Ocean Engineering 36 (2009) 821–830

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Radar cross section analysis of marine targets using a combining method of physical optics/geometric optics and a Monte-Carlo simulation

Kookhyun Kim [a,*], Jin-Hyeong Kim [b], Dae-Seung Cho [b]

[a] Special Ship Hull Design Team, Hanjin Heavy Industries and Constructions, Co. Ltd., 22-1 4-Ga, Jungang-dong, Jung-gu, Busan 600-751, South Korea
[b] Department of Naval Architecture and Ocean Engineering, Pusan National University, 30 Jangjeon-dong, Guemjeong-gu, Busan 609-735, South Korea

A R T I C L E I N F O

Article history:
Received 12 December 2007
Accepted 3 May 2009
Available online 18 May 2009

Keywords:
Radar cross section
Monte-Carlo simulation
Physical optics
Geometric optics
Pierson–Moskowitz ocean wave spectrum

A B S T R A C T

In this paper, the radar cross section of flat plates on ocean surfaces is statistically investigated. A combining method of physical optics and geometric optics is applied to establish an effective backscattering analysis procedure. This method is a high-frequency analysis method originally derived from a simplified Stratton–Chu integral equation, assuming that the radar is far away from the target so that Kirchhoff approximation is valid. A Monte-Carlo simulation method is adopted to statistically analyze the effects of undulated ocean surfaces. The ocean surfaces are randomly generated by Pierson–Moskowitz ocean wave spectrum and a directional distribution function. Numerical investigations are carried out for flat plates, with the same height and width but with different inclined angles, on ocean surfaces of various significant wave heights.

1. Introduction

Kinds of radar cross section reduction techniques such as shaping, shielding, and applying radar absorbing material (RAM) are generally applied to enhance survivability of surface warships against hostile radar sensor-mounted threats. For this purpose, numerical calculations for quantitative assessments of radar cross section values and discrimination of problem areas are performed in warship design stage, where the multi-path effect by the ocean surface is ignored normally. While the measured data necessarily include the multi-path effect because measurements of the radar cross section of marine targets are performed for the warship on the continuously moving ocean surface. Therefore, how to calibrate the difference by multi-path effects between the measured value and the numerically calculated value becomes a crucial issue.

The radar cross section enhancement by multi-path effects can be explained by a function of sea-state numbers; for instance, 8 dBsm for sea state 0, i.e. calm sea and 0 dBsm for sea state 4 (Upson et al., 2001). Although this approach is simple to apply, it could not explain the variation of the ocean wave spectrum depending on the region. Recently, owing to the improvement of computing speed, numerical methods based on the various electromagnetic wave theories and statistical approaches have been proposed by many researchers.

Numerical methods for radar cross section analyses including the multi-path effect are categorized into four-path model (Anastassiu, 2002; Johnson, 2001; Lohrmann, 2001) and statistical approach (Burkholder et al., 2001a,b; Torrungrueng and Johnson, 2001).

On the one hand, four-path model calculates the multi-path effect using bistatic radar cross section values of marine target itself, assuming that ocean surface is infinitely flat and electromagnetic waves propagates just only four paths; (1) transmitter–target–receiver, (2) transmitter–target–ocean surface–receiver, (3) transmitter–ocean surface–target–receiver, and (4) transmitter–ocean surface–target ocean surface–receiver. Lohrmann (2001) calculated the radar cross section of marine targets composed of finite number of point scatters using four-path model based on physical optics. Johnson (2001) studied the four-path model based on moment method for scattering from an object above a dielectrically lossy half space. Anastassiu (2002) analyzed the radar cross section of the vertical flat plate above infinitely flat ocean surface using a four-path model based on physical optics.

On the other hand, the statistical approach directly calculates radar cross sections of the target on randomly generated ocean surfaces using an ocean wave spectrum, and then gives representative values such as average, coherent, incoherent, and maximum values. The statistical approach can consider the undulated features of ocean surface differently with the four-path model. Torrungrueng and Johnson (2001) carried out a numerical

* Corresponding author. Tel.: +82 51 410 8028; fax: +82 51 410 8459; Cel.: +82 10 5399 0430.
E-mail address: kimkh@hanjinsc.com (K. Kim).

