Analysis of Electromagnetic Wave Scattering from a Sea Surface Using a Monte-Carlo FDTD Technique

Dong-Muk Choi[1] · Che-Young Kim[2] · Dong-Il Kim[3] · Joong-Sung Jeon[1]

Abstract

This paper presents a Monte-Carlo FDTD technique to determine the scattered field from a perfectly conducting surface like a sea surface, from which the useful information on the incoherent pattern tendency could be observed. A one-dimensional sea surface used to analysis scattering was generated using the Pierson-Moskowitz model. In order to verify the numerical results by this technique, these results are compared with those of the small perturbation method, which show a good match between them. To investigate the incoherent pattern tendency involved, the dependence of the back scattering coefficients on the different wind speed(U) is discussed for the back scattering case.

Key words : Sea Surface, EM Scattering, Monte-Carlo FDTD.

Ⅰ. Introduction

Recently wave scattering from a random rough surface has been widely studied to characterize wave interaction with sea surfaces, ocean bottoms, and rough terrain as well as focusing on the radar imaging and the nondestructive testing[1]. In particular, the Pierson-Moskowitz surface has been a topic of intense research due to the natural occurrence of sea surfaces in nature[2],[3]. As for evaluating wave scattering from these rough surfaces, analytic and numerical methods are often considered. The most well-known analytical methods are the small perturbation method and the Kirchhoff approximation[1],[4],[5]. The advantage of these methods leads to the expressions of the scattered field in a closed form. However, their drawback is that it would be very difficult to obtain closed form solutions for many natural surfaces. The widely employed numerical techniques for the evaluation of scattering from natural rough surfaces are to use the finite-difference time-domain method(FDTD) and method of moments(MoM)[6]~[9]. MoM is more efficient for the Dirichlet surface scattering problem, but volume scattering, inhomogeneous media, and complex geometries are more easily developed by the FDTD method. In addition, the three-dimensional problem is less expensive to implement using the FDTD approach, either pulsed or CW illumination can be used, propagation of both the total and scattered fields can be observed in the time domain, and a broad band of frequencies can be considered simultaneously. So, we used the FDTD technique for the analysis of the rough surface. In this paper, the back scattering coefficients from the Pierson-Moskowitz surfaces are calculated with different values of the wind speed(U) using a Monte-Carlo FDTD technique. To evaluate the numerical results by this method, the computed values are compared with those of small perturbation method. Then the back scattering coefficients on the different U is investigated to study the tendency of the incoherent part of those.

Ⅱ. FDTD Technique and Small Pertubation Method

In order to evaluate scattering from the Pierson-Mokowitz surface, it is necessary to make this surface. This surface can be generated using the spectral method[4]. The surface realizations are consisted of a set of N points with spacing x over sample size L. The surface height at $x_n = n\Delta x (n=1, 2, \cdots, N)$ can be generated as follows[4]

$$f(x_n) = \frac{1}{L} \sum_{m=-N/2}^{N/2-1} F(K_m) e^{iK_m} \tag{1}$$

Where, for $m \geq 0$,

$$F(K_m) = [2\pi L W(K_m)]^{1/2} \begin{cases} [N(0,1) + jN(0,1)]/\sqrt{2}, & m \neq 0, N/2 \\ N(0,1), & m = 0, N/2 \end{cases} \tag{2}$$

for $m < 0$,

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$$F(K_m) = [2\pi L W(K_m)]^{1/2} \begin{cases} [N(0,1) - jN(0,1)]/\sqrt{2}, & m \neq N/2 \\ N(0,1), & m = N/2 \end{cases} \quad (3)$$

