Research on Electromagnetic Scattering from ocean covered by foams

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Abstract: Back scattering of ocean surface is investigated by considering the foams coverage on its surface. Firstly, by adopting modified two-scale mode and the vector radiative transfer theory, zero and first order scattering coefficients are obtained by solving VRT equations. Then, MIE theory is used to get the scattering from foams, and fraction of foams coverage is analyzed by changing parameters of wind speed and temperature difference of ocean-air. Finally, the modified two-scale model and algorithms are verified by comparing its results with measured results, and simulations of calculating back scattering from ocean surface with and without foams are carried out. The conclusion is obtained that wind speed has different influence on back scattering under different incident angles.

1 INTRODUCTION

In natural world, the ocean surface will be partly covered by foams when the wind speed above the ocean reaches a certain extent. For example, one third of the ocean surface will be covered by foams as the wind speed is 25m/s. Therefore, ocean surface scattering and foams particle volume scattering must be considered both in order to get the accurate calculation results, when the ocean scattering characteristic is analyzed. Manahan treated ocean foams as water-air bubbles, instead of sphere water partial in his research [1]. Y.Q. Jin investigated the EM scattering characteristic of ocean covered by foams firstly by combining vector radiative transfer theory (VRT) and two-scale model [2]. In this paper, the modified two-scale model, the vector radiative transfer theory, and MIE theory are adopted to analyze the EM scattering from ocean surface covered by foams.

Fig.1 Two-scale ocean surface covered by foams

2 VECTOR RADIATIVE TRANSFER EQUATION OF OCEAN SURFACE CONSIST OF FOAMS

In Fig.1, the vector radiation transfer equations [3] of foam layers can be written as,

$$\begin{aligned} \cos \theta_s \frac{d}{dz} \bar{I}(\theta_s, \phi_s, z) = & -\bar{K}_e(\theta_s, \phi_s) \cdot \bar{I}(\theta_s, \phi_s, z) + \int_0^{2\pi} d\phi' \int_0^{\pi/2} d\theta' \sin \theta_s \\ & \cdot \bar{P}(\theta_s, \phi_s; \theta', \phi') \bar{I}(\theta', \phi', z) + \bar{Q}(z, \theta_s, \phi_s) \quad (1) \\ -\cos \theta_s \frac{d}{dz} \bar{I}(\pi - \theta_s, \phi_s, z) = & -\bar{K}_e(\theta_s, \phi_s) \cdot \bar{I}(\pi - \theta_s, \phi_s, z) \\ & + \int_0^{2\pi} d\phi' \int_0^{\pi/2} d\theta' \sin \theta_s \cdot \bar{P}(\pi - \theta_s, \phi_s; \theta', \phi') \cdot \bar{I}(\theta', \phi', z) \\ & + \int_0^{2\pi} d\phi' \int_0^{\pi/2} d\theta' \sin \theta_s \cdot \bar{P}(\pi - \theta_s, \phi_s; \pi - \theta', \phi') \\ & \cdot \bar{I}(\pi - \theta', \phi', z) + \bar{Q}(z, \theta_s, \phi_s) \quad (2) \end{aligned}$$

In formula (1), $\theta', \phi', \theta_s, \phi_s$ represents incident vertical angle, incident horizontal angle, scattering vertical angle and scattering horizontal angle respectively, $I(\theta, \phi, z)$ and K_e represents 4×1 column vector and extinction matrix respectively, $\bar{Q}$ and $\bar{P}(\theta, \phi; \theta', \phi')$ represents source of heat and phase matrix respectively. Partial satisfied Rayleigh approximation, so the phase

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matrix $\bar{P}(\theta, \phi; \theta', \phi')$ can be obtained from Rayleigh approximation.