0029-8018/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.oceaneng.2009.05.005

study on electromagnetic wave backscattering enhancement by two-dimensional rough surfaces using Monte-Carlo simulation based on the forward–backward/spectral acceleration method. Burkholder et al. (2001a,b) calculated electromagnetic field backscattered from small-sized ship-like targets on zero-mean Gaussian surfaces using Monte-Carlo simulations based on an iterative physical optics and a moment method, and they have investigated the features versus incident angle and roughness of surface in terms of averaged, coherent, incoherent, and maximum values. Inan and Ertürk (2006) applied iterative techniques such as forward–backward method, conjugate gradient squared, quasi-minimal residual, bi-conjugated gradient stabilized for electromagnetic scattering from dielectric random and reentrant rough surfaces. Colak et al. (2007) and Kuang and Jin (2007) analyzed electromagnetic scattering from three-dimensional targets on ocean-like rough surfaces using multiple sweep method of moment (MSMM) and finite difference time domain (FDTD), respectively.

In this paper, a novel numerical method to statistically analyze the radar cross section of marine targets including the multi-path effects by an undulated ocean surface is presented. The combining method of physical optics and geometric optics is applied to explain the polarization effect as well as the multi-reflection. This high-frequency analysis method is originally derived from a simplified Stratton–Chu integral equation. Monte-Carlo simulation method is used to explain random features of undulated ocean surfaces, in which ocean surfaces are modeled with short-crested ocean waves randomly generated from Pierson–Moskowitz ocean wave spectrum.

To validate the accuracy of the proposed method, the radar cross section of a vertically oriented flat plate on a flat ocean surface is calculated and compared with four-path model solution. Finally, to observe the statistical characteristics of the radar cross section of marine targets, additional numerical investigations are carried out for three (3) flat plates on ocean surfaces of various significant wave heights; vertically oriented, +10°-inclined and −10°-inclined flat plate.

2. Theories of electromagnetic wave scattering

In spherical coordinates, the radar cross-section matrix $[\sigma]$ and the scattering matrix $[B]$ with polarization are defined by the following matrix equations, respectively (Knott et al., 1993):

$$[\sigma] = \begin{bmatrix} \sigma_{\theta\theta} & \sigma_{\theta\phi} \\ \sigma_{\phi\theta} & \sigma_{\phi\phi} \end{bmatrix} \tag{1}$$

$$[B] = \begin{bmatrix} B_{\theta\theta} & B_{\theta\phi} \\ B_{\phi\theta} & B_{\phi\phi} \end{bmatrix} \tag{2}$$

where θ and ϕ are the azimuth angle and the elevation angle, respectively. σ_{uv} and B_{uv} are uv-polarization components of radar cross-section matrix and scattering matrix, respectively, which are represented by the following relation:

$$\sigma_{uv} = 4\pi|B_{uv}|^2 = \lim_{R\to\infty}\left(4\pi R^2\left|\frac{\vec{E}_{s,u}}{E_{i,v}}\right|\right), \quad (u, v = \theta, \phi) \tag{3}$$

where R is the distance between the receiver and the center of target, $\vec{E}_{i,v}$ and $\vec{E}_{s,u}$ are the electric field vector of incident and scattered electromagnetic waves, respectively.

In this paper, a novel combining method of physical optics and geometrical optics is originally formulated to efficiently calculate the radar cross section of marine targets defined in Eq. (3).

