An equivalent scattering method for a novel cellular medium

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ABSTRACT A new novel structure is proposed for cellular composite radar absorbing materials, and an equivalent method of electromagnetic scattering for the new material is also proposed for the first time. By covering the target surface with non-uniform medium cellular cell elements horizontally, the scattering characteristics of the coated target show strong surface anisotropy, leaving an imaginary space for optimizing the electromagnetic stealth performance of the coated target. In this paper, the equivalent dielectric tensor of horizontal directional composite honeycomb cell element has been calculated by using the equivalent method of electromagnetic scattering based on strong fluctuation theory (SFT) of anisotropic medium. Under the condition of plane wave irradiation with a frequency of 3 GHz, we use FEKO software to estimate the backscatter field of several typical models coated with this new structure. It has been proved that the strong fluctuation theory applied to the honeycomb composite absorbing material of the structure are effective for calculating the equivalent scattering. Based on the validity of the equivalent results, we further estimate the scattering characteristics of complex targets coated with the novel cellular medium.

INDEX TERMS Effective permittivity, equivalent scattering, strong fluctuation theory (SFT), anisotropic dielectric coating targets.

I. INTRODUCTION

Honeycomb structures are widely used to construct stealth materials due to their lightweight and strong properties. In addition, honeycomb composites coated with metal magnetic powder have strong electromagnetic energy absorption capabilities. It supports honeycomb composites as an important candidate weapon for a series of weapon systems to make them less obvious on enemy radar or ideally invisible [1]. Therefore, in recent decades, the radar scattering characteristics of honeycomb composite absorbing materials have been studied extensively [2,3]. After that, the influence of the formation of honeycomb core structure on scattering characteristics has been further study [4,5]. Figure 1 (a) shows the traditional honeycomb unit. Its cross-section forms a regular Hexagon. The length of the hexagon is equal, the angles connecting the adjacent surfaces are fixe. Figure 1 (b) is shown as a honeycomb with different angles within the cross-section. Figure 1 (c) is shown as a honeycomb with a graded gradient of the thickness of the longitudinal section inner wall coating. Many previous studies that have both theoretical and experimental results have shown that the shape of the honeycomb unit itself has a very significant influence on the electromagnetic scattering characteristics of coated targets [6,7,8].

However, it has never been researched the influence of the coating layout of honeycomb composites on electromagnetic properties. As shown in Figure 2 (a), the principal axis \( \hat{z} \) of the coated object is consistent with the propagation direction in most previous anisotropic studies [9-13]. In this case, the two dielectric constant components in the direction perpendicular to the direction of propagation are equal. The dielectric constant tensor is (1).

\[
\bar{\varepsilon}_{\text{eff}} = \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix} = \begin{bmatrix} \varepsilon_{\text{eff}} & 0 & 0 \\ 0 & \varepsilon_{\text{eff}} & 0 \\ 0 & 0 & \varepsilon_{\text{eff}} \end{bmatrix}
\]

From equation (1), we can see that there are two equal dielectric components in the two diameter directions (\( \hat{x}, \hat{y} \)) and one different component in the propagation direction (\( \hat{z} \)), which means the electromagnetic properties on the surface of the coating target are indeed isotropic. On the other hand, the component in the direction of \( \hat{z} \) axis is usually small. Finally, the total scattering of coating targets is
not sensitive to this surface anisotropic media [14]. As a consequence, the research of honeycomb materials with conventional layout of cell structure has little significance for anisotropy. To overcome this difficulty, we present a new coating layout of honeycomb composite material. In this condition, we study the equivalent dielectric tensor and scattering characteristics of the complex coating target. As shown in Figure 2 (b), cellular cells horizontally lay on the target surface. The honeycomb cross-sectional optical axis $\hat{y}$ is perpendicular to the honeycomb cell surface but parallel to target surface. Its effective dielectric constant tensor can be expressed as equation (2).

$$\varepsilon_{\text{eff}} = \begin{bmatrix} \varepsilon_{\text{eff}} & 0 & 0 \\ 0 & \varepsilon_{\text{eff}} & 0 \\ 0 & 0 & \varepsilon_{\text{eff}} \end{bmatrix}$$ (2)

From equation (2), there are two unequal dielectric constant components in two diameter directions perpendicular to the optical axis $\hat{y}$. The target model coated with this layout honeycomb material will provide us with reference raw data for verifying the validity of the electrical parameters equivalent for its strong target surface anisotropy.

