An Effective Methodology to Design Scale Model for Microwave Transmitting Composites

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Abstract. In order to solve the problem on designing scale model for microwave transmitting composites, an effective method has been proposed in this manuscript based on the transmission and reflection (TR) coefficients. By optimizing parameters including the number of layers, the thickness and the electromagnetic parameters of each layer, the TR coefficients of designed scale material could be identical with that of the theoretical scale composite. An example is given according to the proposed method by optimizing the TR coefficients as well as only the reflection coefficient and two designed scale materials are obtained. A combined model of a transmitting hemisphere shell and a PEC paraboloid is constructed to verify the validation of the designed scale materials. FEKO is employed to simulate the monostatic radar cross section (RCS) and comparison is performed between the theoretical scale model and the designed scale models. Result reveals that the model including the designed scale material by optimizing the TR coefficients is more consistent with the theoretical scale model than that including the designed scale material by only optimizing the reflection coefficient. This work has important theoretical and practical significance in electromagnetic measurement.

Keywords: Scale model; microwave transmitting composites; TR coefficients; RCS

1. Introduction

The scale measurement has become a significant method to acquire the radar cross section (RCS) of an object because of it many merits such as low cost, excellent controllability and so on [1,2]. The classic scale theory was proposed by J. A. Stratton J. A. Sinclair on the basis of the linear theory of Maxwell’s equations [3,4]. It is that \( \sigma_{\text{scale}} = \sigma_{\text{full}} + 20 \log p \) when the scale system has the same electrical size with the full scale system. Here, \( p \) is the scale ratio, \( \sigma_{\text{scale}} \) is the RCS of the scale model at the scale frequency and \( \sigma_{\text{full}} \) is the RCS of the full scale model at the full scale frequency. In the scale measurement, one of the keys is to construct an accurate scale model. For metallic object or perfect electric conductor (PEC), there is little difficulty in constructing a satisfactory model. However, more and more composites with good electromagnetic loss properties are applied to tailor the scattering characteristic. The composites always have frequency dependent properties [5], which would bring great difficulty to construct the scale material. Some exist studies have given an approximation method to design the scale composite [6~9]. In these studies, composites are placed on metal substrate and then the transmitting wave can be neglected as investigating the scattering properties of an object. Therefore, there is obvious difference from the existing studies when composites are transmitting and without metal substrate.
In this paper, a method is studied by optimizing the transmission and reflection (TR) coefficients. An example is given by the proposed method. In order to verify the designed scale material, a combined model is constructed and monostatic RCS is simulated by FEKO. Furthermore, Comparison is performed between the designed scale model and the theoretical scale model.

2. Methodology Considerations

2.1. Calculating the TR Coefficients of A Multilayer Composite

At the scale frequency, multilayer structure is always used to make the TR coefficients the same with that of the theoretical scale composite. Figure 1 shows the schematic description for calculating the TR coefficients of an n-layer composite irradiated obliquely by plane microwave. The problem can be solved by the transmission-line method and details on derivation procedure can be found in Ref. [10].

\[ T_{total} = 20 \log \left| \prod_{k=0}^{n} T_k \right| \]  \hspace{1cm} (1)

\[ R_{total} = 20 \log \left| \frac{Z_{m,n} - Z_0'}{Z_{m,n} + Z_0'} \right| \]  \hspace{1cm} (2)

in which, \( T_k \) is the transmission coefficient of \( S_k \), \( Z_{m,n} \) the input impedance of the composite, \( Z_0' \) is the impedance of free space as the composite is irradiated obliquely by plane microwave.

On the basis of the above formulae, the scale model of a microwave transmitting composite can be designed by the TR coefficients. By optimizing parameters including the number of layers, the thickness and the electromagnetic parameters of each layer, the TR coefficients can be made as identical as possible with the theoretical scale composite in wide angle range.

2.2. Optimizing the TR Coefficients of the Scale Material

The TR coefficients of a multilayer composite are determined by parameters including the number of layers, the thickness and the electromagnetic parameters of each layer. The optimizing procedure mainly includes the following four steps.

(i) Input data. The data includes the TR coefficients of the theoretical scale composite in wide angle band, and for the designed scale composite, the maximum number of layers, the maximum thickness, the minimum thickness meeting engineering requirement and the number of loop calculations.

(ii) Prepare electromagnetic parameters at the scale frequency. Mix selected inclusion with a binder in different proportions and measure the electromagnetic parameters. Furthermore, fit the measured data by the effective medium theory and obtain the formula for calculating the electromagnetic parameters. Here, the GEMT formula based on the dilution process model [11] is used to fit the measured electromagnetic parameters. The expression is written as follows,
where, $\phi_n$, $\phi$, and $\phi_l$ denote the electromagnetic parameter of the matrix medium and the composite of low and high inclusion concentration, respectively. Both $\phi_n$ and $\phi_l$ are obtained by experimental measurement. $p_n$ and $p_l$ are the inclusion concentrations of the composites of low and high inclusion concentration, respectively. $V$ is a fitting parameter of a great freedom to let the GEMT formula much more flexible. Here, $V = ap_n^2 + bp_l + c$, in which $a$, $b$ and $c$ are dimensionless parameters and obtained by fitting experimental data. After $\phi_n$, $\phi_l$, $a$, $b$ and $c$ are obtained, $\phi$ can be calculated by Eq.(3).

