A Scaled Simulated Method of Sea Clutter Based on Non-metal Materials

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Abstract— A new method of the simulated sea clutter in laboratory was proposed in this paper. By employing the scaled measurement technology, we can obtain the electromagnetic scattering characteristics of different sea states. According to the dielectric properties of non-metallic materials construction technique, a new kind of composite material has been constructed by epoxy mixing metal powder and material' reflectivity and complex permittivity meet the electromagnetic character of scaled simulated seawater. The material's permittivity can be controlled over a broad range. According to the geometric similarity conditions of scaled principle, the digital data of the different sea states' surface scaled model is generated basing on the classic sea spectrum model proposed by the oceanographer. The sea surface waveform of the scaled material is processed by CNC machine. We have measured the reflectivity and RCS with the incident angle of scaled PM (Pierson-Moskowitz) spectrum sea surface model made of the composite material proposed, and compared the results with theoretical simulation. The compared results verify the feasibility of the scaled simulated sea surface based on non-metal materials.

1. INTRODUCTION

Foreign military powers attach importance to the electromagnetic scattering measurement technique of the sea clutter in laboratory. While taking advantage of the wave pool simulated sea environment in the United States, the sea scale simulated material has been investigated using to measure the composite scattering characteristics between the ships on the sea at different sea states and analyze the effect of multipath. This method can provide a more accurate calibration data for the electromagnetic scattering theoretical model of the ships on the sea surface and improve measurement efficiency.

At present the scaled measurement technology of the sea clutter and scaled ship on a rough sea surface were investigated less in china. The scaled method of the sea clutter (especially high sea conditions simulation) is a key technology. According to the sea clutter scaled theory and the dielectric properties of non-metallic materials construction technique. A new kind of method that can easily be used to simulate sea clutter in laboratory was proposed in this paper. We used epoxy mixing metal powder to construct a new kind of composite material, and its reflectivity and complex permittivity meet the electromagnetic character of scaled simulated seawater. According to the geometric similarity conditions of scaled principle the data of scaled sea surface model at different sea states is produced. Then the surface of the scaled material is processed by CNC machine. we have measured the reflectivity and RCS at the incident angle of PM spectrum sea surface scaled model made of the composite material proposed, and compared the results with theoretical simulation. The compared results verify the feasibility of method proposed basing on scaled simulated sea clutter.

2. CONSTRUCTION TECHNIQUE OF THE SCALED SIMULATED MATERIALS OF SEA ENVIRONMENT

2.1. Electromagnetic Scaled Theory of Non-metallic Targets

Based on the electromagnetic scaled theory, if the parameters such as the geometry of the target, the working wavelength, the electric field and magnetic field strength are scaled in proportion, accordingly the electromagnetic scattering characteristics of the prototype system and the scaled system are the uniform. Clearly, the electromagnetic scaled measurement must ensure that the various elements of the scaled model (including geometric and physical elements) and the corresponding elements of the real system are proportional. For an perfect conductor or electromagnetic system composed of the lossless medium the similarity condition between scaled simulation and prototype is well known. When the prototype system includes lossy non-metallic materials. The scaled physical condition of the perfect conductor is not sufficient to describe all the similar relationship between the prototype and simulation system. But for the non-metallic dielectric materials, the similarity conditions can be derived from Maxwell's equations theoretically. The formula (1) shows that the real and imaginary parts of the permeability, and the real and imaginary parts of the permittivity of the scaled and prototype lossy dielectric material are the same, just are invariant to a change in scale factor, then the electromagnetic scattering characteristics of the prototype system and the scaled system are invariant.

$$\begin{cases} p_{\mu r} = \frac{\tilde{\mu}_r}{\mu_r} = 1 \\ p_{\mu i} = \frac{\tilde{\mu}_i}{\mu_i} = 1 \\ p_{\varepsilon r} = \frac{\tilde{\varepsilon}_{1r}}{\varepsilon_{1r}} = \frac{\tilde{\varepsilon}_r}{\varepsilon_r} = 1 \\ p_{\varepsilon i} = \frac{\tilde{\varepsilon}_{1i}}{\varepsilon_{1i}} = \frac{\tilde{\varepsilon}_i + \tilde{\gamma}/\tilde{\omega}}{\varepsilon_i + \gamma/\omega} = 1 \end{cases} \tag{1}$$