In (1), (2), (3), $K_m = 2\pi m/L$ is the spatial frequency, $j=\sqrt{-1}$, and $N(0, 1)$ indicates an independent sample taken from a zero mean, unit variance Gaussian distribution. Equation (1) is computed with a Fast Fourier Transform(FFT). The power spectrum of a Pierson-Moskowitz is given as follows[2]

$$W(K_m) = [\alpha/(4|K_m|^3)]\exp[-(\beta g^2)/(K_m^2 U^4)] \quad (4)$$

where U is the wind speed at a height of 19.5[m], $g=9.81$ $[m/s^2]$ is gravity acceleration and other constants α, β are 8.10×10^{-8} and 0.74, respectively[2]. The mean-square surface height is

$$h^2 = \int_{-\infty}^{+\infty} W(K)dK = \frac{\alpha U^4}{4\beta g^2} \quad (5)$$

The power spectrums of the Pierson-Moskowitz surfaces versus the wind speed U are shown in Fig 1.

An example of a Pierson-Moskowitz surface realization is shown in Fig. 2. In this paper, the patch size of the surface and the sample point number are set to 128 and 8196, respectively.

Fig. 3 shows the structure used to compute the scattering from the Pierson-Moskowitz surface. The incident field is a horizontally polarized plane wave with a unity magnitude. When a plane wave with a unity magnitude strikes a finite-length surface, edge diffraction occurs in general. The amount of contribution to the scattering pattern by the edge diffraction is different from a flat surface and a randomly fluctuating surface. While the edge diffraction on a flat surface shows a great influence on the pattern, that influence is diluted

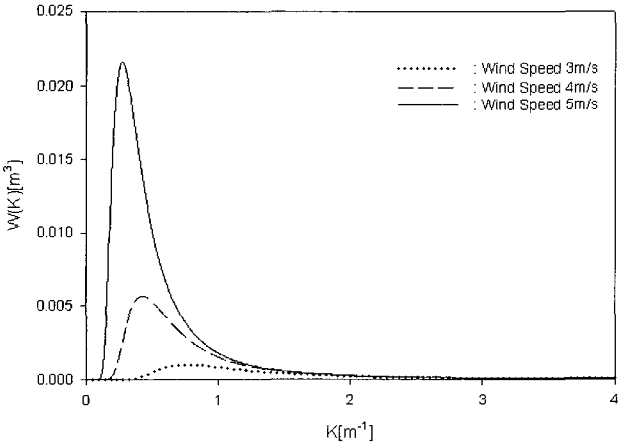

Fig. 1. 1-D Pierson-Moskowitz spectrum for the wind speed.

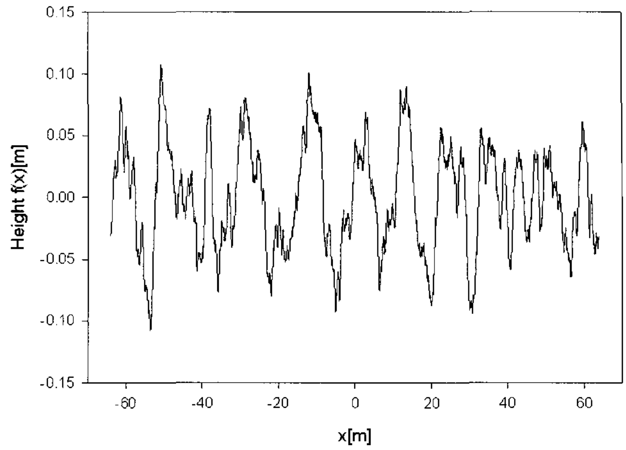

Fig. 2. A sample Pierson-Moskowitz surface, U=4 [m/s].

for the randomly fluctuating surface because the contribution field on the edge is partially blocked and diffused by the inherent surface undulation. Hence many researchers have used the plane wave as an exciting source with no particular comments on the edge diffraction[10],[11]. Whether the edge diffraction effect should be taken into account or not depends upon how many patch sizes are to be employed in the given structure. In fact, the scattering pattern with different surface patch size is of interest in remote sensing applications. More information will be obtained as patch size increased, in contrast, some information will be loosen as patch size decreased. However, further increasing of patch sizes gives no more additional scattering information. Some authors found that the scattering pattern showed no qualitative change if the patch size being greater than a fundamental period[12]. The algorithm to calculate E and H field by FDTD is as follows. The two Maxwell's curl equations show

