Improvements of Edges Diffraction Computing in GRECO

QIN De-hua, WANG Bao-fa, LIU Tie-jun
(Department of Electronic Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100083, China)

Abstract: Graphical Electromagnetic Computing (GRECO) is one of the valuable methods for computing the radar cross section (RCS) of complex radar target in high frequency region. But there are some shortages of wedge detecting method in the original GRECO literature. A new method for collecting the edge pixels and wedge parameters is presented in this paper. An expression of edge diffraction field in the original GRECO literature is in error, the error corrected formulas are derived by using method of equivalent edge currents (MEC) and physical theory of diffraction (PTD). Finally, the total RCS expression is given by physical optics (PO) and PTD method. The computing results are in close agreement with the measured data.

Key words: electromagnetic wave scattering; GRECO; radar cross section; edge diffraction

GRECO[1] method has the advantages of high speed and visualization in predicting high frequency radar cross section (RCS) of large and complex radar targets. The method utilizes 3D graphics hardware accelerator to process the imaging of the 3D target model, as well as to get the unit normal and other parameters at the illuminated surfaces of the target. Reflection at conducting surfaces is computed by using physical optics (PO) approximation, diffraction at edges by equivalent edge currents (MEC) and physical theory of diffraction (PTD). However, the edge detecting method in Ref. [1] is not comprehensive, and there are errors in the edge diffraction field expressions of Ref. [1].

In order to compute edge diffraction with accuracy, the edge pixels must be detected correctly, and the parameters of the edges should also be correctly obtained. In Ref. [1], edges are detected on the target image as discontinuities of the unit normal to the surface when the z coordinate remains continuous. This paper points out the shortages of this method, and presents a more effective method in edges detecting and edge parameters obtaining. The method presented is Edge Modeling. The edge model is automatically generated by program, and the parameters such as edge positions, edge direction vectors, and wedge angles can be obtained accurately by the edge model. For correcting the errors in Ref. [1], this paper also deduces the edge diffraction field expressions by using MEC and PTD method. The total RCS expression is given by...
using PO and PTD method.

1 Edge Modeling

Obtaining edge pixels and their parameters correctly is the start point of computing edge diffraction in GRECO. An incomprehensive edge detection method was introduced in Ref. [1], the edges are detected on the target image as discontinuities of the unit normal to the surface while their coordinate remains continuous. Not all of the edge pixels can be detected by this method and it can only be applied to the edges that both of the two faces of the wedge are illuminated. To fully and correctly obtain the edge pixels and their parameters, the following cases needed to be considered:

1. The boundaries of the target image, e.g., the imaging boundaries of a plate are edges, but the imaging boundaries of a sphere are not edges;
2. In some cases only one face of the wedge is illuminated, and the normal of the invisible wedge face need to be obtained in a different way;
3. In case of plate, the edge direction vector can not be derived by the edge normal and must be obtained particularly.

The method in Ref. [1] can not handle the above cases. This paper uses another distinctive method, Edge Modeling, to handle the problems in detecting edge pixels and obtaining parameters. An edge model is generated for the target, useful parameters such as positions, normals, edge direction vectors and wedge angles are saved in the edge model. Thus the edge pixels and their parameters can be accurately obtained. The Edge Modeling includes the following processes.

1) Edge searching
The geometry shape of the target is modeled by using triangular facets. The normal of each facet can be derived by the positions of the facet’s three vertexes. One border of a facet may coincide with another border of another facet, or does not coincide with any other borders. In the former case, if the angle between the two normals of the two facets is larger than a threshold, the two coincident borders are decided as one edge; in the latter case, the border is decided as a plate edge.

All borders will be inspected by the above criterion, so it is a searching process.

2) Parameters saving
It is required to consider which parameters of an edge should be saved in the edge model. The parameters of an edge include: the two normals of the two wedge faces; the edge direction vector; the wedge angle. These parameters are not independent, and generally the edge direction vector and the wedge angle can be derived by the two normals. However, for plate, the edge direction vector can not be got by the cross product of the two normals. For the integrality of all cases, three kinds of parameters are saved in the edge model; they are one of the normals, the edge direction vector and the wedge angle.

3) Display lists generating
OpenGL [2] technique is used to process the target image. For displaying the edge model and obtaining the edge parameters, edge model display lists need to be generated. The display lists are constructed by lines which represent the edges. The edge parameters are saved in the display lists. Three edge display lists are generated, one for the edge normals, one for the edge direction vectors, and the other for the wedge angles. The normal and edge direction are vectors, they can be represented by the RGB colors of the edge lines. The wedge angles are scalars, they can be represented by one component of the RGB colors and will not change with the model rotation.