Sea environment is non-metallic targets. According to the scaled measurement physical similarity theory, the complex permittivitys of the seawater at the prototype and the scaled frequency should be the same. The complex permittivitys of seawater is expressed as

$$\tilde{\varepsilon} = \varepsilon_r - j\frac{\gamma}{\omega} \tag{2}$$

where, ε_r is the dielectric constant of the medium, γ is the conductivity of the medium, ω is the angular frequency.

According to the scaled measurement similarity conditions, the complex permittivitys of the sea scaled material can be expressed as

$$\bar{\tilde{\varepsilon}} = \bar{\varepsilon}_r - j\frac{\bar{\gamma}}{\bar{\omega}} = \varepsilon_r - j\frac{p\gamma}{p\omega} = \varepsilon_r - j\frac{\gamma}{\omega} \tag{3}$$

where, $\bar{\varepsilon}_r$ is the dielectric constant of the sea scaled material, $\frac{\bar{\gamma}}{\bar{\omega}}$ is the loss of the sea scaled material, p is the scale factor which is the ratio between the size of the scale and full-scale targets.

By comparison of the formulas (2) and (3), the complex permittivitys of the scale and full-scale material must be equal at sea scaled measurement.

For the scaled sea surface, in accordance with the principle of geometric similarity, the wave height and length of scaled sea model should be decreased in scale factor.

2.2. Construction Method of the Seawater Scaled Material

2.2.1. Complex Permittivitys Scaling Simulation

To seawater with 20‰ salinity at 2 GHz as a prototype target the complex permittivity and reflectivity at 2 GHz, are listed in Table 1.

Table 1: Complex dielectric constant and reflectivity of the seawater at 2 GHz.

prototype target	salinity	radar frequency	dielectric constant	reflectivity
seawater	20‰	2 GHz	74.6 + i34	0.8

According to the physical similarity principle, the complex permittivitys of the seawater at scale and full-scale frequency must be equal. The scaled conditions are very harsh, and in laboratory the scaled simulation of sea clutter can not be strictly met, so firstly we developed theoretical simulation to investigate the RCS with the changes of the real part of the seawater' permittivity, imaginary part of the seawater' permittivity, and absolute value of the seawater' permittivity. By theoretical simulation we can select a reasonable simulation range of the seawater' complex permittivity to ensure the accuracy of certain engineering simulation

Using FEKO simulation software, the RCS of the flat made of the non-metallic materials to simulate seawater with the azimuth have been calculated at 10 GHz that non-metallic materials' permittivity is changed with the center of 74.6 + i34. The results show that when the relative error of the permittivity' real and imaginary part are less than 50%, the maximum error of the RCS is less than 1.5 dB.

Using two-scale method to calculate backscattering coefficient of the rough sea surface with the changes of the real part of the seawater' permittivity, imaginary part of the seawater' permittivity, and absolute value of the seawater' permittivity, the results is shown in Figure 1 and Figure 2 that are the mean value of 30 random samples for vertical polarization. Because the seawater' permittivity are larger, the change of the real part of the seawater' permittivity or imaginary part of the seawater' permittivity alone has little effect to the sea surface' backscattering coefficient, especially change of the imaginary part separately affects smaller to sea surface' scattering. The change of permittivity' absolute value has obvious effect to the backscattering coefficient. When the amount of change in permittivity' absolute value is 50%, the error of the sea surface' backscattering coefficient is approximately 1.5 dB. When the amount of change in permittivity' absolute value is 60%, the error of the sea surface' backscattering coefficient is approximately 2.0 dB. When the amount of change in permittivity' absolute value is 80%, the error of the sea surface' backscattering coefficient is approximately 3.8 dB.