2.1. Physical optics

Assuming that an electromagnetic plane wave is incident to any target, the electric field vector scattered to a certain position $\vec{E}_s$ satisfies the following Stratton–Chu integral equation (Knott et al., 1993):

$$\vec{E}_s = -\frac{jke^{-jkR}}{4\pi R}\int_S\{\hat{\zeta}_s \times [\hat{n}\times\vec{E} - \eta\hat{\zeta}_s \times (\hat{n}\times\vec{H})]\}e^{jk\vec{r}\cdot(\hat{\zeta}_s-\hat{\zeta}_i)}\,dS \tag{4}$$

where j is the unit imagery, S is the target surface, $k = \omega_0/c$ is the wavenumber, ω_0 is the circular frequency, and c is the speed of electromagnetic waves. $\hat{\zeta}_i$ and $\hat{\zeta}_s$ are the unit directional vectors of the incidence and scattering of the electromagnetic wave. $\hat{n}$ is the unit normal vector at any position on the target surface. $\vec{E}$ and $\vec{H}$are the electric field vector and the magnetic field vector induced on the surface. $\vec{r}$ is the position vector of receiver. η is the electromagnetic impedance of the air.

Consider the flat surface of which the area is S and the local coordinates is defined as in Fig. 1. By applying Kirchhoff approximation, Eq. (4) can be rewritten as

$$\vec{E}_s = -\frac{jke^{-jkR}}{2\pi R}E_0\vec{W}(\hat{p})\int_S e^{jk\vec{r}\cdot(\hat{\zeta}_s-\hat{\zeta}_i)}\,dS \tag{5}$$

where $E_0(=|\vec{E}_i|)$ is the magnitude of the incident electromagnetic wave field vector $\vec{E}_i$. $\vec{W}(\hat{p})$ is the polarization vector with respect to the unit polarization vector $\hat{p}(=\vec{E}_i/E_0)$ and yields the following vector equation:

$$\begin{aligned}\vec{W}(\hat{p}) = \tfrac{1}{2}\hat{\zeta}_s \times \{&(1+\Gamma_E)(\hat{p}\times\hat{e}_\perp)(\hat{n}\times\hat{e}_\perp) \\ &+ (1-\Gamma_H)(\hat{p}\times\hat{e}^i_\parallel)(\hat{\zeta}_i\times\hat{n})\hat{e}_\perp \\ &+ (1-\Gamma_E)(\hat{p}\times\hat{e}_\perp)(\hat{\zeta}_i\times\hat{n})(\hat{\zeta}_s\times\hat{e}_\perp) \\ &- (1+\Gamma_H)(\hat{p}\times\hat{e}^i_\parallel)[\hat{\zeta}_s\times(\hat{n}\times\hat{e}_\perp)]\}\end{aligned} \tag{6}$$

where Γ_E and Γ_H are the Fresnel reflection coefficients of a certain impedance surface for E-polarization and H-polarization (Klement et al., 1988), respectively. $\hat{e}_\perp$ and $\hat{e}^i_\parallel$ are the vertical unit vector and the parallel unit vector with respect to the incident plane, respectively.

By substituting Eq. (5) into Eq. (3) and rearranging in matrix form, the scattering matrix $[B]$ for the single reflection is written as

$$[B] = [P]I_p \tag{7}$$

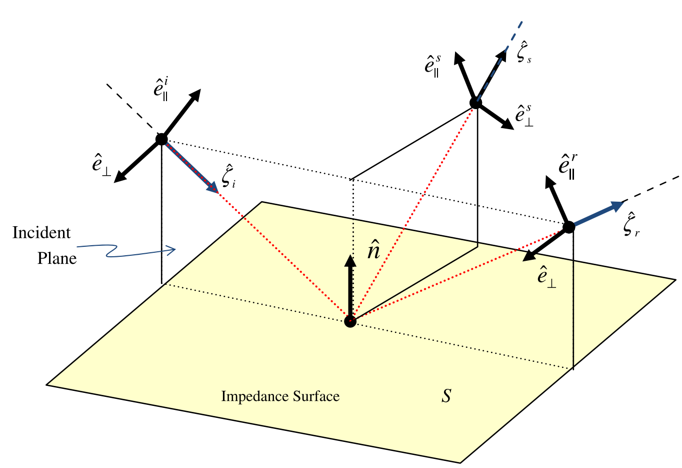

Fig. 1. Local coordinates of an impedance surface.