Honeycomb composites are usually composed of a variety of dielectric materials such as skeleton materials and absorbing coating materials. It is very difficult to simulate the scattering field by directly establishing the honeycomb coating target model. Therefore, it is necessary to calculate the equivalent dielectric constant tensor in order to understand the target scattering characteristics of the coated honeycomb composite. Homogenization is a common and effective way to obtain equivalent dielectric constant tensor and analyze its characteristics. As early as a few years ago, Maxwell Garnett [15], Bruggeman [16], and Polds-Poldner [17] proposed an effective medium theory. With their elegant and extensive mixing formulas, they have made outstanding contributions to homogenization. However, these methods are based on the propagation of electromagnetic waves, but the scattering equivalent method has never been reported. In order to extend the homogenization method to the scattering, we propose a set of solution for equivalent scattering prediction of targets coated with transverse honeycomb composites. Numerical results obtained in the high frequency band validate the effectiveness of this method.

In short, we believe that there are three novelty of the contribution in our paper. First, we propose a novel method for the construction of honeycomb materials. Second, we propose a set of solution for equivalent scattering prediction of targets coated with transverse Honeycomb composites. We validated the effectiveness of this method in the high frequency band. Third, we have studied the electromagnetic scattering characteristics of complex targets coated horizontally. II. THE STRONG FLUCTUATION THEORY OF HONEYCOMB COMPOSITES

The effective permittivity tensor of the scattering anisotropic medium will be calculated in this section for the honeycomb composites with the strong fluctuation theory. Figure 3 (a) shows the hexagonal section of a single honeycomb structure core. It consists of three layers of medium: aromatics paper frame, vacuum and absorbent material. Refer to Figure 3 (a), the effective permittivity of cellular cells is determined entirely by geometric parameters, electrical parameters, permittivity of aromatic paper frames, and the complex dielectric constant of absorbing coatings.

We assume that $\varepsilon_0$ is the permittivity of honeycomb vacuum, $\varepsilon_a$ is the complex relative permittivity of RAM which usually employed metal magnetic micro powder(MMP) for its high wave absorption, $\varepsilon_b$ is the permittivity of the aramid paper frame [24]. It can be approximately considered as an equivalent elliptical particle [25,26,27] as seen in Figure 3. Then, we can treat the honeycomb composite as a two-phase medium with phase I the effective medium of honeycomb frame and vacuum, and phase II the RAM coating. Assuming phase I the host medium with a permittivity $\varepsilon_a$ and phase II the embedded ellipsoidal particles with $\varepsilon_b$. The effective permittivity of a heterogeneous medium is composed of a quasi-static part and a scattering effect part which corresponds for the attenuation...
in wave amplitude and the modification in wave speed due to the non-uniformity, respectively. In the following expression

$$\mathbf{\bar{e}}_{\text{off}} = \mathbf{e}_g + e_0 (\mathbf{T} \cdot \mathbf{\bar{S}}) \mathbf{e}_g' \mathbf{S}_g'^{-1} \mathbf{e}_g'$$

(3)

where $\mathbf{T}$ is the unit dyad, $e_0$ is the permittivity of free space, $\mathbf{\bar{e}}_g = \text{diag}[\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3]$ is an auxiliary permittivity, and $\mathbf{\bar{S}} = \text{diag}[s_1, s_2, s_3]$ is the average dyadic correlation coefficient in the global coordinates. In this model, they can be express as

$$\mathbf{\bar{e}}_g = \begin{bmatrix} e_g & 0 & 0 \\ 0 & e_g & 0 \\ 0 & 0 & e_g \end{bmatrix}$$

(4)

$$\mathbf{\bar{S}} = \begin{bmatrix} s_g & 0 & 0 \\ 0 & s_g & 0 \\ 0 & 0 & s_g \end{bmatrix}$$

(5)

For a medium containing $N$ species, under the condition of $[\mathbf{\bar{e}}_{\text{off}}]_{pm} \ll 1$, the effective dyadic scatter $\mathbf{\bar{e}}_{\text{off}}$ is given by

$$\mathbf{\bar{E}}_{\text{off}} = \sum_{i=1}^{N} k_0 \int_{0}^{2\pi} d\gamma \int_{0}^{2\pi} d\alpha \int_{0}^{1} \rho_{\text{ijkl},p} d\rho_{p} \mathbf{p}(\alpha, \beta, \gamma) \mathbf{\Gamma}_{ij}^{(0)} \mathbf{\Phi}_{i}(\mathbf{\bar{k}}) \mathbf{S}_{ij}^{(0)} \mathbf{\bar{S}}_{ijkl}$$