Fig.2 Geometric structure of foam

In physical practice, the foams resulted by wind speed may be equal to several bubble partial. Foam partial can be described as the structure model in Fig.2 which obeys Gama distribution^[4]. In Fig.2, $a=250\mu\text{m}$ represents the outer radius of foam partial, $b=230\mu\text{m}$ represents the inner radius of foam partial, then the thickness of foam partial membrane can be obtained as $a-b=20\mu\text{m}$. The thickness of ocean foams layer is set to be 2cm in the following simulation. The basic scattering coefficient of ocean surface contained foams can be written as^[3]

$$\sigma_{pq}(\theta_s, \phi_s; \theta_i, \phi_i) = \frac{4\pi \cos \theta_s I_p(\theta_s, \phi_s)}{I_q(\theta_i, \phi_i)} \quad (3)$$

In formula (3), θ_i, ϕ_i represents the incident vertical angle and horizontal angle respectively, I_q, I_p represents incident spectra and scattering spectra respectively. Scattering from single foam can be calculated through Mie theory, then VRT (Vector Radiation Transmission) differential-integral equations are obtained by method of constant variation and boundary conditions. The solution of VRT equations is solved by using iteration method. Finally, zero order and first order scattering coefficients of ocean surface covered by foams are obtained accordingly. $\sigma_{pq(a)}^{(0)}$ represents zero order scattering coefficient, $\sigma_{pq(b)}^{(1)}, \sigma_{pq(c)}^{(1)}, \sigma_{pq(d)}^{(1)}$ and $\sigma_{pq(e)}^{(1)}$ represent first order scattering coefficients. Their formulas can be written as follow^[4]:

(1) Scattering only from two-scale ocean surface

$$\sigma_{pq(a)}^{(0)}(\theta_s, \phi_s; \theta_i, \phi_i) = \sigma_{pq} e^{-k_e d (1/\cos \theta_s + 1/\cos \theta_i)} \quad (4)$$

(2) Scattering only from water bubble partial

$$\sigma_{pq(b)}^{(1)}(\theta_s, \phi_s; \theta_i, \phi_i) = \frac{4\pi}{k_e} \cos \theta_s \bar{P}_{pq}(\theta_s, \phi_s; \pi - \theta_i, \phi_i) (1 - e^{-k_e d (1/\cos \theta_s + 1/\cos \theta_i)}) \quad (5)$$

(3) Scattering firstly from water bubble partial then from rough surface

$$\sigma_{pq(c)}^{(1)}(\theta_s, \phi_s; \theta_i, \phi_i) = \frac{4\pi}{k_e} \cos \theta_s \int_0^{2\pi} d\theta' \sin \theta' \int_0^{2\pi} d\phi' \sum_{l=v,h} \bar{P}_{pl}(\theta_s, \phi_s; \theta', \phi') \times \bar{R}_{pq}(\theta', \phi'; \pi - \theta_i, \phi_i) \times \frac{\cos \theta'}{\cos \theta_s - \cos \theta'} e^{-k_e d (1/\cos \theta' - 1/\cos \theta_s)} \quad (6)$$

(4) Scattering firstly from two-scale ocean surface then from water bubble partial

$$\sigma_{pq(d)}^{(1)}(\theta_s, \phi_s; \theta_i, \phi_i) = \frac{4\pi}{k_e} \cos \theta_s \int_0^{2\pi} d\theta' \sin \theta' \int_0^{2\pi} d\phi' \sum_{m=v,h} \bar{R}_{pm}(\theta_s, \phi_s; \pi - \theta', \phi') \times \bar{P}_{mq}(\pi - \theta', \phi'; \pi - \theta_i, \phi_i) \times \frac{\cos \theta_i}{\cos \theta_i - \cos \theta'} e^{-k_e d (1/\cos \theta' - 1/\cos \theta_i)} \quad (7)$$

(5) Scattering firstly from two-scale ocean surface then from water bubble partial, finally from two-scale ocean rough surface

$$\sigma_{pq(e)}^{(1)}(\theta_s, \phi_s; \theta_i, \phi_i) = \frac{4\pi}{k_e} \cos \theta_s \int_0^{2\pi} d\theta' \sin \theta' \int_0^{2\pi} d\phi' \sum_{l=v,h} \bar{R}_{pl}(\theta_s, \phi_s; \pi - \theta', \phi') \times \int_0^{2\pi} d\theta'' \sin \theta'' \int_0^{2\pi} d\phi'' \sum_{m=v,h} \bar{P}_{lm}(\pi - \theta', \phi'; \theta'', \phi'') \bar{R}_{mq}(\theta'', \phi''; \theta_i, \phi_i) \times \frac{\cos \theta''}{\cos \theta' + \cos \theta''} (1 - e^{-k_e d (1/\cos \theta' + 1/\cos \theta'')}) e^{-k_e d (1/\cos \theta_i + 1/\cos \theta_s)} \quad (8)$$

Where K_e is extinction coefficient, σ_{pq} can be obtained by two-scale model. Physical meanings of the coefficients above are demonstrated in Fig. 3 (a)~(e).

