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Computational method for radar absorbing composite lattice grids

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ABSTRACT

Composite lattice grids reinforced by glass fibers (GFRC) and carbon fibers (CFRC) filled with spongy materials can be designed as lightweight radar absorbing structures (RAS). In the present paper, a computational approach based on periodic moment method (PMM) has been developed to calculate reflection coefficients of radar absorbing composite lattice grids. Total reflection backing (TRB) is considered directly in our PMM program by treating it as a dielectric material with large imaginary part of permittivity. Two different mechanisms of reflection reduction for radar absorbing lattice grids are revealed. At low frequency, reflection coefficients increase with the volume fraction of the grid cell wall. At high frequency, several grating lobes propagate away from the doubly periodic plane, and reflection coefficients depend on both the cell wall volume fraction and interelement distance.

1. Introduction

Radar absorbing materials (RAM) are extensively utilized in many fields, especially for military purpose. Conventional RAM such as stealthy coating for aircraft and various shapes of spongy foam absorbers in darkroom have been well developed [1]. However, these materials are either too brittle or flexible to bear load. Besides, stealthy coatings bring aircrafts undesirable extra weights and expensive maintenance costs.

Radar absorbing structures (RAS) have been studied since the end of last century. Design of RAS includes consideration of its load-bearing ability as well as radar absorbing. For structures used in aircraft, lightweight is also an important factor. By blending conductive carbon black or carbon nanotubes with the binder matrix of glass/epoxy composite, solid RAS have been fabricated [2,3]. This kind of solid RAS is not an efficient load-bearing structure due to its high density. Porous structures such as SiC-foams [4] and polyurethane foams with carbon black or carbon nanotubes [5] have also been studied as RAS.

As porous structures, lattice grids are more efficient for load-bearing than foams [6–9]. Lattice grids are periodic in two orthotropic directions of a plane, with a finite thickness in the third direction. They possess superior mechanical properties, such as high specific stiffness and high specific strength, for which they can be utilized as cores of sandwich structures. The characteristic of high porosity ratio provides it huge potentials in multifunctional design. Recently, composite lattice grids reinforced by glass fibers and carbon fibers filled with radar absorbing lightweight spongy foams were designed as RAS [10]. Measurements of reflection coefficients reveal their outstanding radar absorbing performances. However, experimental measurements are time-consuming and resource-wasting in design procedure. It is of great value to develop a computational method for reflection coefficient.

The characteristic length of the lattice unit cell is usually in the same order as the operating wavelength. Transmission-line theory and transfer matrix method (TMM) based on effective medium theory fail in such cases [11]. The commercial FDTD and FEM codes based on solving differential equations are not so efficient as method of moment (MOM) when dealing with scattering problems in an infinite space [12,13]. Periodic moment method (PMM) has been established to simulate scattering from wedge and pyramid RAM [14], and total reflection backing (TRB) was treated in an indirect way by combining PMM with transmission-line theory.

In the present paper, we develop a computational method for radar absorbing composite lattice grids, based on PMM. TRB is

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considered directly in our method by treating it as a dielectric material with large imaginary part of permittivity. The calculated results are in good agreement with the measurement. Different radar absorbing mechanisms at low frequency and high frequency have been revealed. Volume fraction of the grid cell wall and the interelemant distance are found to be key factors for reflection reduction.

2. Theory and model

According to Chinese national standard GJB 2038-94, the measurement of reflection coefficient is performed in the condition of plane wave incidence. When a time harmonic ($e^{j\omega t}$) plane wave illuminates an infinite doubly periodic structure with total reflection backing, several grating lobes as well as the specular reflected wave can be observed in the scattering far field, as shown in Fig. 1. To simulate this scattering pattern, the dielectric materials can be replaced by free space and a set of equivalent electric volume currents, which are given by

$$\vec{J}^s = j\omega[\varepsilon(\vec{R}) - \varepsilon_o]\vec{E} \tag{1}$$

where $\varepsilon(\vec{R})$ denotes the permittivity of dielectric material at $\vec{R}$, and ε_0 is the free space permittivity. This is the main idea of MOM [12,13]. For doubly periodic structures, these equivalent currents must satisfy the Floquet theorem [14]:

$$\vec{J}^s(\vec{R}' + \hat{x}D_x m + \hat{z}D_z n) = \vec{J}^s(\vec{R}')e^{-jk_o(D_x m s_x + D_z n s_z)}, \quad m, n = 0, \pm 1, \pm 2, \cdots \tag{2}$$

where m and n are integers numbering the periodic elements, with $m = n = 0$ being the reference element. D_x and D_z are the interelement distances in the x and z directions, as shown in Fig. 2. $\hat{s} = s_x\hat{x} + s_y\hat{y} + s_z\hat{z}$ is the directional vector of the incident wave. And k_0 denotes the free space propagation constant. PMM solution for the scattering far field can be written in the following form [14]:

$$\vec{E}^s(\vec{R}) = \frac{Z_0}{2D_x D_z}\sum_{p=-\infty}^{\infty}\sum_{q=-\infty}^{\infty}\int\int\int_{ref}\hat{r}_{+} \times [\vec{J}^s(\vec{R}')]\frac{e^{-j\vec{k}_{+}(\vec{R}-\vec{R}')}}{r_y}dv' \tag{3}$$

where Z_0 denotes the wave impedance in free space. The triple integral is carried out over reference element V'. $\vec{k}_{\pm} = k_0\hat{r}_{\pm}$, with the directional vector

$$\hat{r}_{\pm} = \left(s_x + \frac{p\lambda_0}{D_x}\right)\hat{x} \pm r_y\hat{y} + \left(s_z + \frac{q\lambda_0}{D_z}\right)\hat{z},\ for\, y \underset{>}{<} y' \tag{4}$$