(6)

In (6), subscript $i$ stands for species $i$, $k_0$ is the wave number in free space, $\mathbf{\Gamma}_{ij}^{(0)}$ is the variance of the scattering fluctuations, $\mathbf{\bar{S}} = \text{diag}[s_1, s_2, s_3]$ is the local dyadic coefficient, and $p(\alpha, \beta, \gamma)$ is the probability density function of orientations given by Eulerian rotation tensor (7).

$$\mathbf{\bar{T}} = \begin{bmatrix} \cos \beta & 0 & -\sin \beta \\ 0 & 1 & 0 \\ \sin \beta & 0 & \cos \beta \end{bmatrix}$$

(7)

In this model, the random orientation distribution of the multi species scatters is simply related to $\beta$. Therefore, the probability density function of orientation is shown as (8).

$$p(\alpha, \beta, \gamma) = p(\beta) = \pi/2$$

(8)

The anisotropic Green’s function $\mathbf{G}_g$ which is invariant under the Eulerian rotation of the $z$ axis is expressed in the wave-vector $\mathbf{k}$ domain. Auxiliary permittivity $\mathbf{\bar{e}}_g$ and dyadic coefficient $\mathbf{\bar{S}}$ is determined by the condition of secular-term elimination. The size and shape of scatter species $i$ is described with the Fourier transform $\mathbf{\Phi}_{i}(\mathbf{\bar{k}})$ of the normalized local correlation function of the form (9)

$$R_i(\mathbf{\bar{k}}) = \exp\left(\frac{1}{2} \frac{x^2}{E_x} + \frac{y^2}{E_y} + \frac{z^2}{E_z} \right)$$

(9)

in which $l_x$, $l_y$, and $l_z$ are three different correlation lengths in the local coordinates corresponding to the minor, the meridian, and the major axes of an ellipsoidal scatter of species $i$. The local principal coordinate system $(x', y', z')$ of an ellipsoid is related to the global coordinate system $(x, y, z)$ by Eulerian rotation tensor. Applying the Fourier transform, $\Phi_i(\mathbf{\bar{k}})$ can be rewritten as (10) for ellipsoids.

$$\Phi_i(\mathbf{\bar{k}}) = \frac{l_x l_y l_z}{\pi^2 (1 + k_x^2 l_x^2 + k_y^2 l_y^2 + k_z^2 l_z^2)}$$

(10)

To calculate the effective permittivity tensor according to (3), $\mathbf{\bar{e}}_g$ and $\mathbf{\bar{S}}$ are needed to be determined. Because of the global symmetry by the $x$ axis, auxiliary permittivity in coordinate is uniaxial, as indicated previously, and the elements in $\mathbf{\bar{e}}_g$ are subject to the condition $<\mathbf{\bar{e}}_g> = 0$ such that

$$<\mathbf{\bar{e}}_g> = \frac{1}{8} \int d\beta \mathbf{p}(\beta) \mathbf{T} \begin{bmatrix} \mathbf{\bar{e}}_{x'} & 0 & 0 \\ 0 & \mathbf{\bar{e}}_{y'} & 0 \\ 0 & 0 & \mathbf{\bar{e}}_{z'} \end{bmatrix}$$

(11)

with $i = 1, \ldots, N$. And single effective dyadic scatter $\mathbf{\bar{e}}_i$ is also given by (12).

$$\mathbf{\bar{e}}_i = \left( \frac{\mathbf{I} - \mathbf{\bar{S}}}{e_0} \right)^{-1} \left[ \begin{array}{c} \mathbf{\bar{e}}_{x'} \\ \mathbf{\bar{e}}_{y'} \\ \mathbf{\bar{e}}_{z'} \end{array} \right]$$

(12)

The subscript $i$ denotes scatter species $i$. $\mathbf{\bar{e}}_i$ can take on the value of $\mathbf{\bar{e}}_i$ in a scatter or $\mathbf{\bar{e}}_0$ in the background medium. Local quantities $\mathbf{\bar{e}}_{x'}$, $\mathbf{\bar{e}}_{y'}$ and $\mathbf{\bar{e}}_{z'}$ are related to the elements of dyadic coefficient $\mathbf{\bar{S}} = \text{diag}[s_1, s_2, s_3]$ by (13)(14)(15).