Fig.3 Zero and first order solution of the scattering

In conclusion, the scattering coefficients of ocean surface covered by foams are written as

$$\sigma_{pq}^{\text{foam}}(\theta_s, \phi_s; \theta_i, \phi_i) = \sigma_{pq(a)}^{(0)}(\theta_s, \phi_s; \theta_i, \phi_i) + \sigma_{pq(b)}^{(1)}(\theta_s, \phi_s; \theta_i, \phi_i) + \sigma_{pq(c)}^{(1)}(\theta_s, \phi_s; \theta_i, \phi_i) + \sigma_{pq(d)}^{(1)}(\theta_s, \phi_s; \theta_i, \phi_i) + \sigma_{pq(e)}^{(1)}(\theta_s, \phi_s; \theta_i, \phi_i) \quad (9)$$

3 SCATTERING AND EXTINCTION COEFFICIENTS OF FOAMS

MIE theory can be adopted to analyze scattering from sphere hollow partial in Fig.2, T matrix^[5] of MIE scattering can be written as.

$$T_n^{(M)} = -\frac{[\delta j_n(\delta)]' [j_n(\zeta) + B_n(\zeta, \chi) y_n(\zeta)] - \{[\zeta j_n(\zeta)]' + B_n(\zeta, \chi) [\zeta y_n(\zeta)]'\} j_n(\delta)}{[\delta h_n(\delta)]' [j_n(\zeta) + B_n(\zeta, \chi) y_n(\zeta)] - \{[\zeta j_n(\zeta)]' + B_n(\zeta, \chi) [\zeta y_n(\zeta)]'\} h_n(\delta)} \quad (10)$$

$$T_n^{(N)} = -\frac{[\delta j_n(\delta)]' [\zeta j_n(\zeta) + A_n(\zeta, \chi) y_n(\zeta)] - \{[\zeta j_n(\zeta)]' + A_n(\zeta, \chi) [\zeta y_n(\zeta)]'\} \delta^2 j_n(\delta)}{[\delta h_n(\delta)]' [\zeta j_n(\zeta) + B_n(\zeta, \chi) y_n(\zeta)] - \{[\zeta j_n(\zeta)]' + B_n(\zeta, \chi) [\zeta y_n(\zeta)]'\} h_n(\delta)} \quad (11)$$

Where j_n is spherical Bessel function, h_n is spherical Hankel function, y_n is Neumann functions, $\delta = ka$, $\zeta = k_a a$, $\chi = k_b b$, $\chi = k_b a$, a is the outer radius of the partial, b is the inner radius of the partial, k is the wavenumber of incident wave in free space, k_b is wavenumber in nucleus, k_a is wavenumber in shell. And extinction cross and cross section can be written as below,

$$Q_{\text{ext}} = \frac{2}{(ka)^2} \sum_{n=1}^{\infty} (2n+1) \text{Re}(-T_n^{(N)} - T_n^{(M)}) \quad (12)$$

$$Q_{sca} = \frac{2}{(ka)^2} \sum_{n=1}^{\infty} (2n+1) \left(\left| -T_n^{(N)} \right|^2 + \left| -T_n^{(M)} \right|^2 \right) \quad (13)$$

Then the formulas of extinction coefficient and scattering coefficient of foams are obtained as below^[6],

$$K_e = N_0 \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1) \operatorname{Re} \left(-T_n^{(N)} - T_n^{(M)} \right) \quad (14)$$

$$K_s = N_0 \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1) \left(\left| -T_n^{(N)} \right|^2 + \left| -T_n^{(M)} \right|^2 \right) \quad (15)$$

where N_0 represents foams numbers in unit volume, and it can be calculated by volume intergration.

