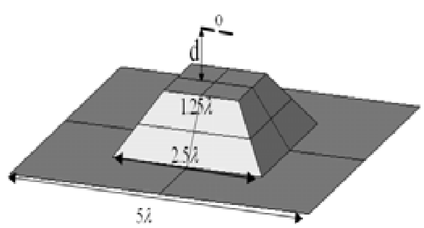

Figure 1. Dipole on a 3D structure model.

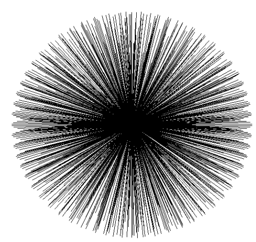

Figure 2. Complex rays.

The reflection of the fields is computed by the methods of CRE. The CRE technolgy is studied as an base of this hybrid method, and the detail of the study of the CRE technolgy and results is published in [20]. A well-proportioned rays' distribution in all directions is achieved by introducing the grid of Buckyball in generating the shooting directions of the rays, which leads to a more symmetrical rays' distribution than that by the traditional ways that use $\Delta\theta, \Delta\phi$ to generating the directions of rays. This paper focuses on the hybrid method. According to [20], the radiation fields $\vec{E}(\theta', \varphi', r)$ can be expanded into a cluster of complex rays in a suppositional sphere as shown in Fig. 2. The cent of the sphere "o" is chosen at the reference point of the antenna's radiation pattern, but the suppositional sphere on which the CRE is operated need not be the sphere the far fields are computed. The recombination of the radiation fields can be operated by using (1).

$$\vec{E}'(\theta,\varphi,R) \approx c_0 \left(\frac{e^{-jkr}}{4\pi r}\right)^{-1} \sum_{\mathrm{i}=1}^{L} \frac{e^{-jkR}}{4\pi R} \vec{E}\left(\theta'_{\mathrm{i}},\varphi'_{\mathrm{i}},r\right) \exp\left[-2kb\sin^2\left(\frac{\phi}{2}\right)\right] \tag{1}$$

where $k = 2\pi/\lambda$ is wave number; L is the number of complex rays; b is beam width; $\phi = \arccos(\sin\theta\cos\varphi\sin\theta'_{\mathrm{i}}\cos\varphi'_{\mathrm{i}}+\sin\theta\sin\varphi\sin\theta'_{\mathrm{i}}\sin\varphi'_{\mathrm{i}}+\cos\theta\cos\theta'_{\mathrm{i}})$ is the angle between the directions of (θ,φ) and $(\theta'_{\mathrm{i}},\varphi'_{\mathrm{i}})$. Since $\exp[-2kb\sin^2(\phi/2)]$ attenuates rapidly with the increase of ϕ, for a fast numerical computation of (1), $\phi_{\max} = \arccos(1-1/kb)$ is chosen as the cut angle at where the fields attenuate to $1/e$ of that on the axis. Hence, the fields of $\phi > \phi_{\max}$ will be ignored. c_0 is a constant that ensures the power of the complex rays equal to that of the antenna. The choice of parameters can refer to literature [20].

After complex rays expansion of the radiation fields of the antenna, the ray tracing is operated for all rays. The detailed numerical computing of traces depends on the 3D model of the carrier. To characterizing a complex host body, such as aircraft, the NURBS model is a good candidate. The ray tracing and shadowing judgment for the NURBS model are difficult tasks for the numerical but not analytical algorithm. The polygonal-face is another tool in modeling the 3D host body. The analytical character of the faces model makes the computation of the ray tracing and shadowing judgment much faster than that for NURBS model, but simulating a complex body with the triangle faces will leads to a great number of faces. Fortunately, considering the stealth character, the design of the host body, such as war ship, has been developing in the direction that uses few simple and large surfaces. In this paper, mixed faces including triangle faces and rectangle faces as shown in Fig. 3 are adopted to model the 3D host. The main parts of the surface are simulated by rectangle faces, while the triangle faces are employed to simulate the parts close to the edges. The ray tracing and shadowing judgment for faces model can be simplified to the computation of the intersection points of the axial line of rays and polygonal-faces.