$$\mathbf{\bar{e}}_{x'} = \frac{\mathbf{\bar{e}}_i - \mathbf{\bar{e}}_0}{\mathbf{\bar{e}}_0 + s_1 (\mathbf{\bar{e}}_0 - \mathbf{\bar{e}}_i)}$$

(13)

$$\mathbf{\bar{e}}_{y'} = \frac{\mathbf{\bar{e}}_i - \mathbf{\bar{e}}_0}{\mathbf{\bar{e}}_0 + s_2 (\mathbf{\bar{e}}_0 - \mathbf{\bar{e}}_i)}$$

(14)

$$\mathbf{\bar{e}}_{z'} = \frac{\mathbf{\bar{e}}_i - \mathbf{\bar{e}}_0}{\mathbf{\bar{e}}_0 + s_3 (\mathbf{\bar{e}}_0 - \mathbf{\bar{e}}_i)}$$

(15)

From (11)(12)(13)(14)(15), $\mathbf{\bar{e}}_i$ and $\mathbf{\bar{e}}_{y'}$ can be written as (16) and (17).
Figure 4 (a) gives an algorithm for calculating the static dielectric constant tensor. In addition, the process of obtaining the scattering equivalent dielectric constant tensor is shown in Figure 4 (b). The sum of the two is the equivalent dielectric constant tensor.

\[
e_{\text{eff}} = e_{\text{a}} + f_s \frac{e_s - e_{\text{a}}}{1 - f_s} + 2e_{\text{a}} + (s_x + s_y)(e_s - e_{\text{a}}) \\
e_{\text{a}} + s_x(e_s - e_{\text{a}}) e_{\text{a}} + s_y(e_s - e_{\text{a}}) \\
e_{\text{a}} + s_x(e_s - e_{\text{a}}) e_{\text{a}} + s_y(e_s - e_{\text{a}}) \\
(16)
\]

\[
e_{\text{eff}} = e_{\text{a}} + f_s \frac{e_s - e_{\text{a}}}{1 - f_s} + 2e_{\text{a}} + (s_x + s_y)(e_s - e_{\text{a}}) \\
e_{\text{a}} + s_x(e_s - e_{\text{a}}) e_{\text{a}} + s_y(e_s - e_{\text{a}}) \\
(17)
\]

III. WERIFICATION OF EQUIVALENT SCATTERING

In this section, we calculate the equivalent dielectric constant tensor of a set of transverse honeycomb coated materials by using strong fluctuation scattering equivalence theory. The radar cross-section (RCS) of the honeycomb lateral coating model and the equivalent uniform coating model are calculated by FEKO software. Then the effectiveness of the equivalent method is verified effective by comparing the match between the RCS of the honeycomb coating model and the equivalent uniform coating model. Here, permittivity constants are \( e_{\text{a}} = 1.0 \), \( e_{\text{b}} = 4.0 \), \( e_{\omega} = 15.0 - j10.0 \) for free space, frame and MMP respectively. Assume the permeability of them are \( \mu_{\text{a}} = \mu_{\text{b}} = \mu_{\omega} = 1.0 \). Table I shows equivalent dielectric constant tensors achieved by different volume fractions of MMP on 3GHz.

### TABLE I

| \( f \) (%) | \( e_{\text{eff}} \) | \( e_{\text{eff}} \) | \( e_{\text{eff}} \) |
|-----------|----------------|----------------|----------------|
| 0.05      | 2.6478-0.8737j | 1.7424-0.0140j | 2.6478-0.8737j |
| 0.1       | 3.7965-1.5499j | 1.9807-0.0456j | 3.7965-1.5499j |
| 0.15      | 4.8032-2.1415j | 2.3163-0.1168j | 4.8032-2.1415j |
| 0.2       | 5.7063-2.6781j | 2.7854-0.2726j | 5.7063-2.6781j |
| 0.25      | 6.5256-3.1713j | 3.4072-0.5788j | 6.5256-3.1713j |
| 0.3       | 7.2728-3.6267j | 4.1661-1.0810j | 7.2728-3.6267j |
| 0.35      | 7.9551-4.0470j | 5.0283-1.7595j | 7.9551-4.0470j |
| 0.4       | 8.8276-4.4339j | 5.9569-2.5422j | 8.8276-4.4339j |