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\left[\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right] \quad (6)$$

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu}\frac{\partial E_z}{\partial y} \quad (7)$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\frac{\partial E_z}{\partial x} \quad (8)$$

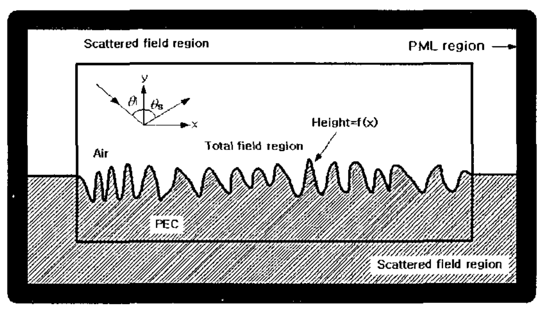

Fig. 3. Geometric structure for FDTD method.

Using central differences approximation on (6)~(8), the resultant equations are found to be

$$E_z^n(i,j)=E_z^{n-1}(i,j)+\frac{\Delta t}{\varepsilon\Delta}[(H_y^{n-1/2}(i+1/2,j)-H_y^{n-1/2}(i-1/2,j))-(H_x^{n-1/2}(i,j+1/2)-H_x^{n-1/2}(i,j-1/2))] \tag{9}$$

$$H_x^{n+1/2}(i,j+1/2)=H_x^{n-1/2}(i,j+1/2)-\frac{\Delta t}{\mu\Delta}[(E_z^n(i,j+1)-E_z^n(i,j)] \tag{10}$$

$$H_y^{n+1/2}(i+1/2,j)=H_y^{n-1/2}(i+1/2,j)+\frac{\Delta t}{\mu\Delta}[(E_z^n(i+1,j)-E_z^n(i,j)] \tag{11}$$

where $\Delta x=\Delta y=\Delta$ is grid cell size and Δt is time interval. The scattering from the rough surface is the unbounded problem. However, the computational domain must be restricted to a finite size depicted in Fig. 3 since no computer can store an unlimited amount of data. Hence an absorbing boundary condition on the outer perimeter of the domain must be imposed to simulate its extension to infinity. In this paper, a perfectly matched layer(PML) having 16 layers is used as an absorbing boundary condition. The scattering coefficient is obtained by dividing the average radar cross section by a sample size(L)[6],[13].

$$\sigma(\theta_i,\theta_s)=\lim_{r\to\infty}\frac{2\pi r}{L}\frac{1}{N}\sum_{n=1}^{N}\left|\frac{\widetilde{E}_s^n}{\widetilde{E}_i}\right|^2 \tag{12}$$

Here r is the distance between the origin and the observation point, $\widetilde{E}_s^n(r)$ is a phasor quantity of the scattered field $E_s^n(\underline{r})$ from the n-th surface, $\widetilde{E}_i$ is a phasor quantity of incident field E_i and N is the total number of surfaces. The phasor quantity $\widetilde{E}_s^n(r)$ is obtained by taking the near-to-far field transformation [6],[14]. It can be shown that

$$\widetilde{E}_s^n(\underline{r})=\frac{e^{-jkr}}{\sqrt{r}}\frac{e^{j(\pi/4)}}{\sqrt{8\pi k}}\int_{C_a}\omega\mu\hat{z}'\cdot[\hat{n}_a\times\underline{\widetilde{H}}(\underline{r}')]+k\hat{z}'\times[\hat{n}_a\times\underline{\widetilde{E}}(\underline{r}')]\cdot\hat{r}e^{jk\hat{r}\cdot\underline{r}'}dC' \tag{13}$$

where $\underline{r}$ is the distance vector from the origin to the observation point and $\underline{r}'$ is the distance vector from origin to source point, and $\hat{n}_a$ is the unit outward normal vector. $\underline{\widetilde{E}}(\underline{r}')$ and $\underline{\widetilde{H}}(\underline{r}')$ are the phasor quantity of $\underline{E}(\underline{r}')$ and $\underline{H}(\underline{r}')$. These phasor quanties can be evaluated by using discrete Fourier transform. Fig. 4 shows the integration path to obtain the far-field from the near field.

