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EM Scattering from Conducting Flat Plates Coated with Thin RAM

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Abstract: **According to the equivalence principles, high frequency approximation and boundary conditions, a method has been developed to deal with the EM scattering by a rectangular conducting flat plate coated with uniaxial anisotropic radar absorbing material (RAM). The simple and effective method is available to the system of RCS prediction in which the large complex targets modeled by facets and wedges. Numerical results show some properties of EM scattering by conducting plate coated with thin uniaxial anisotropic RAM.**

Key words: **EM scattering; equivalence principles; radar absorbing material**

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0 Introduction

The problem of EM scattering by targets coated with absorbing materials has been a subject of importance in many areas of applications involving radar, electromagnetic wave propagation, and antenna studies. It is known that the radar cross section of a conducting body can be reduced if it is coated with absorbing materials especially with anisotropic RAM. For object with small electrical dimensions, this subject has been studied extensively. The EM scattering from coated circular cylinders as well as composite anisotropic circular cylinders has been analyzed[1]. An efficient formulation has been proposed to handle EM scattering by a conductor with a very thin coating[2].

In practice, it is desirable to predict the RCS of large complex targets coated with RAM. However, various numerical methods such as MOM, FDTD, BIE-IBC and FEM-BI are not efficient when the coated conductor is electrically large. In this paper, the scattered fields can be considered to be radiated by the equivalent sources. For the case of thin coating, the integral equations for the scattered fields can be simplified. At the same time, according to far field approximation and boundary conditions, the integral equations can be established to calculate the RCS of rectangular conducting flat plates with uniaxial anistropic material, which form is similar to the physical optics integral formula. This method is available to the system of RCS predicting in which complex targets modeled by the facets[3].

1 Derivation of Integral Equations

In this section, the integral equation is derived based on the equivalence principles, and the focus is placed on the extreme case of a conductor with a thin anistropic RAM. As shown in Fig. 1, a conducting body is coated with RAM which of permeability tensor and permittivity tensor are denoted by $\boldsymbol{\mu}_r, \boldsymbol{\varepsilon}_r$. The total fields $(\boldsymbol{E}^T, \boldsymbol{H}^T)$ in the free space can be considered to be sum of the incident fields $(\boldsymbol{E}^i, \boldsymbol{H}^i)$ and the scattered fields$(\boldsymbol{E}^s, \boldsymbol{H}^s)$.

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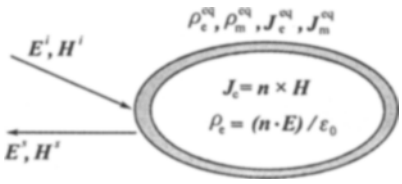

Fig. 1 The total fields is the sum of incident fields and scattered fields maintained by equivalent sources

$$E^T = E^i + E^s \tag{1}$$

$$H^T = H^i + H^s \tag{2}$$

On the basis of the equivalence principles, the scattered fields are produced by the equivalent source in anisotopic material and equivalent current on the surface of the conductor. The integral equations can be established as

$$E^T = TE^i + T\int_V [-j\omega\mu_0 J_e^{eq}\Phi - J_m^{eq} \times \nabla'\Phi + \frac{\rho_e^{eq}}{\varepsilon_0}\nabla'\Phi]dV + T\int_s [-j\omega\mu_0 (n \times H)\Phi + (n \times E) \times \nabla'\Phi + (n \cdot E)\nabla'\Phi]ds \tag{3}$$

$$H^T = TH^i + T\int_V [-j\omega\varepsilon_0 J_m^{eq}\Phi + J_e^{eq} \times \nabla'\Phi + \frac{\rho_m^{eq}}{\mu_0}\nabla'\boldsymbol{\mu}]dV + T\int_s [j\omega\varepsilon_0 (n \times E)\Phi + (n \times H) \times \nabla'\Phi + (n \cdot H)\nabla'\Phi]ds \tag{4}$$

$$\Phi(r, r') = e^{-jkR}/4\pi R \tag{5}$$

$$R = | r - r' | \tag{6}$$

$$J_m^{eq} = j\omega\mu_0(\boldsymbol{\mu}_r - I) \cdot H \tag{7}$$

$$J_e^{eq} = j\omega\varepsilon_0(\boldsymbol{\varepsilon}_r - I) \cdot E \tag{8}$$

$$\rho_e^{eq} = -\nabla \cdot [(\boldsymbol{\varepsilon}_r - I) \cdot \varepsilon_0 E] \tag{9}$$

$$\rho_m^{eq} = -\nabla \cdot [(\boldsymbol{\mu}_r - I) \cdot \mu_0 H] \tag{10}$$