A. NUMERICAL RESULTS OF TABLETS

The flat plate model of honeycomb composite material with absorption layer space ratio is selected. The honeycomb flat plate with different sizes and its equivalent uniform flat plate is figured in FEKO software. The far scattering field (normalized to RCS) of honeycomb flat plate and its equivalent uniform flat plate irradiated by plane wave is calculated by the method of moments (MOM). Then, the scattering field of honeycomb flat plate and equivalent uniform flat plate is compared. To verify the effectiveness of the equivalent method, we calculated the original non-uniform honeycomb plate and the equivalent uniform plate model as shown in Figure 5 (a).
Figure 5(a) is a model of honeycomb tablet. 20 honeycomb cells are arranged transversely in the axis direction, and 10 groups of honeycombs are arranged head to tail in the axis direction, forming a honeycomb tablet as a whole. It is equivalent to a uniform tablet as shown in Figure 5 (b). The size of the equivalent uniform tablet is still the same, and irradiation angles of the incident wave at 3 GHz are as follows: A) Azimuth =0 and elevation changes from 0 to 90; B) Azimuth =90 elevation changes from 0 to 90. When the duty cycle of the absorbing layer is equal, Figure 6 shows the single station RCS of the tablet when the volume fraction of MMP is equal to 0.4. Figure 6 (a) and Figure 6 (b) are the comparison of single-station RCS of meridian plane and meridian plane respectively. It is not difficult to see that the single-station scattering RCS of the original honeycomb plate and the equivalent uniform plate can be well matched on both meridian planes, whether VV polarization or HH polarization. We can effectively obtain the scattering field of the original honeycomb model by predicting the scattering field of the equivalent flat plate, which shows that the scattering field of the original honeycomb model. In other words, the equivalent dielectric constant can be used to replace the original inhomogeneous honeycomb tablet while the expected scattering field remains unchanged.

**B. NUMERICAL RESULTS OF CYLINDERS**

In addition to flat tablets, we are also concerned about whether we can obtain an equivalent uniform scattering field model when non-uniform honeycomb materials build other targets. Figure 7 (a) is a schematic diagram of a honeycomb coated horizontally on a cylinder. The homogenized uniform cylinder shown as Figure 7 (b). Its equivalent plate dielectric constant is $\varepsilon_{\text{eff}} = \text{diag}(8.83 - 4.43 j, 5.96 - 2.54 j, 8.83 - 4.43 j)$.

Figure 8 is a comparison of RCS of honeycomb cylinder and equivalent uniform cylinder in two equivalent cases. We can see that the RCS of honeycomb cylinder is in good agreement with that of original honeycomb cylinder except for a few very small angles of RCS. It denotes that the non-uniform cylinder formed by honeycomb composite material is effective to be equivalent to a homogeneous cylinder. From the numerical results, it can be seen that it is effective to replace the original complex mixed model with the uniform model of equivalent electromagnetic parameters by the strong fluctuate medium equivalence theory, and to expect the scattering field to remain unchanged, no matter the shape of non-uniform composite materials such as plate, cylinder. In addition, the RCS obtained by irradiation of the honeycomb model with the same incident wave at different azimuth angles is obviously different, which proves that the scattering characteristics of the target of the horizontally coated honeycomb material have strong anisotropy.

Table II shows some details and the runtime performances of different methods for two models. Thanks to the homogenization of non-uniform honeycomb media, calculated iterations of original models were greatly reduced by more than 90 percent. It is shown that faster convergence of our approach is obtained as compared to MOM-FEKO in both cases. Consequently, our proposed homogeneous scattering equivalence method requires less CPU times.
FIGURE 8. (a) Single station RCS of honeycomb cylinder compare with equivalent cylinder. Azimuth =0 and elevation angle changes from 0 to 180.

FIGURE 8. (b) Single station RCS of honeycomb cylinder compare with equivalent cylinder. Azimuth =90 and elevation angle changes from 0 to 180.

TABLE II
EFFECTIVE PERMITTIVITY OF HORIZONTAL HONEYCOMB

| Model       | Number of unknowns | CPU time |
|-------------|--------------------|----------|
| MOM-FEKO   | Method in this paper | MOM-FEKO Method in this paper |
| Tablet      | 30 860             | 2 534    | 485.56 s | 31.34 s |
| Cylinder    | 78 092             | 5 198    | 793.27 s | 53.91 s |

IV. SCATTERING OF ELECTRIC-LARGE SIZE COMPLEX TARGETS COATED HORIZONTALLY WITH HONEYCOMB

Honeycomb composites usually use on electrical-large size complex non-uniform complex shape targets. In this section, we study the scattering characteristics of complex targets with transverse honeycomb coating. The method of physical optics has obvious advantages because of its speed and effectiveness in obtaining RCS of complex coated targets. We will use physical optics to estimate the scattering field of complex targets coated with transverse honeycomb composites. All the simulation results in this section are obtained by using H Feel which a piece of high-frequency prediction software independently developed by the Electromagnetic Engineering Laboratory of Wuhan University in China.