4 ANALYSIS OF FRACTION OF FAOMS COVERAGE

Fraction of foams coverage on ocean surface driven by wind, is closely related to wind speed, temperature of seawater. Before accurately analyzing scattering property of different ocean zone covered by foams, fraction of foams coverage on ocean surface must be analyzed firstly. Under stable atmosphere conditions, fraction of foams coverage on ocean surface may be solved by the following formula^[7].

$$C = 2.32 \times 10^{-6} U_{10}^{3.4988} \quad (16)$$

Otherwise, when aimosphere is in unstable conditions ($2^\circ\text{C} < \text{temperature difference of ocean-air} < 12^\circ\text{C}$), the formula of fraction of foams coverage is

$$C = 0.43 \times 10^{-6} U_{10}^{3.6842} \quad (17)$$

Only the correlation between fraction of foams coverage and wind speed is reflected in formula (17). In order to analyze how temperature difference of ocean-air influences fraction of foams coverage, the following model is adopted,

$$C = 1.95 \times 10^{-5} U_{10}^{2.55} \exp(0.0861 \Delta T) \quad (18)$$

Where ΔT represents temperature difference of ocean-air, U_{10} represents wind speed 10 meters above ocean surface. Fig.4 shows the correlations between fraction of foams coverage and wind speed, temperature difference of ocean-air. As the wind speed and temperature difference increase, fraction of foams coverage is increasing. And the following simulations of fraction of foams coverage are done by formula (16) under the conditions of moderate temperature difference and stable atmosphere.

Fig.4 Relations of foams coverage – temperature difference of ocean-air and wind speed

The scattering coefficients of two-scale ocean surface considering foams influence can be written as,

$$\sigma_{pq}^{all} = (1 - C) \sigma_{pq} + C \sigma_{pq}^{foam} \quad (19)$$

5 CALCULATION SIMULATION AND ANALYSIS

Before calculating the EM scattering from ocean surface containing foams with the modified two-scale model, the accuracy of algorithm must be validated. The hh-polarized back scattering coefficient of two-scale gauss rough ocean surface is calculated by adopting the modified two-scale model, and the results are validated by comparing with measured datas of literature^[7] in Fig.5. In the simulation, frequency of incident wave is 8.93GHz, in Gaussian spectral, parameters m, kh, kl are obtained

Fig.5 Test of algorithm accuracy

by converting the ocean spectral with wind speed of 14~16 n mile/hour into Gaussian spectral, and h represents rms height of rough surface, l represents correlation length, m represents rms fraction of foams coverage, the temperature of ocean surface is set to be 17.4°C which is the global average seawater temperature. The salinity of seawater is set to be 32.54‰ as the global average salinity. And the dielectric permittivity of seawater is calculated as (57.63, 37.73). By analyzing results in Fig.5, the difference is slight by comparing foams and no-foams, and both are coincide well with the measured results. But under increasing incident angle, the decay of two-scale results becomes larger. The decay trend can be effectively weakened under large intendance angle, and the calculating results coincide with measured data better. Another thesis from Fig.5 is that back scattering coefficient of ocean surface is decreasing as the incident angle increasing.

Fig.6 Back scattering coefficients of ocean surface under different wind speed

Then, the modified two-scale model is adopted to get the back scattering property of oceans surface generated by E- spectral functions, and the influence of wind speed to back scattering coefficient is specially considered. The simulation results is shown in Fig.6, under Ku frequency band with VV polarization, the dielectric permittivity of seawater is calculated as(42.08, 39.46) by the same model used in the previous example in Fig.5. It is indicated that foams coverage and wind speed have slight influence on the back scattering under the smaller incident angle. While, under large incident angle, the back scattering of ocean surface is increasing as wind speed increasing. When wind speed is 4m/s, foams coverage has un-obvious influence on back scattering. And as wind speed increasing, the difference of with and without foams becomes more and more obvious. This is explained by fraction of foams coverage becomes larger as wind speed increasing.

6 CONCLUSION

Through the investigation of calculating back scattering from ocean surface covered by foams, we can conclude that back scattering coefficients of ocean with and without foams have significant difference, and under larger incident angle, greater wind speed caused larger back scattering coefficient.

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