4) Edge model displaying and parameters obtaining
In displaying the edge model lists, blanking should be carry out to hide the invisible edges. This is implemented by displaying a black target model with the edge model, and the target model is translated a bit along the \(-z\) axis direction; through z-buffer hiding, the blanking of the edge model is achieved.

By setting illumination to the edge models or displaying the colors of the edge lines, the RGB colors of each edge pixel can be read from the color...
buffer. Thus the edge parameters can be restored from the edge pixels’ colors.

Fig. 1 displays the edge model of an airplane. The edge model is visual on the screen, so it is straightforward to see if the edge model is correct. Because the edge model image displays only the visible pixels, there are no problems of how to determine if the boundaries of an image are edges. For the edges of which only one face is visible, the edges can also be correctly displayed and their parameters can be got. The edges of plate are also considered and the edge direction vectors are saved in the edge model, so the parameters for plate edges can also be obtained comprehensively.

Fig. 1 One edge model on the screen

2 Edge Diffraction

By Method of Equivalent Currents (MEC), the far-field scattering from a wedge is:

\[ E_d = \frac{e^{-jR}}{4\pi R} e^{j\pi n} \left[ Z_0 I \hat{\mathbf{s}} \times \hat{\mathbf{l}} \times \hat{\mathbf{l}} + I_m \hat{\mathbf{s}} \times \hat{\mathbf{l}} \right] \cdot e^{j\omega t} \mathrm{d}l \]  

where \( \hat{\mathbf{l}} \) is the edge direction vector, \( \hat{\mathbf{s}} \) is the unit vector from edge to observation point, \( R \) is the position vector of the edge, \( e^{-jR} \) is the Green’s function, \( R \) is the distance from the target to the far-zone observation point. The equivalent electric current and magnetic currents \( I_e \) and \( I_m \) are

\[ I_e = \frac{2}{k} \left( \hat{\mathbf{l}} \cdot \mathbf{E}_I \right) D_e \frac{1}{k Z_0 \sin \beta_i \sin \beta_s} \]  

\[ I_m = \frac{2}{k} \left( \hat{\mathbf{l}} \cdot \mathbf{H}_I \right) D_m \frac{1}{k Y_0 \sin \beta_i \sin \beta_s} \]  

where \( \beta_i \) and \( \beta_s \) are, respectively, the angle between incident direction and \( \hat{\mathbf{l}} \), the angle between observation directions and \( \hat{\mathbf{l}} \). \( D_e \) and \( D_m \) are diffraction coefficients. The diffraction fields of PTD are revisions to fields of PO, so the \( D_e \) and \( D_m \) can be written in PTD formation

\[ D_{PTD,e} = \begin{cases} 
(X - Y) - (X_1 - Y_1) & 0 \leq \phi_1 \leq \alpha - \pi \\
(X - Y) + (Y_1 + Y_2) & \alpha - \pi \leq \phi_1 \leq \pi \\
(X - Y) + (X_1 + Y_2) & \pi \leq \phi_1 \leq \alpha 
\end{cases} \]  

(3a)

\[ D_{PTD,m} = \begin{cases} 
(X + Y) - (X_1 + Y_1) & 0 \leq \phi_1 \leq \alpha - \pi \\
(X + Y) - (Y_1 + Y_2) & \alpha - \pi \leq \phi_1 \leq \pi \\
(X + Y) + (X_1 - Y_2) & \pi \leq \phi_1 \leq \alpha 
\end{cases} \]  

(3b)

\[ X = \frac{1}{n} \frac{\sin \pi}{\cos \frac{\pi}{n} - \cos \left( \phi_i - \phi_0 \right)} \]  

(4)

\[ Y = \frac{1}{n} \frac{\sin \pi}{\cos \frac{\pi}{n} - \cos \left( \phi_i + \phi_0 \right)} \]  

(5)

\[ X_1 = -\frac{1}{2} \tan \left( \frac{\phi_i - \phi_0}{2} \right) \]  

(6)

\[ Y_1 = -\frac{1}{2} \tan \left( \frac{\phi_i + \phi_0}{2} \right) \]  

(7)

\[ Y_2 = -\frac{1}{2} \tan \left( \frac{\alpha - \phi_i}{2} \right) \]  

(8)

where \( \phi_i \) and \( \phi_0 \) are, respectively, the angle between the reference wedge face and the incident face, the angle between the reference wedge face and the scattered face, \( \alpha \) is the exterior wedge angle, \( n = \alpha/\pi \). The above \( D_{PTD,e} \) and \( D_{PTD,m} \) are identical with the PTD diffraction coefficients \( f \) and \( g \) in Ref. [4]. The monostatic \( f \) and \( g \) curves according to the interior wedge angle and \( \phi_i \) are given in Ref. [4].

