Analysis of Electromagnetic Backscattering by Rotating Flat Blades

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1. Introduction

As the small flights which are usually used for aerial reconnaissance have small radar cross section (RCS) like a bird, discriminative feature extraction is necessary for target recognition. A propeller in front or on top of body makes distinct electromagnetic feature, and numerous studies have been carried out to analyze wave scattering from this structure. In 1979, Lahaie [1] attempted to solve the problems by using quasi-stationary approach and physical optics (PO) approximation. They apply the quasi-stationary approach, proposed by Van Bladel firstly. In 1992, Bor and Yang [2] tried to employ physical theory of diffraction (PTD)-equivalent currents method (ECM) to estimate RCS of three rotating metal blades, assuming infinitely perfect electric conducting (PEC) rectangular plates. In 1994, Sun [3] proposed geometrical theory of diffraction (GTD) and ECM. In 2002, Pouliguen [4] used PO/PTD and ECM to calculate scattered fields considering locations of a radar transmitter and a receiver in relation to the center of symmetry of the rotor.

In this paper, GTD and ECM are used to analyze backscattering far fields from four rotating PEC and dielectric covered PEC rectangular plates considering phase differences among the plates.

2. Theoretical Approach

Almost equations used in this paper are based on GTD and ECM. Monostatic case is assumed for scattered field calculation when a phi-polarized time harmonic plane electromagnetic wave is incident on skew rotating rectangular plates. Figure 1 shows a basic analysis model which is rotating around y-axis with $\theta_s = \omega t$. Because angular frequency (ω) is enough small relatively to radar frequency and rotating speed ($v = r\omega$) of all points on the blades are much less than speed of light, the quasi-stationary approach can be used in this case. When a plane wave is incident to rotating blades with $\theta = 90^\circ$, E^i and H^i can be expressed by (1) and (2), respectively.

$$\bar{E}^i = \hat{\phi} E_0 e^{jk(\cos\phi x + \sin\phi y)} \tag{1}$$

$$\bar{H}^i = \hat{\theta} \frac{E_0}{\eta_0} e^{jk(\cos\phi x + \sin\phi y)} \tag{2}$$

where E_0, k and η_0 are the magnitude of electric field, wave number and intrinsic wave impedance in free space, respectively. Then the ECM equivalent electric and magnetic edge currents are represented by (3) and (4), respectively [5].

$$\bar{I}_e = -\frac{e^{-j\frac{\pi}{4}}}{\sin\beta_0 \eta_0} \sqrt{\frac{8\pi}{k}} D_s (\bar{E}^i \bullet \hat{e}) \hat{e} \tag{3}$$

$$\overline{I}_m = -\frac{e^{-j\frac{\pi}{4}}\eta_0}{\sin\beta_0}\sqrt{\frac{8\pi}{k}}D_h(\overline{E}^i \bullet(\hat{e}\times\hat{k}))\hat{e} \qquad (4)$$

where $\hat{e}$ is each unit edge vector, β_0 is an internal angle between incident wave and edge and $D_{s,h}$ is GTD diffraction coefficients for PEC plate of rectangular form in backscattering case. Scattered far field E^s can be obtained by integrating the equivalent currents $\overline{I}_e$ and $\overline{I}_m$ along each of edges by (5).

$$\overline{E}^s = -\frac{jk}{4\pi}\int_C\left[\hat{r}\times(\hat{r}\times\overline{I}_e\eta_0)+\hat{r}\times\overline{I}_m\right]\frac{e^{-jkr}}{r}dl' \qquad (5)$$

where $\hat{r}$ is the unit vector in the direction of reflection.

Using the equation (5) and methods proposed by Sun [3] and McNamara [5], the extended model can be analysed. In practically, many of cases small flight have four blade propellers, so the extended model is appropriate to actual case as Fig. 2. Backscattered electric field can be calculated easily by considering superposition principle and phase differences caused by reflection corresponding to each plate by (6) and (7) which are modified equations from Sun's [3]. In far field backscattering situation, very small difference of distance relative to propagation range can be negligible.

$$E^s = \sum_{n=1}^{4} P_n E_n{}^s \qquad (6)$$

$$P_n = e^{\frac{jk}{2}\left(\frac{L1}{2}+L3\right)\cos\phi\sin\left(\frac{(n-1)\pi}{2}+wt\right)} \qquad (7)$$

where $E_n{}^s$ is backscattered electric field from each of blade. P_n is phase factor for each blade.

