The Simulation of Electromagnetic Fields with Large Wavelengths

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Abstract: When the wavelength of an electromagnetic wave is much larger than the microscopic size of the material, the numerical solution of the model to study the effect of the material microstructure on the electromagnetic wave propagation usually fails to be obtained due to computational overload. In this paper, a method using a large-scale simulated structure instead of the real microstructure has been proven. With the simulated structure, the computational load is greatly reduced, and the numerical solution can be obtained. Furthermore, the simulated structure conditions needed to achieve an effect on the electromagnetic wave propagation equivalent to that of the real microstructure were studied.

Key words: large wavelength; electromagnetic simulation; microscopic particles.

1. Introduction

With the application of electromagnetic technology in various fields, electromagnetic material science has also been widely developed [1,2]. Numerical simulation is an effective means of analyzing the effects of material characteristics on electromagnetic wave propagation [3, 4].

According to the ratio of the electromagnetic field wavelength to the size of the material, different simulation schemes have been developed. When the wavelength is much smaller than the size of the material, the optical path can be studied by the method of ray optics, for example, by using the design of the Luneburg lens [5]. When the wavelength of the electromagnetic field is close to the size of the material, it is necessary to solve the complete Maxwell equations. Many research studies have been conducted on the design of artificial electromagnetic materials [6, 7].

With the development of controllable preparation technology for nanomaterials, simulation research concerning the influence of the material microstructure on the electromagnetic wave propagation with large wavelengths (wavelengths larger than the size of the material microstructure) has been needed. For example, the elements of iron and carbon are recombined into nanoparticles of different shapes to achieve effective absorption of radar waves [8-10]. The microstructure of the material is at the nanometer scale, while the wavelength of the radar wave is on the order of centimeters. Current computational capabilities cannot afford the computational load required to describe both the microscopic structures of the material and the electromagnetic waves.
A method that considers the average effect is usually used for the study of large-wavelength electromagnetic fields. In this paper, keeping the same volume, we use a large-scale simulated structure instead of multiple real microstructures to reduce the computational load. Furthermore, the conditions of the simulated structure application are discussed.

2. Size condition for the simulated structure

2.1. Numerical model
A model is built to investigate the effects of spherical bilayer materials on electromagnetic wave propagation. As shown in Fig. 1, a rectangular simulation domain is carried out around a unit cell; floquet-periodic boundary conditions are used on four sides of the unit cell to simulate the infinite 2D array of the sphere. Perfectly matched layers (PMLs) on the top and bottom of the unit cell are used to absorb the electromagnetic field from the ports and to simulate infinite space. A transverse electromagnetic wave (TEM) with a power of 1 W is excited from the source port, and the distance between the source port and the listener port is 1.4 mm. The side lengths of the square ports are 0.28 mm. The electromagnetic waves in the simulation domain are solved in the frequency domain, and the control equations are as follows:

\[ \nabla \times H = j \omega \varepsilon_r \varepsilon H \]
\[ \nabla \times E = -j \omega \mu_r \mu H \]  

(1)

To reduce the computational load, a large-scale simulated sphere is selected for calculation. The outer layer of the sphere is made of carbon material with a thickness of 0.08 mm and dielectric parameters of \( \varepsilon_r = 30 - 30j, \mu_r = 1 \). The inner sphere is made of iron with a radius of 0.2 mm and dielectric parameters of \( \varepsilon_r = 30 - 2j, \mu_r = 2 - 2j \). The frequency of the electromagnetic wave is changed from 2 GHz to 10 GHz.

To keep the volume of the material unchanged, the simulated sphere is decomposed into \( n^3 \) spheres; each of the spheres has a radius of \( 1/n \), and the size ratio of the double-layer structure remains unchanged. For example, when \( n=2 \), the simulated sphere is decomposed into eight smaller simulated spheres. With the increase in \( n \), the size of the simulated sphere decreases and tends to be the actual size of the microscopic particles.