Setting out from the sphere where complex rays expansion is operated, every ray is likely to bounce on the surface of the carrier in a series of points marked as $(x_{\mathrm{j}}, y_{\mathrm{j}}, z_{\mathrm{j}})$, with $\mathrm{j} = 0,1,\ldots,k$, and k being the times that the ray bounces on the surface of the host. $(x_{\mathrm{j}}, y_{\mathrm{j}}, z_{\mathrm{j}})$ are computed during the process of ray tracing, and the axial fields of the rays are calculated at the same time by (2) until the rays leave the host.

$$\vec{E}_{\mathrm{i}}\left(x_{\mathrm{j}+1}, y_{\mathrm{j}+1}, z_{\mathrm{j}+1}\right) = DF_{\mathrm{j}} \times \overline{\overline{\Gamma}}_{\mathrm{j}} \cdot \vec{E}_{\mathrm{i}}\left(x_{\mathrm{j}}, y_{\mathrm{j}}, z_{\mathrm{j}}\right) \times e^{-jkS_{\mathrm{j}}} \tag{2}$$

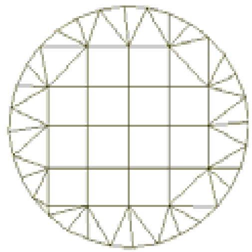

Figure 3. Mixed-face model of a circular surface.

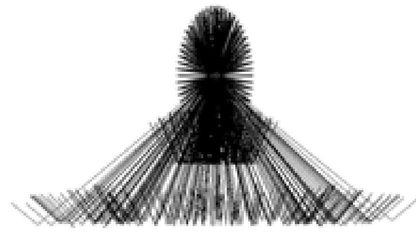

Figure 4. Complex rays after ray trace.

where DF_{j} is the diffuse factor from $(x_{\mathrm{j}}, y_{\mathrm{j}}, z_{\mathrm{j}})$ to $(x_{\mathrm{j+1}}, y_{\mathrm{j+1}}, z_{\mathrm{j+1}})$, $\overline{\overline{\Gamma_{\mathrm{j}}}}$ is the dyadic reflection coefficient and S_{j} is the distance form $(x_{\mathrm{j}}, y_{\mathrm{j}}, z_{\mathrm{j}})$ to $(x_{\mathrm{j+1}}, y_{\mathrm{j+1}}, z_{\mathrm{j+1}})$.

$$\vec{E}_{\mathrm{i}}(x_0, y_0, z_0) = c_0 \left(\frac{e^{-jkr}}{4\pi r} \right)^{-1} \vec{E}_{\mathrm{i}}\left(\theta_{\mathrm{i}}', \varphi_{\mathrm{i}}', r\right), \ (x_0 = 0, y_0 = 0, z_0 = 0) \tag{3}$$

Figure 4 shows traces of the rays in Fig. 2 reflected by the structure in Fig. 1. It can be seen that only a part of rays are reflected by the 3D host, while the residual rays shoot in the original direction without reflection. The far radiation fields include the contributions of all complex rays whether they are reflected by the carrier or not.

The paraxial approximation calculation is employed to calculate the contributions of rays to the radiation field. Fig. 5 shows a ray reflected at the point M and shooting in the direction of $\hat{k}_r$. $\overrightarrow{\mathrm{MP}}$ is the axial of the out shooting complex ray. If the test point is placed at p' (p is the pedal point of p' in $\overrightarrow{\mathrm{MP}}$), the fields at the test point p' contributed by all rays are (4) [21]:

$$\vec{E}^{\mathrm{Go}}(p') = \sum_{\mathrm{i}=1}^{L} \vec{E}_{\mathrm{i}}(p) \exp\left[-2kb \sin^2\left(\frac{\phi}{2}\right)\right] \exp\left(jk\tilde{\delta}\right) \tag{4}$$