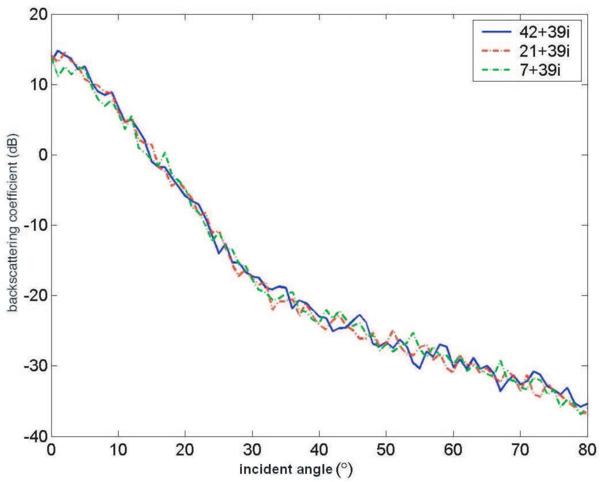

Figure 1: Backscattering coefficient vs. the incident angle plot at the various permittivity' real part.

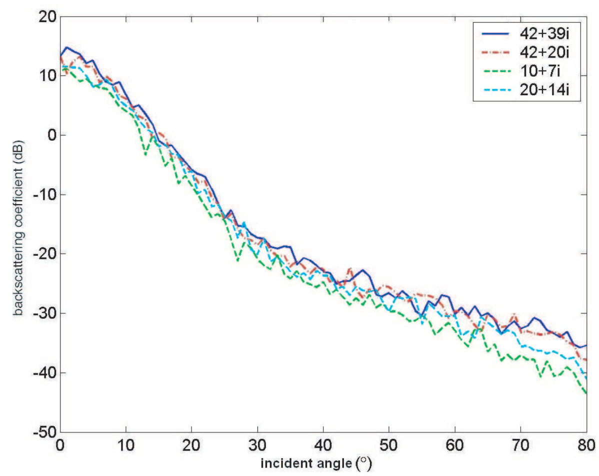

Figure 2: Backscattering coefficient vs. incident angle plot at the various permittivity.

From the above analysis of simulation results, the change of permittivity' absolute value has obvious effect to the backscattering coefficient. Investigating scaled simulated method of sea clutter based on non-metal materials, we can mainly consider the simulation accuracy of the absolute value of the permittivity according to the error demand.

2.2.2. Seawater Scaled Material Construction

We use the known permittivity epoxy mixing metal powder to construct a new composite material that its reflectivity and complex permittivity meet the electromagnetic character of scaled simulated seawater. The metal powder is the filler and the epoxy is the binder. The complex permittivity is determined by the microstructure of each component in the composite material [1]. According to Bruggeman [2] effective medium expression, the complex permittivity of the composite material is be calculated. In the course of constructing composite material, we adjust the percentage of metal powder and epoxy in the composite material repeatedly, measure the complex permittivity and electromagnetic scattering characteristics of the composite materials repeatedly, until the composite material is constructed that matches the permittivity of scaled simulated seawater. Considering the scaled conditions of the simulated seawater and simulation accuracy of the complex permittivity, the composite material has been constructed that its permittivity can be controlled over a broad range while the volume ratio of metal powder and epoxy changes. Figure 3 shows the scaled simulated composite material samples of the seawater. The reflectivity and complex permittivity have been measured at X, Ka band. Table 2 shows the reflectivity results of the composite materials that meet the reflectivity of scaled simulated seawater.

Using short circuit line method and resonant cavity method to measure the complex permittivity of the composite materials that meet the reflectivity of scaled simulated seawater, the real part of composite material permittivity is approximately 61 and the imaginary part is approximately 18 at X band. Relative error of the real part of the permittivity is approximately 18% relative error of the imaginary part of the permittivity is approximately 47% and relative error of permittivity' absolute value is approximately 22%. The real part of composite material permittivity is between 45 and 100 at Ka band and the relative error of the permittivity is less than 40%.