In GRECO, the wave incident direction is \( \hat{\mathbf{z}} \), and in monostatic case, the observation direction \( \hat{\mathbf{s}} = \hat{\mathbf{z}} \). Eq. (1) can be separated to expressions of fields for co-polar and cross-polar polarizations. For the case of VV polarization (both of the transmitting and receiving electronic polarization are \( \hat{\mathbf{y}} \) direction), the field

\[ E_{d,yy} = -2 E_0 \frac{e^{-jR}}{4\pi R} \int_{\text{EDGE}} \frac{1}{t_x^2 + t_y^2} \]
\[
\left[-D e^2 + D_m t^2\right] e^{j2kz} dl \tag{9}
\]

In Eq. (9), the signs before \(D_e\) and \(D_m\) are opposite, and for the corresponding expression in Ref. [1], the signs before \(D^\parallel\) and \(D^\perp\) are identical. The differences come from that the expressions of the equivalent currents are different. According to Refs. [4] and [5], the Michaeli equivalent currents are

\[
I_e = \frac{2(1 \cdot E_s) D_e}{k z \sin^2 \beta_i} + \frac{2(1 \cdot H_s) D_m}{k \sin \beta_i} \tag{10a}
\]

\[
I_m = - \frac{j2(1 \cdot H_s) D_m}{k y \sin \beta_i \sin \beta_i} \tag{10b}
\]

Compared with Eq. (2b), there is an additional negative sign in Eq. (10b). Compared with Eq. (1), there is also an additional negative sign in the diffraction field equation of Ref. [4].

\[
E_d = - j k \frac{e^{-jkR}}{4\pi R} \left[ Z_0 I \left( \hat{s} \times \hat{t} + I \right) + I_m \right] e^{j\varphi} dl \tag{11}
\]

So the conclusion is got that if the direction of observation is on the Keller cone, the values of \(D_e\) expressed by Eqs. (10a) and (2a) have opposite sign, and the values of \(D_m\) expressed by Eqs. (10b) and (2b) have identical sign. According to the expressions of \(D_e\) and \(D_m\) in Ref. [4], it can be proven that if the direction of observation is on the Keller cone or back scattering, the \(D_e\) and \(D_m\) are equal to the Keller diffraction coefficient \((X - Y)\) and \((X + Y)\). The \(X\) and \(Y\) are expressed in Eqs. (4) and (5). In Refs. [4] and [6], the Mätzner incremental length diffraction coefficients (ILDC) [7] are expressed in Michaeli form,

\[
D^\parallel = D_e - D_m \tag{12}
\]

\[
D^\perp = D_m - D_e \tag{13}
\]

\[
D^\parallel = D^\parallel \sin \beta_i - D^\perp \tag{14}
\]

where the diffraction coefficients with prime are PO terms. According to the expressions of \(D_e\), \(D_m\), \(D^\parallel\) and \(D^\perp\) in Ref. [4], it can be proven that if the observation direction is on the Keller cone or back scattering, the \(D^\parallel\) and \(D^\perp\) computed by Eqs. (12) and (13) are equal to the PTD diffraction coefficients \(f\) and \(g\) computed by Eqs. (3a) and (3b).

The diffraction field equations in Ref. [1] can be derived by Eqs. (11), (10a) and (10b). Therefore, for monostatic RCS, the \(- D^\parallel\) and \(D^\perp\) in Ref. [1] are equal to PTD diffraction coefficients \(f\) and \(g\). That is, the values of \(D^\parallel\) and \(f^\prime\) have opposite sign. However, in Ref. [1], they are explicitly stated to be equal. The computing examples indicate that if the RCS are computed by using \(D^\parallel\) = \(f^\prime\), the results have large difference to the measurements (Fig. 4).

3 RCS Expressions

The far zone PO scatter field is \[3\]

\[
E_{s, PO} = jkZ_0 \frac{e^{-jkR}}{4\pi R} \int \hat{s} \times \hat{t} \times (2\hat{n} \times H_s) e^{j\varphi} dl \tag{15}
\]

where \(\hat{n}\) is the unit normal at the target surfaces. Define the wave incident direction to be - \(\hat{z}\), in monostatic case, Eq. (15) lead to

\[
E_{s, PO} = - 2jkE_0 \frac{e^{-jkR}}{4\pi R} \int \hat{n} \times \hat{z} \times e^{j2kz} dl \tag{16}
\]