The plates, spheres, cylinders and cones in Figure 9 are ideal conductor scattering targets for large electrically coated honeycomb composites. The wavelength of the incident wave is represented by \( \lambda \), Select a flat plate with a side length of 50\( \lambda \), a sphere with a radius of 10\( \lambda \), a cylinder with a section radius of 10\( \lambda \) and a cone with a base radius of 10\( \lambda \) with a height of 30\( \lambda \) as our subject. The vacancy ratio of the absorbing material in the honeycomb material is 0.4. Its equivalent dielectric constant tensor is

\[
\varepsilon_{\text{eff}} = \text{diag}(8.83 - 4.43j, 5.96 - 2.54j, 8.83 - 4.43j)
\]

Figure 10 shows single-station RCS of PEC scattering targets coated with honeycomb material by the irradiation of incident plane wave of 3GHz. From the numerical results shown in Figure 10, we can see these characteristics: Almost all HH-polarized scattering fields at the same angle do not coincide with VV-polarized scattering fields. In other words, under the same incident wave angle, The RCS obtained by polarization direction of different electric fields are very different. Therefore, we can conclude that the scattering of these models exhibits anisotropy in the direction of V polarization and H polarization, that is, ideal conductor targets of horizontally coated honeycomb composites have a strong scattering surface anisotropy. The results are consistent with our predictions. Let us pay attention to the example of the cylinder. As shown in Figure 10(c), it is a single-station RCS curve of the coated cylinder at the incident plane wave of 3GHz with the observation plane of elevation angle. The wave peaks correspond to the contribution of scattering fields from the top, side and bottom of the coated cylindrical surface, respectively. Under different polarization plane waves, when the elevation angles are located in the range of 0 to 60 and 120 to 180, the RCS at the same azimuth angle is not equal, reflecting the anisotropy characteristics. At the same time, at the elevation angle of 60 to 120, the RCS with azimuth angle = 0 and the RCS with azimuth angle = 90 are roughly the same. The reason for this situation is that the dielectric constant component parallel to the plane of the elevation angle is inconsistent in different elevation angles ranges. The range difference of this parameter refers to the coating...
direction. On the one hand, the honeycomb coat on the surface of the column along the wall. The hexagonal section of the honeycomb is parallel to the bottom surface of the column. On the other hand, the honeycomb lies horizontally on the bottom surface of the column and its hexagonal section is perpendicular to the bottom surface of the column. It means that the coating direction of the transverse honeycomb can also affect RCS. What’s more, it is proved from the side that the lateral coating of the honeycomb material can produce strong scattering anisotropy of the target.

**FIGURE 10.** (a) Single station RCS in the meridian plane of the coated flat plate.

**FIGURE 10.** (b) Single station RCS in the meridian plane of the coated sphere.

**FIGURE 10.** (c) Single station RCS in cylindrical meridian plane of the coated cylinder.

**FIGURE 10.** (d) Single station RCS in the conical meridian plane of the coated cone

Figure 11 is a missile coated with transverse honeycomb material. Its bottom radius =10λ, body length =53λ, tail length =3.5λ and coating thickness =0.1λ. The equivalent dielectric constant tensor of honeycomb material is 

\[
\mathbf{\varepsilon} = \text{diag}(8.83 - 4.43 j, 5.96 - 2.54 j, 8.83 - 4.43 j)
\]

**FIGURE 11.** Missile coated with honeycomb material.

Figure 11 (a) shows single-station RCS obtained by irradiation of a plane wave with a frequency of 3 GHz from the missile warhead to the missile tail to the missile warhead on the x-o-z plane (the azimuth = 0, pitch angle changes from 0 to 360). Figure 11(b) shows the missile single station RCS obtained on the y-o-z plane (the azimuth = 90, pitch angle changes from 0 to 360). From this, RCS is extremely sensitive to the polarization direction of incident waves. At almost all incident angles, the change in the polarization direction of the incident wave inevitably causes a change in the RCS, which means that the scattering of the missile horizontally coat with honeycomb material has a clear anisotropy.