In above expressions, T equals two when r is on the body and equals one otherwise. J_e^{eq} and J_m^{eq} are equivalent electric and magnetic current sources respectively ρ_m^{eq} and ρ_m^{eq} are equivalent surface electric and magnetic charge densities. I is unit tensor. Obviously the second terms in Eq. (3) and Eq. (4) are contributed by the equivalent volume sources in the coating and the third terms are come from the equivalent surfaces sources of the conductor. If the coating is very thin, we may approximate that:

$$\rho_e^{eq} \approx 0 \qquad \rho_m^{eq} \approx 0 \tag{11}$$

By using the boundary conditions on the surfaces of a conductor, the scattering fields can be derived as:

$$E^s(r) = \int_V [-j\omega\mu_0 J_e^{eq}\Phi - J_m^{eq} \times \nabla'\Phi]dV + \int_s [-j\omega\mu_0 (n \times H)\Phi + (n \cdot E)\nabla'\Phi]ds \tag{12}$$

$$H^s(r) = \int_V [-j\omega\mu_0 J_m^{eq}\Phi - J_e^{eq} \times \nabla'\Phi]dV + \int_s (n \times H) \times \nabla'\Phi ds \tag{13}$$

The volume integrals in Eq. (12) and Eq. (13) can be approximated with surface integrals when coating thickness t is very small.

$$\int_V [(-j\omega\varepsilon_0 J_e^{eq}\Phi)dV = \int_s \omega^2\mu_0\varepsilon_0(\boldsymbol{\varepsilon}_r - I) \cdot Et\Phi ds \propto 0 \tag{14}$$

$$\int_V [(-j\omega\varepsilon_0 J_m^{eq}\Phi)dV = \int_s \omega^2\mu_0\varepsilon_0 t\,(\boldsymbol{\mu}_r - I) \cdot H\Phi ds \tag{15}$$

Thus the scattered field as follows:

$$E^s(r) = \int_{s'} [-j\omega\mu_0 t\,(\boldsymbol{\mu}_r - I) \cdot H \times \nabla'\Phi - j\omega\mu_0 (n \times H)\Phi]ds' \tag{16}$$

$$H^s(r) = \int_{s'} [\omega^2\varepsilon_0\mu_0 t\,(\boldsymbol{\mu}_r - I) \cdot H\Phi + (n \times H) \times \nabla'\Phi]ds' \tag{17}$$

2 The EM Scattering of Flate Plate with Thin Uniaxial Anisotropic RAM

As shown in Fig. 2, the conductor plate coated with uniaxial anistropic materials lies in the $Z=0$ plane. The relative permeability tensor and relative permittivity tensor of the coating respectively is $\boldsymbol{\mu}_r$ and $\boldsymbol{\varepsilon}_r$, and the thickness of which is t. The incident wave propagation vector confined to the X-Z plane and the direction of incidence is denoted by θ.

$$\boldsymbol{\mu}_r = \begin{bmatrix} \mu_s & 0 & 0 \\ 0 & \mu_s & 0 \\ 0 & 0 & \mu_z \end{bmatrix} \quad \boldsymbol{\varepsilon}_r = \begin{bmatrix} \varepsilon_s & 0 & 0 \\ 0 & \varepsilon_s & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix}$$

Let incident TE polarized plane wave as follows:

$$E^i = E_0^+ e^{-jk_0[x\sin\theta + (z+t)\cos\theta]} e_y$$

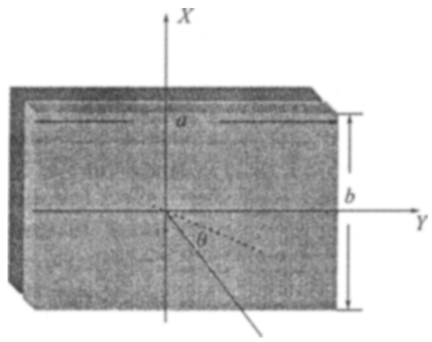

Fig. 2 The rectangular conductor plate coated with uniaxial anistropic material

where E_0^+ is the amplitude of electric field at $z=-t$ surface, $k_0=\omega\sqrt{\mu_0\varepsilon_0}$. The electromagnetic fields in free space can be simply expressed as:

$$\begin{aligned}\boldsymbol{E}^i =& E_0^+ e^{-jk_0[x\sin\theta+(z+t)\cos\theta]} \\ &+ E_0^- e^{-jk_0[x\sin\theta-(z+t)\cos\theta]})\boldsymbol{e}_y \end{aligned} \tag{18}$$