Considering the contribution of the diffraction field, the total monostatic scatter field can be written as

\[
E_s = - 2jkE_0 \frac{e^{-jkR}}{4\pi R} (jkS_{PO} + L_{PTD}) \tag{17}
\]

and

\[
S_{PO} = \int \left( \hat{n} \times \hat{z} \right) e^{j2kz} dl \tag{18}
\]

\[
L_{PTD, yz} = \int_{EDGE} \frac{1}{t^2} \left[ - f t^2 + g t^2 \right] e^{j2kz} dl \tag{19}
\]

\[
L_{PTD, xx} = \int_{EDGE} \frac{1}{t^2} \left[ - f t^2 + g t^2 \right] e^{j2kz} dl \tag{20}
\]

\[
L_{PTD, yz} = \int_{EDGE} \frac{1}{t^2} \left[ - f t^2 + g t^2 \right] e^{j2kz} dl \tag{21}
\]

\[
L_{PTD, yz} = \int_{EDGE} \frac{1}{t^2} \left[ - f t^2 + g t^2 \right] e^{j2kz} dl \tag{22}
\]

Eqs. (19)~(22) are the \(L_{PTD}\) expressions for different polarizations. The \(f\) and \(g\) are PTD diffraction coefficients.

The RCS can be written as

\[
\sigma = 4\pi R^2 \left| \frac{E_s}{E_0} \right|^2 = \frac{1}{\pi} \left| jkS_{PO} + L_{PTD} \right|^2 \tag{23}
\]
where $S_{PO}$ and $L_{PTD}$ are defined by Eqs. (18)-(22). $S_{PO}$ and $L_{PTD}$ can be regarded as complex area and length. For a perpendicularly illuminated plate, $|S_{PO}|$ is right to the plate’s area; if the plate is quadratic, $|L_{PTD}| = 0$. For a glancing illuminated plate, $|S_{PO}| = 0$, $|L_{PTD,y}|$ is just the length of the illuminated edge of the plate.

4 Computing Examples

4.1 Plate

Fig. 2 and Fig. 3 show the RCS results for a $5\lambda \times 5\lambda$ ($\lambda = 0.03m$) square plate. Fig. 2 shows measuring and theoretical results from Ref. [4]. Fig. 3 shows computing results. It can be observed that the computing results agree well with the measurements and the theoretical results.

![Fig. 2](image-url)

**Fig. 2** RCS of $5\lambda \times 5\lambda$ plate (measurement and theory)

![Fig. 3](image-url)

**Fig. 3** RCS of $5\lambda \times 5\lambda$ plate (computing results)

4.2 Cube

Fig. 4 and Fig. 5 show RCS results of a $300mm \times 300mm \times 300mm$ cube, the polarizations are respectively co vertical and co horizontal, and the frequency is 9.375GHz. Because the edge diffraction has evident contribution to the RCS at about $45^\circ$ for the cube, for making the curves clear, the figures show only the RCS at aspect angle of $30^\circ - 60^\circ$. The solid curves are results computed by the method and expressions of this paper, they agree well with the measurements, the average difference is less than 1dBsm. The dot curves are results computed by using the expressions in Ref. [1], it can be observed that the result of VV polarization (Fig. 4) has large difference with the measurement and its VV polarization RCS curve is close to the HH polarization RCS curve in Fig. 5. So the relevant expression in Ref. [1] is in error and the correctness of this paper are proved.

![Fig. 4](image-url)

**Fig. 4** RCS of $300mm \times 300mm \times 300mm$ Cube (VV polar)

![Fig. 5](image-url)

**Fig. 5** RCS of $300mm \times 300mm \times 300mm$ Cube (HH polar)

5 Conclusions

This paper presents an effective edge modeling method for edge pixels detecting and edge parameters obtaining in GRECO. The method solves the problems in the conventional edge detecting approach. The edge pixels and edge parameters can be accurately obtained by the edge modeling technique. The edge diffraction field expressions are
deduced, and the error of diffraction coefficients in Ref. [1] is pointed out. The total RCS expressions by using PO and PTD method are also given. The RCS results computed by the method and expressions agree well with the measurements.

References


Biography:

Qin Dehua  Born in 1975. He is a Ph. D. candidate at the Dept. of Electronic Engineering, Beijing University of Aeronautics and Astronautics. He received B. S. and M. S. from Beijing Broadcasting Institute in 1997 and 2000 respectively. His research interests include Computational Electromagnetics and Radar Target Recognition. E-mail: qindehua@hotmail.com.

Wang Baofa  Born in Aug. 1938. He received B. S. degree in 1961 from Beijing Institute of Aeronautics and Astronautics. From 1961 to 1983 he was a lecturer of the BIAA. From 1983 to 1985 he was a visiting scholar of the EM Lab. at the University of Illinois. He is currently a Professor of the Beijing University of Aeronautics and Astronautics. His researches include EM wave propagation and scattering, microwave and antenna application, electromagnetic compatibility.

LIU Tiejun  Born in 1941. He received B. S. degree in 1960 from Taiyuan Institute of Technology. He is currently a Senior Engineer and Professor of the 207 institute in China Aerospace Corporation. His researches include EM Scattering and Inverse Scattering, Radar Target Recognition.