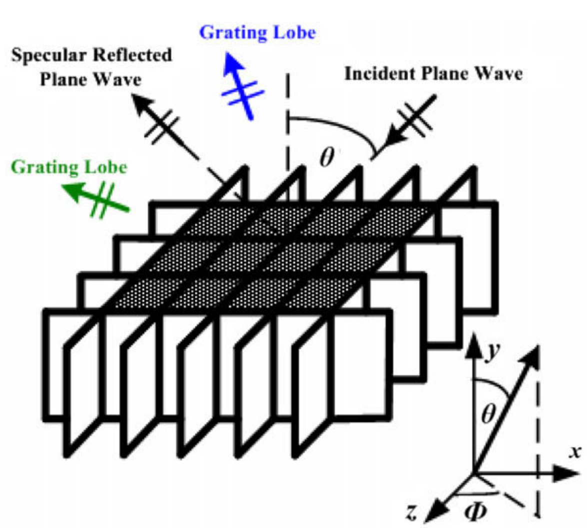

Fig. 1. Sketch of the scattering far field of an infinite doubly periodic structure with total reflection backing illuminated by a plane wave.

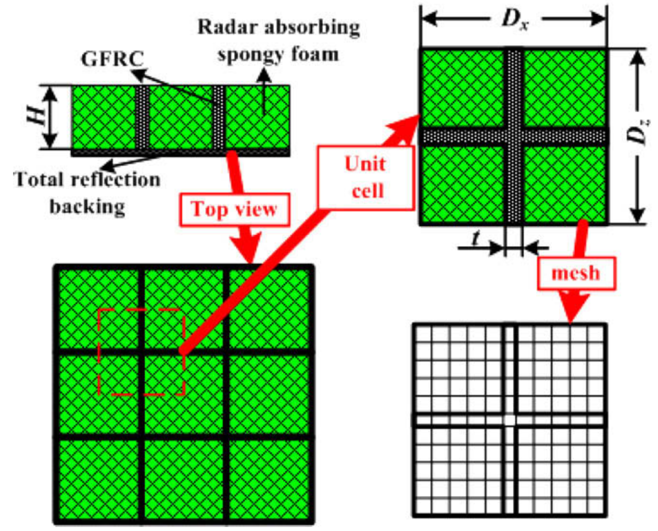

Fig. 2. Sketch of GFRC square lattice grid filled with radar absorbing spongy foam and its unit cell, as well as mesh.

and

$$r_y = \begin{cases} \sqrt{1 - r_x^2 - r_z^2}, & for\ r_x^2 + r_z^2 \leqslant 1 \\ -j\sqrt{r_x^2 + r_z^2 - 1}, & otherwise \end{cases} \tag{5}$$

When r_y becomes imaginary number, the corresponding grating lobe attenuates exponentially with y, and does not contribute to the scattering far field. Thus, the infinite double summation in Eq. (3) can be replaced by finite summation of several items, with $p = q = 0$ representing the specular reflected wave and others representing the non-attenuating grating lobes.

In the present paper, we calculate the reflection coefficients of GFRC square lattice grids filled with radar absorbing spongy foam. The sketch of radar absorbing square lattice grid is shown in Fig. 2. One unit cell of the lattice grid is chosen as PMM reference element, and meshed by many cube subfields for closed-form integral in Eq. (3). We only deal with vertical incidence ($\theta = 0$ in Fig. 1) as in most experimental measurements. A flat slab with permittivity $\varepsilon = 1 - 5000j$ and thickness 1 mm is introduced to simulate the TRB in our PMM program.

3. Results and discussion

The commercial radar absorbing spongy foam filled in the lattice grids is a 5-layer dielectric dissipation gradient RAM with density of about 0.2 g/cm^3. The photo and measuring permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$, of each layer are shown in Fig. 3. The thickness of each layer is 4 mm, and the value of H in Fig. 2 is 2 cm. The reflection coefficients calculated by our PMM program and the conventional transfer matrix method (TMM) together with measurement result [10] are shown in Fig. 4. The commercial gradient RAM can reach a reduction below −10 dB over the range of 4–18 GHz. The result of our PMM program with total reflection backing is in good agreement with the measurement and conventional TMM. However, PMM without TRB is not an exact simulation for standard measurement. These results validate our PMM program and the treatment of total reflection backing.

Load bearing lattice grids are doubly periodic structures with unit cell dimensions usually in the order of centimetre. The wavelengths of 4–18 GHz electromagnetic waves are in the range of 1.7–7.5 cm. Thus, the conventional TMM and transmission-line theory fail in calculating reflection coefficients of radar absorbing