![Figure 1. Geometry of the numerical model.](image)

2.2. The numerical results
The electromagnetic wave emitted by port 1 is converted into a reflected wave and a transmitted wave. The remaining energy is absorbed by the material. Port parameters S11 and S21 are defined to measure the effects of the material on the electromagnetic wave propagation, as follows [11]:

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Where $E_{in}$ is the incident electric field strength from port 1 and $E_{r}$ and $E_{t}$ are the reflected and transmitted electric field strength, respectively. Numerical results show that the curves of the port parameters with frequency tend to be consistent for different values of $n$ (Fig. 2). In other words, large-scale simulated particles can be used to replace the set of small spheres and maintain the effect of the material on the electromagnetic wave propagation.

When the electromagnetic frequency is decreased from 2 GHz, the effect of the material on the electromagnetic wave propagation remains the same for different values of $n$. However, the computational load required to obtain the numerical solution is greatly increased. On the other hand, when the frequency of the electromagnetic field is greater than 50 GHz, the curves of the port parameters as a function of the electromagnetic frequency for different values of $n$ are no longer consistent (Fig. 3). This is because the wavelength of the electromagnetic wave is close to the size of the simulated structure and does not satisfy the condition of the large-wavelength electromagnetic wave.

![Figure 2. Changes in the port parameter with frequency (the solid line is the parameter of S11, the dotted line is the parameter of S21, and the number of layers is represented by different colors).](image)

![Figure 3. Changes in the port parameter with the frequency of the electromagnetic field.](image)

When the electromagnetic wave frequency is less than 20 GHz, the wavelength is larger than 16 mm, and the maximum diameter of the simulated sphere is 0.56 mm. Therefore, when the ratio of the electromagnetic field wavelength to the simulated particle diameter is larger than 30, simulated particles can be used to replace multiple real particles in the same volume and maintain the equivalent effect on the electromagnetic wave propagation.

3. Conditions for the simulated structure

The above analysis focuses on the equivalent effects between spherical bodies. Below, the requirements of the equivalent effects for structures are studied. To maintain the volume of the material, the spherical structure is changed into a flat structure. The size of the simulation domain remains unchanged. For $n=1$, the volumes of carbon and iron in the sphere were divided by the port area to obtain the thickness of the plate. Then, the carbon and iron layers are decomposed into an average of $n$ layers. The carbon layer and the iron layer are alternately arranged.
Under different values of $n$, the port parameters change with the electromagnetic frequency, as shown in Fig. 4. The calculation results show that the equivalent effect on electromagnetic wave propagation is still valid for the flat structure. Compared with Fig. 2, the reflection coefficient $S_{11}$ of the flat structure is greater than that of the spherical structure, and the transmission coefficient $S_{21}$ is less than that of the spherical structure. The energy losses in the material are expressed as follows:

$$\text{loss} = 10\log\left(1 - \left|\frac{E_r}{E_{in}}\right|^2 - \left|\frac{E_t}{E_{in}}\right|^2\right)$$

(3)

As shown in Fig. 5, in the case of the same volume of material, the plate structure is better than the spherical structure in terms of the characteristics for absorbing electromagnetic waves (Fig. 5).

**Figure 4.** Changes in the port parameter with the frequency of the electromagnetic wave for the flat structure.

**Figure 5.** Energy losses in different materials (the solid line is for the structure of the sphere, and the dotted line is for the flat structure).

Furthermore, the distributions of the electromagnetic fields for $n=1$ and $f=16\, \text{GHz}$ are shown in Fig. 6. The distribution of the electromagnetic field varies greatly under different structures. For the spherical structure, the amplitude and direction of the electromagnetic field change when subject to a square structure. For the plate structure, the electromagnetic field is evenly distributed. Therefore, the equivalent effect on the electromagnetic wave propagation is based on maintaining the microstructure of the material.

**Figure 6.** The distributions of the electric field in the simulation domain. (The electric field line is blue, and the magnetic field line is red)
4. Conclusion
When the wavelength of the electromagnetic field is much larger than the size of the material microstructure, the computational load required to simulate the effect of the microstructure on the electromagnetic wave propagation is excessive. In this paper, a method of using a large-scale simulated structure instead of multiple real structures has been studied. To ensure that the simulated structure and the real structure have the same effect on the electromagnetic wave propagation, the requirements for the simulated structure are as follows:

1. The ratio of the wavelength of the electromagnetic wave to the size of the simulated structure is larger than 30.
2. The simulated structure and microscopic structure maintain similar structures and equal volumes.

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