where ϕ is the angle between $\overrightarrow{\mathrm{MP}}$ and $\overrightarrow{\mathrm{MP}'}$, $\vec{E}_{\mathrm{i}}(p)$ is the axial fields of the ith ray, which can be calculated using (2) by take the point M as $(x_{\mathrm{j}}, y_{\mathrm{j}}, z_{\mathrm{j}})$ and P as $(x_{\mathrm{j+1}}, y_{\mathrm{j+1}}, z_{\mathrm{j+1}})$. $\delta = (Q_{11}x_0^2 + (Q_{12} + Q_{21})y_0x_0 + Q_{22}y_0^2)/2$ is the phase rectification factors. The detailed formulation of DF_i, $\overline{\overline{\Gamma_{\mathrm{j}}}}$ and δ can refer to [21]. It should be pointed out that in the sum computing of (4), the fields for $\phi > \phi_{\max}$ are ignored. The reason is that the same treatment is taken in the deduction of c_0.

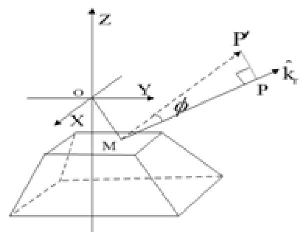

Figure 5. Paraxial approximation calculation.

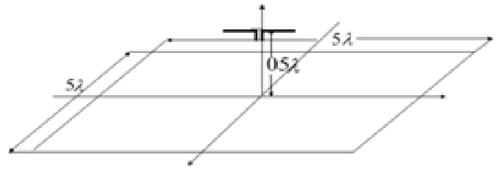

Figure 6. A dipole on a rectangular ground plane.

The field contributed by the diffraction of edges can be calculated by UTD as (5) [22].

$$\vec{E}^{\mathrm{UTD}} = \vec{E}^{\mathrm{i}}(Q_E) \cdot \left(-\hat{\beta}'_0\hat{\beta}_0 D_s - \hat{\varphi}'_0\hat{\varphi}_0 D_h\right) A(s)e^{-jks} \tag{5}$$

where $\vec{E}^{\mathrm{i}}(Q_E)$ is the incident field in the scattering point Q_E on the host's edge, and $D_{s,h}$ is the dyadic diffract coefficient in the ray base coordinate. $A(s)$ is the diffuse factor. The detailed formulation of $D_{s,h}$ and $A(s)$ of UTD can refer to [22].

The final radiation fields are the sum of (4) and (5):

$$\vec{E} = \vec{E}^{\mathrm{Go}} + \vec{E}^{\mathrm{UTD}} \tag{6}$$

The radiation pattern of antennas in large carriers can be calculated from $\vec{E}$ in (6).

3. NUMERICAL RESULTS

To illustrate the validity of the proposed method, numerical results are generated for a dipole in two different geometries. The dipole resonates at 3.0 GHz is firstly placed above a rectangular ground plane as shown in Fig. 6. The computed result of the radiation pattern for $\phi = 0°$ and $\phi = 90°$ is compared with that of the same antenna generated by FEM in Fig. 7. In above computation the time used by the hybrid method is 427.87 seconds. The computational results of the dipole in Fig. 1 (The high of the cone is 0.5λ, and the dipole is placed 0.5λ above the top of the cone. The model includes 58 faces) and that from FEM is shown in Fig. 8. The time consumed by the hybrid method is 445.95 seconds.

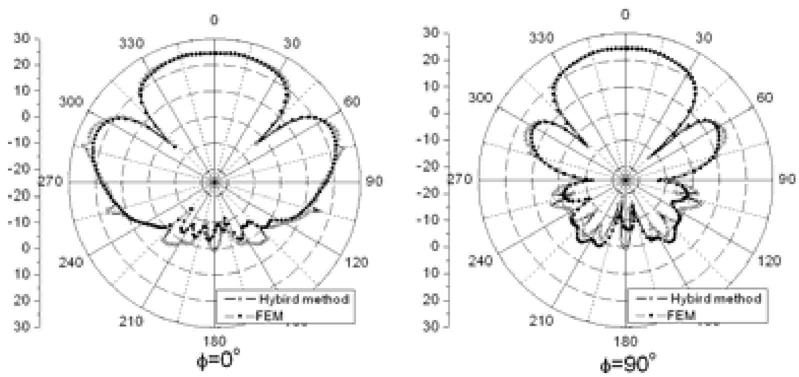

Figure 7. Radiation patterns of the dipole in Fig. 5.