$$\begin{aligned}\boldsymbol{H}^i =& (-E_0^+ e^{-jk_0[x\sin\theta+(z+t)\cos\theta]} \\ &+ E_0^- e^{-jk_0[x\sin\theta-(z+t)\cos\theta]})(\cos\theta/\eta_0)\boldsymbol{e}_x \\ &+ (E_0^+ e^{-jk_0[x\sin\theta-(z+t)\cos\theta]} \\ &+ E_0^- e^{-jk_0[x\sin\theta-(z+t)\cos\theta]})(\sin\theta/\eta_0)\boldsymbol{e}_z \end{aligned} \tag{19}$$

where E_0^- is the aptitude of electronic field of reverse wave at $z=-t$ face and $\eta_0=\sqrt{\mu_0\varepsilon_0}$. Based on the boundary condition at $z=-t$ face and wave vector of free space, the wave number in coating is :

$$k_x = k_0\sin\theta, \quad k_y = 0$$

$$k_{z1} = k_0(\mu_s\varepsilon_s - \mu_s\mu_z{}^{-l}\sin^2\theta)^{\frac{1}{2}}.$$

Thus in coating object, the electromagnetic fields are as follows:

$$\begin{aligned}\boldsymbol{E} =& [E^+ e^{-j(k_0 x\sin\theta+k_{z1}z)} \\ &+ E^- e^{-j(k_0(x\sin\theta-k_{z1}z)}]\boldsymbol{e}_y \end{aligned} \tag{20}$$

$$\begin{aligned}\boldsymbol{H} =& (\frac{k_{z1}}{\omega\mu_0\mu_s})(-E^+ e^{-j(k_0 x\sin\theta-k_{z1}z)} \\ &+ E^- e^{-j(k_0 x\sin\theta-k_{z1}z)})e_x \\ &+ (\frac{\sin\theta}{\eta_0\mu_z})(E^+ e^{-j(k_0 x\sin\theta+k_{z1}z)} \\ &+ E^- e^{-j(k_0 x\sin\theta-k_{z1}z)})\boldsymbol{e}_z \end{aligned} \tag{21}$$

By matching the boundary conditions on the surface $z=0$ and $z=-t$, we can obtain:

$$\boldsymbol{H} = -2(\frac{k_{z1}\cos k_1 z}{\omega\mu_0\mu_s}\boldsymbol{e}_x + j\frac{\sin\theta\sin k_{z1}z}{\eta_0\mu_z}\boldsymbol{e}_z)e^{-jk_0 x\sin\theta}E^+ \tag{22}$$

Substituting Eq. (22) into Eq. (16) gives the scattering electric fields:

$$\boldsymbol{E}^s(r) = \int_{s'}\omega\mu_0[k_0 t(\boldsymbol{\mu}_r - \boldsymbol{I})\cdot\boldsymbol{H}\times\boldsymbol{r}$$

$$-(\boldsymbol{n}\times\boldsymbol{H})]e^{-jk_0\boldsymbol{r}'\cdot\boldsymbol{r}}ds'\frac{e^{-jk_0 r}}{4\pi r} \tag{23}$$

It is obvious that Eq. (23) becomes the physical optical formation when the conductor plate without coating materials.

3 Numerical Results

In this section, as Fig. 2 shown, the RCS of rectangular conducting flat plate with thin RAM is calculated. By using high frequency and far field approximation, the integral Eq. (23) can be simply evaluated, and the conducting flat plate is assumed to be thin compared to a wavelength. From symmetry considerations, a description of the backscattered fields over the interval $0°\leqslant\theta\leqslant 90°$ defines the radar cross section over a complete azimuth rotation of the target.

When $\mu_r=\mu_z$ and $\varepsilon_r=\varepsilon_z$ the coating is isotropic RAM. Fig. 3(a) plots a monostatic RCS versus incident angle for a rectangular plate coated with a set of parameters: $\varepsilon_r=\varepsilon_z=7.75-0.969j$, $\mu_r=\mu_z=1.47-0.853j$. for TE polarization. Thickness of coating $t=0.762$ mm and sizes 15×15 cm, incident wavelength is 5 cm. The RCS results of experiment and Ref. [4] for above coating plate are shown in Fig. 3(b). It is seen that our calculation for plate coating with isotropic RAM is good agreement with results of experiment when incident angle $\theta<50°$. When $\theta>50°$ the derivation can be traced back to the physical-optics approximation: equating the tangential magnetic field at the conductor plate surface to twice the incident magnetic field can be justified only for plate aspects near specular value, which can be seen from Eq. (22).

The rectangular flat plates treated in the following with $a=b=0.0825$ m and incident wavelength is 34 mm with TE polarization. In Fig. 4 and Fig. 5, the dashed plots show the RCS of uncoated plate calculated by PO method, and the solid plots show the RCS of plate coated with uniaxial anisotropic materials calculated using method of this paper, of thickness $t=\lambda/20$. For Fig. 4, the coating called negative uniaxial RAM has a set of parameters: $\varepsilon_s=25.59-3.89j$, $\varepsilon_z=8.19-1.3j$, $\mu_s=2.16-1.68j$, $\mu_z=1.39-0.56j$.