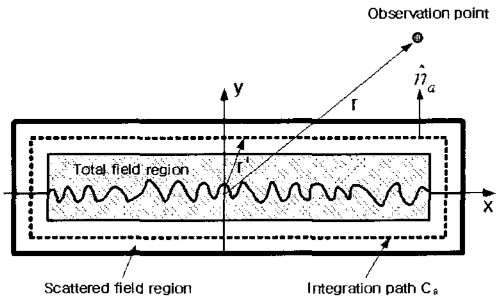

Fig. 4. Integration path to obtain far-field from near field.

To verify the numerical results obtained by a Monte-Carlo FDTD, the computed numerals are compared with those of small perturbation method. According to the small perturbation method, the back scattering $\sigma_{pq}(\theta_i,-\theta_i)$ coefficient of a Pierson-Mokowitz random rough surface is expressed as [9]

$$\sigma_{pq}(\theta_i,-\theta_i)=4k^3\cos^4\theta_i|\beta_{pq}|^2W(2k\sin\theta_i) \tag{14}$$

provided that the incidence angle is not small and

$$k^2h^2=\frac{k^2\alpha U^4}{4\beta g^2}\ll 1 \tag{15}$$

In (14), (16), p and q denote each horizontal and vertical polarization, h is the surface height standard deviation. The hh is the Fresnel reflection coefficient for the horizontal polarization. And the vv is written as [9]

$$\beta_{vv}=(\varepsilon_r-1)\frac{\sin^2\theta_i-\varepsilon_r(1+\sin^2\theta_i)}{[\varepsilon_r\cos\theta_i+(\varepsilon_r-\sin^2\theta_i)^{1/2}]^2} \tag{16}$$

Ⅲ. Numerical Result and Discussions

Fig. 5, 6, 7 represent the angular distribution of the

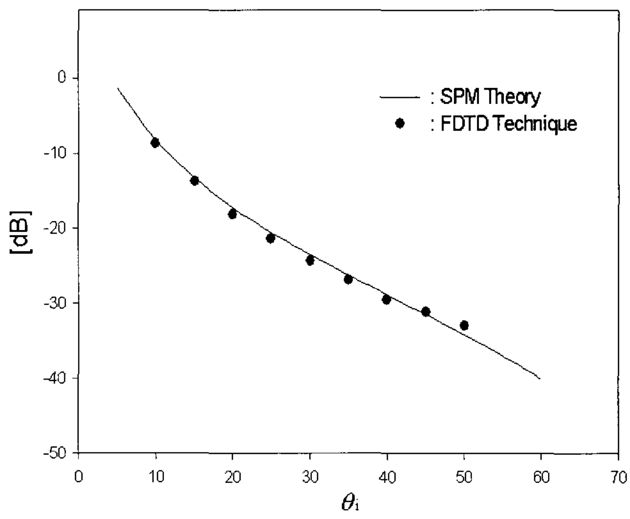

Fig. 5. In case U=3 [m/s], the back scattering coefficient.

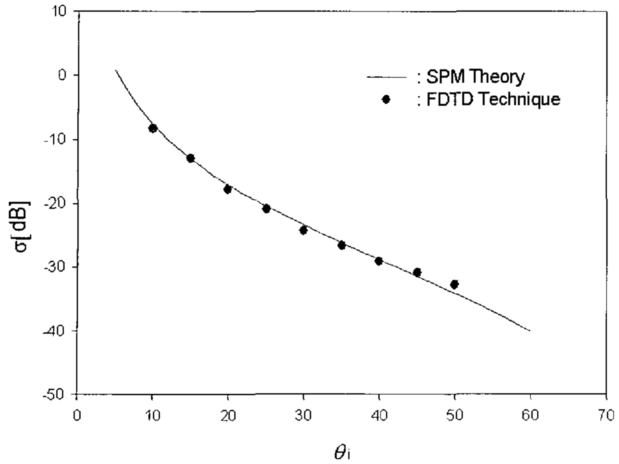

Fig. 6. In case U=4 [m/s], the back scattering coefficient.