The two group results are in good agreement with each other in the majority of the computing angle. But it is obvious that there are four breaks at 75°, 285°, 105° and 255° in all patterns. This is because the field contributions of the complex rays near the shadow boundaries can not jump to zero like GO fields, but attenuate to zero from the boundary to $\phi_{\max}$. The sharp variation of UTD fields near the boundary to counteract the sharp variation of GO fields leads to those breaks at the shadow boundaries. It can be anticipated that for a larger carrier, the edges are in the far region of the antenna, and the diffraction fields will be less important than the reflection ones, which will make the breaks at the shadow bounding inconspicuous. However, this is still a problem to be solved.

Thus the main purpose of developing the hybrid method is the fast computation of the radiation pattern for antennas in extra large ships. The time used by the hybrid method includes the time used in the analyzing of antenna in free space by FEM, and the time used by CRE and UTD. It is obvious that the time used by CRE and UTD increase with the number of the faces of 3D model, but not the square of dimension of the carrier as in low frequency methods. This advantage will become powerful for analyzing the antenna on extra large carriers. Because the hybrid method is not affected by the limitation of memory, another advantage of the hybrid method is that it can analyze the antenna on extra large carriers that can not be computed by low frequency methods. These two advantages are shown in the following computing example.

The symbol $*$ in Fig. 9 represents an antenna on a large ship (length: 165 m and width: 15 m). Fig. 10 shows the computed 3D radiation patterns of the antenna in free space and the radiation

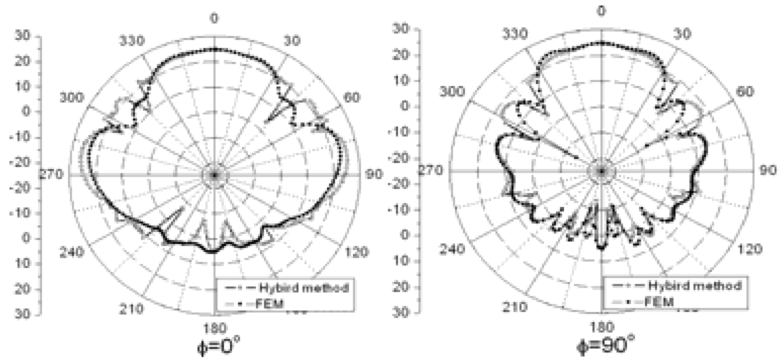

Figure 8. Radiation patterns of the dipole in Fig. 1.

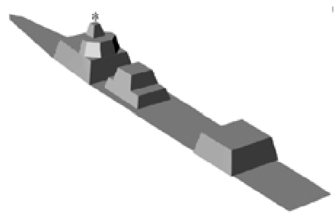

Figure 9. An antenna on a large ship.

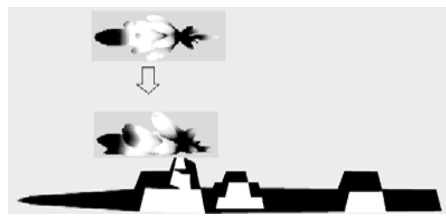

Figure 10. 3D radiation patterns of an antenna in free space and of that on ship.

pattern of the antenna mounted on the large ship. The generation of the results by the proposed methods consumes 1671.20 seconds in a DELL PC computer (CPU: 1.8 G), of which, 831.20 seconds are consumed by CRE and UTD. During the computing process, 117 faces are used to model the ship, and 38442 rays are traced, and the memory demand is less than 1 GB during the CRE and UTD computation.

4. CONCLUSION

The technique for fast computing the radiation pattern of antenna on large carriers is developed. The radiation patterns of a dipole on two different geometry structures are computed by the hybrid method. The numerical results from the proposed method are in good agreement with that generated from FEM. The advantages of the proposed hybrid method are analyzed. Finally an antenna in a large ship is computed to show the fast speed of the hybrid method.

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