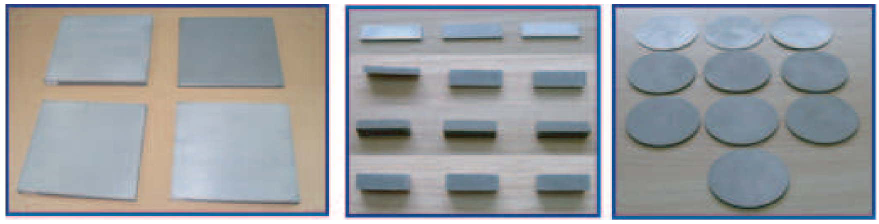

Figure 3: The scaled simulated composite material samples of the seawater.

Table 2: The reflectivity results of the composite materials.

prototype target	full-scale frequency	permittivity	reflectivity	scaled composite material	scale band	reflectivity	reflectivity relative error
seawater	2 GHz	74.6 + i34	0.8	epoxy + metal powder	X	0.794	0.8%
				epoxy + metal powder	Ka	0.79	1.3%

3. PM SPECTRUM SEA SURFACE SCALED MODEL TAILOR AND VERIFICATION

3.1. Digital Data Technique of the PM Spectrum Scaled Sea Surface Models

Basing on the classic sea spectrum model proposed by the oceanographer, the digital data of sea surface models at different sea states are produced. Then according to the geometric similarity conditions of scaled principle the digital data of the sea surface scaled model is calculated and converted into a three-dimensional model. At last the sea surface waveform of the scaled material is processed by CNC machine.

Sea environment is mainly described by the PM spectrum model

$$S(k)=\begin{cases} S_1(k)=\frac{0.00405}{k^3}\exp\left(\frac{-0.74g^2}{k^2u^4}\right) & 0<k<K_1\\ S_2(k)=0.00405K_1^{-1/2}k^{-5/2} & K_1<k<K_2=0.359\\ S_3(k)=S_4(K_3)(k/K_3)^q & K_2<k<K_3=0.942\\ S_4(k)=0.875(2\pi)^{p-1}\frac{g+3gk^2/13.177}{(gk+gk^3/13.177)^{(p+1)/2}} & K_3<k \end{cases} \tag{4a}$$

$$p=5.0-\log_{10}(u_*),\quad q=\log_{10}[S_2(k)/S_4(k)]/\log_{10}(K_2/K_3) \tag{4b}$$

where, $S(k)$ is one dimension sea spectrum ($S_1(k)$ is PM sea spectrum), $k=2\pi/\lambda$ is wave number of a sine wave component in the sea spectrum, λ is wavelength $g=980\,\mathrm{cm/s^2}$ and $K_1=K_2u_{*m}^2/u_*^2$, Friction wind speed $u_*>u_{*m}=12\,\mathrm{cm/s}$, u is calculated by the formula (5) and is the wind speed at the height of the sea surface.

$$u=\frac{u_*}{40}\ln\frac{19.5}{z_0}\,\mathrm{m/s},\quad z_0=0.684/u_*+0.0000428u_*^2-0.0443\,\mathrm{cm} \tag{5}$$

Formula (6) gives the two dimension sea spectrum calculation formula:

$$S(k,\phi)=\frac{1}{(2\pi)^2k}S(k)\left[1+a_1\left(1-e^{-bk^2}\right)\cos(2\phi)\right] \tag{6a}$$

$$a_1=2(1-R)/[(1-B)(1+R)] \tag{6b}$$

$$B=\frac{1}{S_t^2}\int_0^\infty k^2S(k)e^{-bk^2}dk \tag{6c}$$

$$R=\frac{S_{ct}^2}{S_{ut}^2},\quad S_t^2=S_{ct}^2+S_{st}^2 \tag{6d}$$

where, ϕ is propagation direction for a sine wave component, $b \approx 1.5\,\mathrm{cm}^2$, S_t^2, S_{st}^2 and S_{ct}^2 are separately the total average gradient' square, the average gradient' square against the wind direction, and the average gradient' square at the crosswind direction, Cox and Munk give a simplified formula:

$$S_{ct}^2 = 0.003 + 0.00192u \tag{7a}$$

$$S_{ut}^2 = 0.00316u \tag{7b}$$

To tailor sea surface scaled model, firstly the wave number and propagation direction of sine wave components in the sea spectrum need to be discrete, and according to the measurement electromagnetic band to confirm the maximum of wave number or the minimum wavelength of the sine wave components that should be less than the minimum electromagnetic wavelength. Secondly the amplitude of each discrete sine wave components at a sea surface wind speed is calculated by the formula (8):

$$A_n = \sqrt{2k_n S(k_n, \phi_n)\Delta k \Delta\phi} \tag{8}$$

According to the geometric similarity conditions of scaled principle, the height of the sea surface model is calculated:

$$z = \frac{1}{p}\sum_{n=1}^{N} A_n \sin\left[pk_n\left(x\cos\phi_n + y\sin\phi_n\right) + \varphi_n\right] \tag{9}$$

where, p is scale factor, k_n is discrete sine wave number A_n is the amplitude of discrete sine wave, ϕ_n is the propagation direction of discrete sine wave, φ_n is the random phase, N is the number of discrete sine wave.

Finally the digital data of the sea surface scaled model is converted into a three-dimensional model and the sea surface waveform of the scaled material is processed by CNC machine.

The depth of the true sea is big enough, and the size of scaled sea model is limited. The thickness of the scaled sea model will affect measurement accuracy. Because the seawater is lossy medium, when the transmission of electromagnetic waves in the sea, the intensity gradually decreases. The penetration depth of electromagnetic wave can be calculated according to the electromagnetic wave attenuation characteristics. The thickness of scaled sea model can only simulate the penetration depth of the true sea.

3.2. Feasibility Measurement and Verification

The PM spectrum sea surface scaled models are tailored using of non-metallic composite materials that meet the complex permittivity and reflectivity of scaled simulated seawate at 2 GHz. Figure 4 is the PM sea surface scaled model of the sea states 2, and scale factor is 1/20. The backscattering coefficient with the incident angle of this model has been measured at 40 GHz, and compared with theoretical simulation result. Figure 5 shows the measurement and simulation RCS with the incident angle, the scale frequency is 40 GHz, and the full-scale frequency is 2 GHz. The solid line curve is the measurement result and the dashed line curve is a simulation result in Figure 5. Within a certain range of the incident angle the measurement and simulation results are basically consistent. The root mean square error that the measurement result is compared with the simulation value of

Figure 4: The PM sea surface scaled model of the sea states 2.

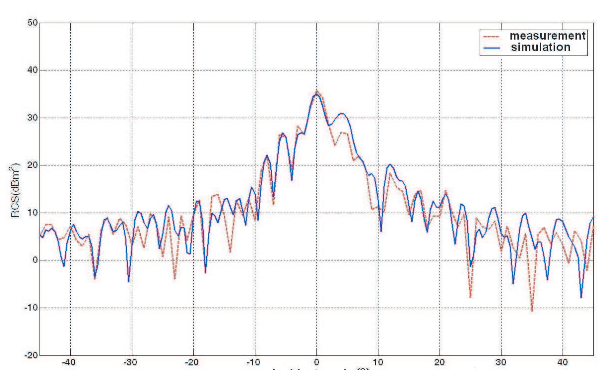

Figure 5: The measurement and simulation RCS plot with the incident angle.

the PM sea spectrum model is 0.29 dB. The research illustrates the sea surface scaled models have feasibility. If the size of the PM spectrum sea surface scaled model is larger, the incident angle range of simulated sea surface backscattering is larger.

4. CONCLUSION

A new method used to simulate sea clutter in laboratory was proposed in this paper. Base on employing the the electromagnetic scaled engineering condition of the sea clutter and the dielectric properties of non-metallic materials construction technique, the composite material to simulate seawater was been constructed by the epoxy mixing metal powder. According to the digital data of the PM spectrum sea surface scaled models. The sea surface waveform of the scaled material was processed by CNC machine. The PM spectrum sea surface scaled model of the sea states 2 was been tailored the backscattering coefficient with the incident angle was been measured and compared the results with theoretical simulation. The compared results verify the feasibility of method proposed basing on scaled simulated sea clutter.

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