In addition, most propellers are coated with synthetic resins. To consider this problem, the equation should be modified in part of reflection coefficient. Two layers model is assumed when dielectric medium covers PEC as Fig. 3. The total layer reflection coefficient can be expressed in series form when infinite reflection is considered by (8) [6, 7].

$$R = R_1 + T_1(R_1-1)P_l^2 P_d{}^2 P_a\sum_{n=0}^{\infty}(R_1 P_l^2 P_d{}^2 P_a)^n \qquad (8)$$

where R_1 and T_1 are reflection and transmission coefficients at the boundary between medium 1 and 2, respectively. P_l, P_d and P_a are propagation losses in the medium , phase delay caused by medium thickness, phase delay associated with each of the reflected field terms, respectively.

This modified reflection coefficient is substituted in diffraction coefficient to correct it suitable for dielectric medium added two layers case by (9).

$$D_{s,h} = \frac{-e^{-j\frac{\pi}{4}}}{2\sqrt{2\pi k}\,\sin\beta_0}\left(1\mp\frac{R}{\cos\phi}\right) \qquad (9)$$

3. Numerical Results

The extended analysis model in Fig. 2(a) is verified the result through simulation where $L1 = 5\lambda, L2 = 2\lambda$ and $L3 = \lambda$. The skewed angle, ϕ_s, is 45°, and the incident wave angle, ϕ, is 20°. In Fig. 2(b), the analytic result for the extended structure shows good agreements around $0^\circ, 180^\circ$ and 360° compare with that of FEKO simulations which use method of moment (MoM) and physical optics (PO) for electromagnetic field calculation and the tendency is almost same.

In the double layered model case as Fig. 3(a), the length of edges are $L1 = 5\lambda$ and $L2 = 2\lambda$. The skewed angle, ϕ_s, is 0° and the incident wave angle, ϕ, is 20° . The thickness of medium is $3\,mm$, the relative permittivity $\varepsilon_1 = 3$ and $\tan\delta = 0.020$. In Fig. 3(b), the analysis result for the medium added double layer structure shows good agreements almost through $0^\circ \sim 180^\circ$ with that of FEKO simulation and the tendency of both result are mostly identical.

4. Conclusion

The analysis of simplified four propeller blades considering phase difference among them and added dielectric medium on PEC are represented using modified GTD and ECM equations. The numerical results are agree well with the results of MoM based FEKO. These outcomes can be also useful for post signal processing to extract features that are helpful for target recognition.