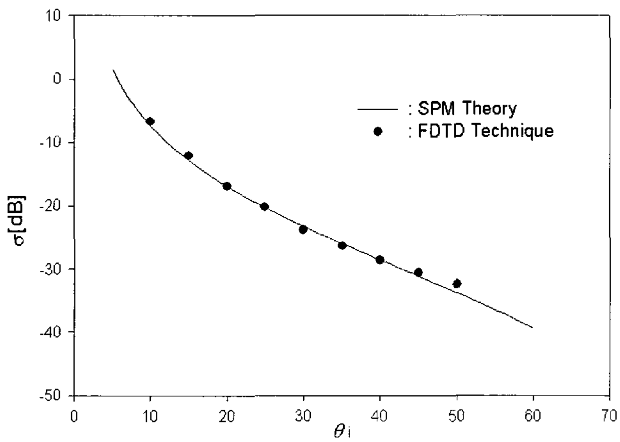

Fig. 7. In case U=5 [m/s], the back scattering coefficient.

scattering coefficient pattern of the Pierson-Mokowitz surfaces using both of the small perturbation theory and FDTD technique for each wind speed. The computed results show favorable match between two methods. It is natural that with increasing the wind speed U, the incoherent component is gradually larger because increasing U augments the slope of a Pierson-Mokowitz surface.

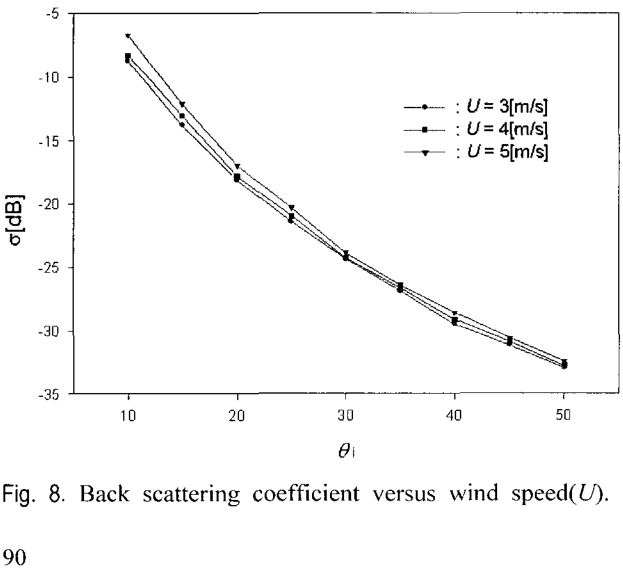

Fig. 8. Back scattering coefficient versus wind speed(U).

Fig. 8 represents the angular distribution of the scattering coefficient pattern of the Pierson-Mokowitz surfaces versus the wind speed(U). The magnitude of scattering coefficient is decreasing as the incident angle is increasing, because less echo return from the rough surfaces is expected when the incident wave is toward the grazing angle.

Ⅳ. Conclusions

This paper evaluates the back scattering coefficient from the Pierson-Moskowitz surface using a Monte-Carlo FDTD technique. The numerical results of FDTD method show fairly good agreements with those by the small perturbation theory. To further investigate the incoherent pattern tendency, the dependence of the back scattering coefficient on the different U is discussed. From these results, we can estimate the shape of the Pierson-Moskowitz surface versus the wind speed. Future investigation will include the electromagnetic wave scattering from dielectric random rough surfaces and extend to two dimensional rough surfaces.

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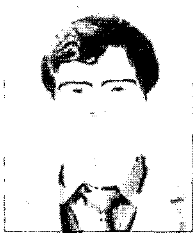

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