**FIGURE 11.** (a) RCS in x-o-z plane of missile coated with honeycomb material.
In this paper, the high frequency estimation method based on strong fluctuation scattering equivalence theory is proposed to solve the problem of complex honeycomb coating scattering prediction in bulk. The simulation results show that it is effective to replace the target coated with the effective electromagnetic parameter model and expect the scattering field to remain unchanged. It can be expected that this set of solutions will greatly facilitate the scattering estimation of complex coated targets. For the first time, we present the method of lateral coating honeycomb, and proved the anisotropy of strong scattering surface in numerical results, and expanded the coating method to provide an application idea for hiding the scattering characteristics of coated targets.

In the future, we will further explore the reliability of the strong fluctuation scattering equivalence theory on the scattering equivalence of other complex coated materials. The scattering characteristics of complex targets with more transverse coating of honeycomb materials are also worthy of further study. In addition, the absorbing efficiency of the honeycomb medium of this structure and how to improve the absorbing efficiency will also be our focus direction.

REFERENCES

[1] F. C. Smith and F. Scarpa, “Design of honeycomb-like composites for electromagnetic and structural applications,” Sci. Meas. Technol. IEE Proc., vol. 151, pp. 9–15, Feb. 2004, doi: 10.1049/ip-smt:20030851.

[2] A. A. Khurram, N. Ali, S. A. Rakha, P. Zhou, and A. Munir, “Optimization of the Carbon Coating of Honeycomb Cores for Broadband Microwave Absorption,” IEEE Trans. Electromagn. Compat., vol. 56, no. 5, pp. 1061–1066, 2014, doi: 10.1109/TEMCC.2014.2311294.

[3] H. Luo et al., “Preparation and microwave absorption properties of honeycomb core structures coated with composite absorber,” AIP Adv., vol. 8, p. 56635, May 2018, doi: 10.1063/1.5005163.

[4] Z. Sun, S. Shi, and H. Chen, “On compressive properties of composite sandwich structures with grid reinforced honeycomb core,” Compus. Part B Eng., vol. 94, Mar. 2016, doi: 10.1016/j.compositesb.2016.03.054.

[5] Y. Li et al., “Electromagnetic and acoustic double-shielding graphene-based metamaterials,” Nanoscale, vol. 11, Jan. 2019, doi: 10.1039/C8NR06143B.

[6] Y. He, R. Gong, H. Cao, X. Wang, and Y. Zheng, “Preparation and microwave absorption properties of metal magnetic micropowder-coated honeycomb sandwich structures,” Smart Mater. Struct., vol. 16, p. 1501, Jul. 2007, doi: 10.1088/0964-1726/16/5/001.

[7] Y. He and R. Gong, “Preparation and microwave absorption properties of foam-based honeycomb sandwich structures,” EPL (Europhysics Lett.), vol. 85, p. 58003, Mar. 2009, doi: 10.1209/0295-5075/85/58003.

[8] P. Zhou, L. Huang, J. Xie, D. Liang, H. Lu, and L. Deng, “Prediction of Microwave Absorption Behavior of Grading Honeycomb Composites Based on Effective Permittivity Formulas,” IEEE Trans. Antennas Propag., vol. 63, no. 8, pp. 3496–3501, 2015, doi: 10.1109/TAP.2015.2431721.

[9] J. M. V. A. Koelman and A. Kuijper, “An effective medium model for the electric conductivity of an N-component anisotropic percolating mixture,” Phys. A Stat. Mech. its Appl., vol. 247, pp. 10–22, Dec. 1997, doi: 10.1016/S0378-4371(97)00385-3.

[10] T. Mackay, A. Lakhktia, and W. Weigelhofer, “Third-order implementation and convergence of the strong-property-fluctuation theory in electromagnetic homogenization,” Phys. Rev. E Stat. Nonlin. Soft Matter Phys., vol. 64, p. 66616, Jan. 2002, doi: 10.1103/PhysRevE.64.066616.

[11] A. J. Duncan, T. G. Mackay, and A. Lakhktia, “The homogenization of orthorhombic piezoelectric composites by the strong-property-fluctuation theory,” J. Phys. A, vol. 42, no. 16, p. 165402, 2009.

[12] B. Jasiok, E. Postnikov, and M. Chorazewski, “The prediction of high-pressure densities of different fuels using fluctuation theory-based Tait-like equation of state,” Fuel, vol. 219, pp. 176–181, May 2018, doi: 10.1016/j.fuel.2018.01.091.