Acknowledgments

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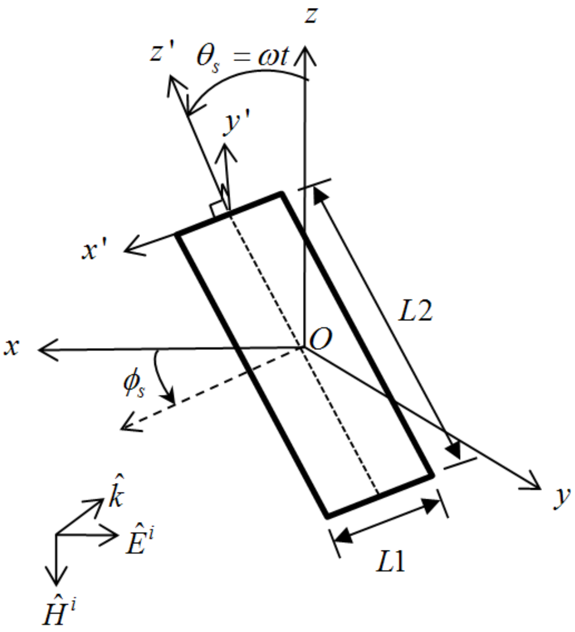
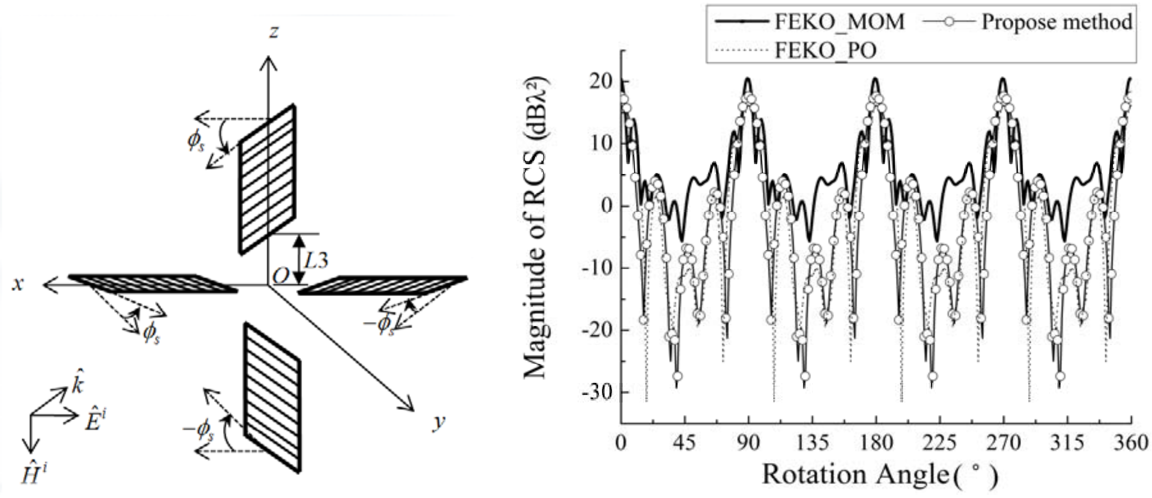
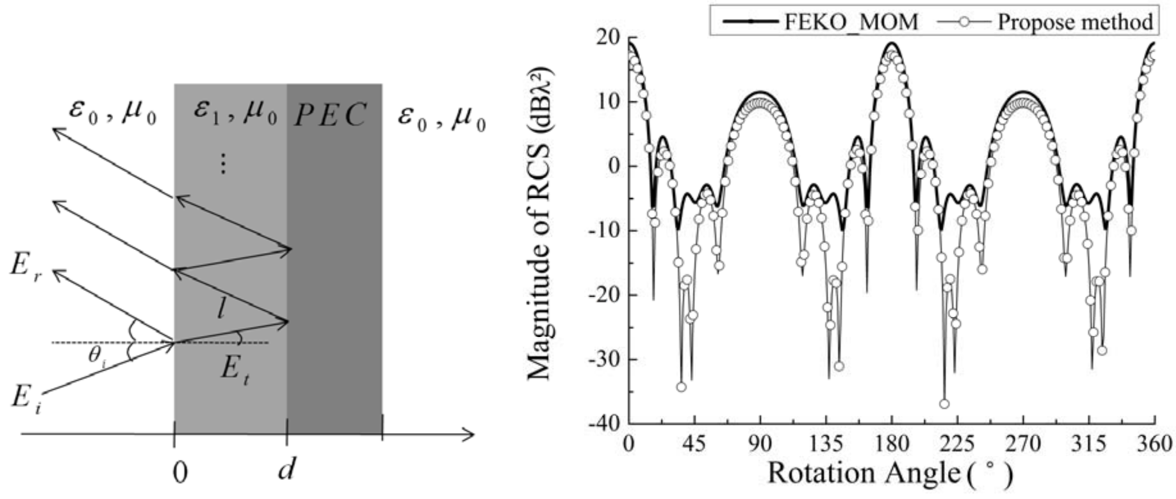


Figure 1. A basic skew plate rotating around y-axis with $\theta_s = \omega t$



(a) (b)

Figure 2. (a) Extended Analysis Model
(b) Comparison between FEKO Simulation and proposed method Results



(a) (b)

Figure 3. (a) Double Layered Medium Model
(b) Comparison between FEKO Simulation and proposed method Results

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