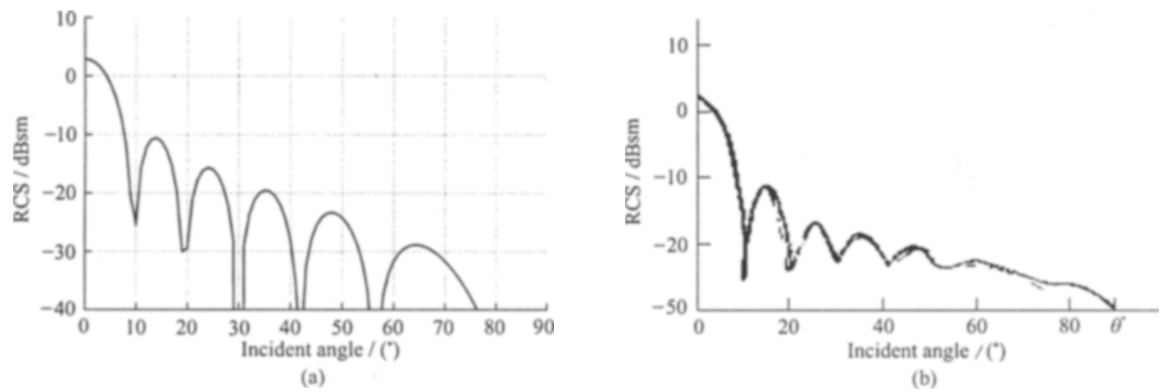

Fig. 3 The RCS of plate coated with isotropic RAM
(a) a monostatics RCS versus incident angle for a rectangular plate coated with a set of parameters;
(b) the RCS results of experiment and Ref. [4] for above coating plate

For Fig. 5, the coating is called positive uniaxial RAM which has a set of parameters: $\varepsilon_s = 8.19 - 1.3j$, $\varepsilon_z = 25.59 - 3.89j$, $\mu_s = 1.39 - 0.56j$, $\mu_z = 2.16 - 1.68j$. From Fig. 4, we can see that the RCS of plate coating with RAM is reduced about 10dB compared with the uncoated plate in the near specular direction, and the values of reduction about 1dB in Fig. 3(b). Above calculations indicate that negative uniaxial RAM is more useful than the positive uniaxial RAM for reducing RCS of targets, which is consistent with some results obtained by other methods[3].

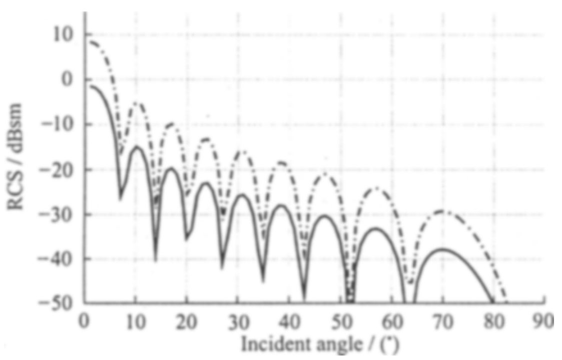

Fig. 4 The RCS of plate coated with negative uniaxial RAM

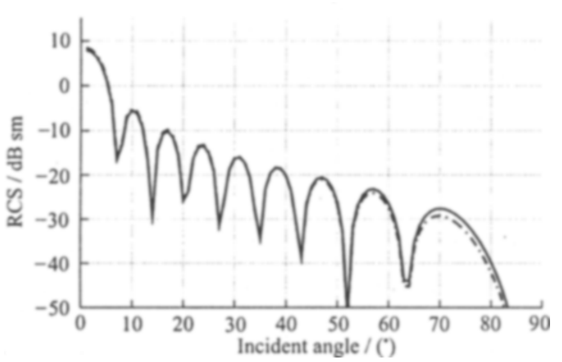

Fig. 5 The RCS of plate coated with positive uniaxial RAM

4 Discussion

Although the objects of this paper is a coating conductor rectangular plate, the method is also applicable to electrical large bodies modeled in terms of facets and wedges for the system of RCS prediction. Meanwhile, the scattering fields must handle the wedges formed by facets, which can improve the precision of RCS predicting. When the properties of RAM get to some extent, the value of RCS contributed by facets is the same as that of wedges. In addition, since the scattering of coated wedges don't well interpret the properties of RAM, the similar method as physical optics add physical theory of diffraction can deal with the RCS prediction for large coating complex targets, which will be a part of our next task.

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