[13] C. Liu, E. R. Moog, and S. D. Bader, “Polar Kerr-effect observation of perpendicular surface anisotropy for ultrathin ferromagnetic films: fcc Fe/Cu(100),” J. Appl. Phys., vol. 64, no. 10, pp. 5325–5327, 1988.

[14] J. C. M. Garnett, “Colours in Metal Glasses, in Metallic Films, and in Metallic Solutions. II,” Philos. Trans. R. Soc. A, vol. 205, pp. 237–288, 1906.

[15] R. Kampa and A. Lakhktia, “Bruggeman Model for Chiral Paniculate Composites,” J. Phys. D. Appl. Phys., vol. 25, p. 1390, Apr. 2000, doi: 10.1088/0022-3727/25/10/002.

[16] D. Polder and J. H. Santeen, “The effective permeability of mixtures of solids,” Physica, vol. 12, pp. 257–271, Jan. 1946, doi: 10.1016/S0031-8914(46)80066-1.

[17] W. M. Merrill and N. G. Alexopoulos, “Propagation within fractal composite systems with strong permittivity fluctuations,” in IEEE Antennas and Propagation Society International Symposium 1997. Digest, 1997, vol. 4, pp. 2568–2571 vol.4, doi: 10.1109/APS.1997.625526.

[18] A. Stogryn, “A note on the singular part of the dyadic Green’s function in strong fluctuation theory,” Radio Sci., vol. 18, no. 6, pp. 1283–1286, Nov. 1983, doi: 10.1029/RS018i006p01283.

[19] J.-W. Hu, S.-Y. He, Z.-M. Rao, G.-Q. Zhu, and H.-C. Yin, “Effective Electromagnetic Parameters and Absorbing Properties for Honeycomb Sandwich Structures with a Consideration of the Disturbing Term,” Chinese Phys. Lett., vol. 30, no. 10, p. 107702, 2013, doi: 10.1088/0256-307X/30/10/107702.

[20] D. Shamoon, S. Lasquellec, and C. Brosseau, “Low-order statistics of effective permittivity and electric field fluctuations in two-phase heterogeneous structures,” J. Appl. Phys., vol. 122, no. 4, p. 44106, Jul. 2017, doi: 10.1063/1.4955799.

[21] C. Bedard and A. Desterche, “Kramers-Kronig Relations and the Properties of Conductivity and Permittivity in Heterogeneous Media,” J. Electromagn. Anal. Appl., vol. 10, Jan. 2018, doi: 10.4236/jema.2018.102003.

[22] S. Tu et al., “Enhancement of Dielectric Permittivity of Ti 3 C 2 T x MXene/Polymer Composites by Controlling Flake Size and Surface Termination,” ACS Appl. Mater. Interfaces, vol. 11, Jul. 2019, doi: 10.1021/acsami.9b09137.

[23] Y.-F. He, R.-Z. Gong, X. Wang, and Q. Zhao, “Study on equivalent electromagnetic parameters and absorbing properties of honeycomb-
structured absorbing materials,” Acta Phys. Sin. -Chinese Ed., vol. 57, pp. 5261–5266, Aug. 2008.

[24] L. Tsang and J. A. Kong, “Scattering of electromagnetic waves from random media with strong permittivity fluctuations,” Radio Sci., vol. 16, no. 03, pp. 303–320, 1981, doi: 10.1029/RS016i003p00303.

[25] Lueng Tsang, Jin Kong, and R. Newton, “Application of strong fluctuation random medium theory to scattering of electromagnetic waves from a half-space of dielectric mixture,” IEEE Trans. Antennas Propag., vol. 30, no. 2, pp. 292–302, 1982, doi: 10.1109/TAP.1982.1142774.

[26] S. V Nghiem, R. Kwok, J. A. Kong, and R. T. Shin, “A model with ellipsoidal scatterers for polarimetric remote sensing of anisotropic layered media,” Radio Sci., vol. 28, no. 05, pp. 687–703, 1993, doi: 10.1029/93RS01605.

[27] J. Yao, S. He, Y. Zhang, H. Yin, C. Wang, and G. Zhu, “Evaluation of Scattering From Electrically Large and Complex PEC Target Coated With Uniaxial Electric Anisotropic Medium Layer Based on Asymptotic Solution in Spectral Domain,” IEEE Trans. Antennas Propag., vol. 62, no. 4, pp. 2175–2186, 2014, doi: 10.1109/TAP.2014.2300537.

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