(iii) Perform loop calculations. In each loop calculation, generate parameters including the number of layers, the thickness and the inclusion concentration of each layer by normal distribution random functions. Record these parameters. The electromagnetic parameters of each layer can be calculated by the formulae introduced in step (ii). Calculate the TR coefficients of the multilayer composite in corresponding angle band. Then calculate and record the deviation by comparing with the TR coefficients of the theoretical scale composite. Here, the deviation is defined as follows,

$$\delta^k = \sqrt{\sum_{n=1}^{N} \left[ |T_{n}^k - T_{n}^{Theo}|^2 + |R_{n}^k - R_{n}^{Theo}|^2 \right]}$$

where $N$ are the number of incident angles; $T_{n}^k$, $R_{n}^k$, $T_{n}^{Theo}$ and $R_{n}^{Theo}$ are elements of the TR coefficients of the $k$th calculation and the theoretical scale composite, respectively.

(iv) Search the optimal result. After the loop calculations, find out the minimum deviation and obtain the corresponding configuration parameters of the optimal scale absorber, which include the number of layers, the thickness and the inclusion concentration of each layer.

3. Results and Discussions

Here an example is given to verify the validation of the proposed method. The full scale frequency is 1.0 GHz, at which, a transmitting composite has a thickness of 10.0 mm and its permittivity and permeability are 14.49-0.12 $j$ and 3.56-1.12 $j$, respectively. Then the scale frequency is 10 GHz as the scale ratio is 1:10. The theoretical scale composite has the same electromagnetic parameters with the full scale composite but its thickness is 1.0 mm. Here TE wave is just taken into account.
electromagnetic parameters of the as-prepared mixtures could be measured by transmission/reflection method [12]. Then fit the measured electromagnetic parameters according to step (ii) in section 2.2. The calculated result is plotted in Figure 2. It can be seen that there is an excellent agreement between the calculated results and the measured data. Then electromagnetic parameters of a mixture of any inclusion concentration can be calculated by the fitting formulae.

According to the optimized procedure in section 2.2, the designed scale material is obtained and assigned as M01. Besides, another designed scale material is obtained by only optimizing the reflection coefficient instead of the TR coefficients and assigned as M02. Table 1 gives the related information of M01 and M02.

Table 1. The designed scale materials.

|       | Permittivity   | Permeability  | Thickness | Inclusion concentration |
|-------|----------------|---------------|-----------|-------------------------|
| M01   | 5.36 - 0.09 j  | 1.20 - 0.51 j | 2.3 mm    | 21vol%                  |
| M02   | 7.36 - 0.12 j  | 1.24 - 0.70 j | 1.2 mm    | 27vol%                  |

Figure 3 plots the TR coefficients of M01 and M02. It can been seen that the transmission property of M01 agrees well with the theoretical scale composite at any incident angle, while there is an obvious deviation between M02 and the theoretical scale composite. As the incident angle is small, about <20°, the reflection property of M01 and M02 both agree well with the theoretical scale composite, while the incident angle is in about 20°~80°, there is a little deviation between the both designed scale materials and the theoretical scale composite.

In order to verify the designed result, the commercial software FEKO is employed to simulate the monostatic RCS of a combined model of a transmitting hemisphere shell and a PEC paraboloid. The symmetric axis of the PEC paraboloid and the hemisphere shell are the same, and the peak point of the PEC paraboloid is located at the centre of the hemisphere shell. The theoretical scale hemisphere shell has a radius of 50 mm and a thickness of 1.0 mm; the radii of the designed scale shell M01 and M02 are also 50 mm, but the thicknesses are 2.3 mm and 1.2, respectively. The PEC paraboloid reflects the transmitting wave back. The focal depth and radius of the PEC paraboloid are both 30 mm. This combined model includes many electromagnetic scattering mechanisms such as specular-reflection, multiple-reflection, creeping wave scattering and so on. Figure 4 shows the simulated results. It can be seen there are similar change tendency and some deviation between the design scale models and the theoretical scale model. But the deviation of M01 is much smaller than M02. The mean deviation of M01 and M02 are 0.79 dB and 1.13 dB, respectively. The deviations are within the RCS measurement tolerance.
4. Conclusions

In this paper, an effective method based on the TR has coefficients been proposed to solve the problem on designing scale model for microwave transmitting composites and the optimizing procedure has been introduced. An example is given according to the proposed method by optimizing TR coefficients as well as only the reflection coefficient and two designed scale materials are obtained. A combined model of a transmitting hemisphere shell and a PEC paraboloid is employed to verify the validation of the designed result. The monostatic RCS of these models are simulated by the commercial software FEKO and comparison is performed between the theoretical scale model and the designed models. Result reveals that the model including the designed material by optimizing the TR coefficients is more consistent with the theoretical scale model than that including the designed material by only optimizing the reflection coefficient. Meanwhile, the method can break the limitation of physical and geometrical parameters by the absolute scale theories. This work will have important theoretical and practical significance in electromagnetic measurement.

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