Angle-dependent SIBC model of metamaterial in FDTD method

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Abstract

To control the diffraction of a target illuminated by a RADAR wave, one technique is to consider metamaterials. Simulating their behaviour can be complex especially when they are applied as thin heterogeneous layers on the surface of the target. This can be achieved, by first determining an angle-dependent surface impedance model, that is after implemented in a 3D FDTD solver.

Keywords: SIBC, metamaterial, FDTD

1 Introduction

The interest of using a surface impedance model (SIBC) is multiple. First, it avoids meshing a complex geometry covering some parts of the target. Then, the spatial mesh can be released. Indeed, it is supposed to be small enough to capture the field variations inside the thin layer of metamaterials. Since the latter is replaced by a SIBC model, the chosen spatial mesh can be larger because it is not governed anymore by the thin layer thickness. As a result, the computational volume is reduced as R^3 and the computational time by R^4 where R is the factor of relaxed meshing.

For this purpose, both the wideband and efficiency finite-difference time-domain (FDTD) method is used to compute the electromagnetic fields. In a first step, the surface impedances are calculated with the Spectral FDTD (SFDTD) scheme [1] for all incidence angles and for the TE and TM modes. SFDTD method is a good candidate because no additional constraint is needed on the CFL criterion. Thus, periodic Floquet boundary conditions (PBC) are applied around the elementary pattern of the periodic metamaterial. In a second step, the frequency-angle-polarization-dependent SIBC model is decomposed by the vector fitting (VF) technique [2] and the Leontovich relation is used to introduce the metamaterial on the target surface [3]. This approach allows a simple and efficient calculation of the tangential electric field at the metamaterial surface. Morevover, the VF decomposition avoids the processing of a convolution product in the time domain.

2 SIBC model construction

Let k be the unit vector along the incident axis. For each cell containing an interface with a metamaterial, we identify the local coordinates reference (u, v, n) where n is the normal outgoing unit vector and (u, v) are the unit tangential vectors on the surface of the metamaterial. The

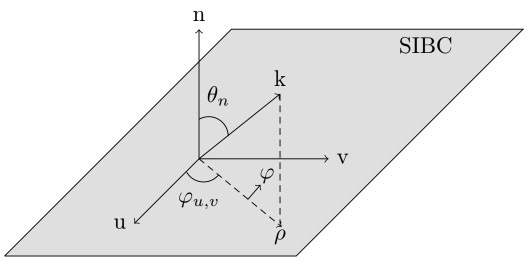

Figure 1: Local coordinates at an interface between air and a metamaterial.

local elevation angle θ_n and azimuth $\varphi_{u,v}$ defined on the figure 1 are deduced as

$$\theta_n = \arccos k_n, \quad \varphi_{u,v} = \arctan \frac{k_v}{k_u}, \tag{1}$$

where (k_u, k_v, k_n) are the components of vector k in the local benchmark. The electric field components in the cylindrical coordinates (ρ, φ) are then calculated by the Leontovich relation

$$\begin{bmatrix} E_\rho \\ E_\varphi \end{bmatrix} = \begin{bmatrix} 0 & -Z_\rho(\omega, \theta_n, \varphi_{u,v}) \\ Z_\varphi(\omega, \theta_n, \varphi_{u,v}) & 0 \end{bmatrix} \begin{bmatrix} H_\rho \\ H_\varphi \end{bmatrix}. \tag{2}$$

Note that the metamaterial surface impedances Z_ρ and Z_φ in (2) are known as they have been previously computed by the SFDTD method. Let $\mathcal{M}$ be the transform matrix between the cylindrical basis and the local cartesian basis. The local components (E_u, E_v) read

$$\begin{bmatrix} E_u \\ E_v \end{bmatrix} = \mathcal{M}^{-1}(\varphi) \begin{bmatrix} 0 & -Z_\rho \\ Z_\varphi & 0 \end{bmatrix} \mathcal{M}(\varphi) \begin{bmatrix} H_u \\ H_v \end{bmatrix}. \tag{3}$$

To solve (3), the impedances are decomposed using the VF technique to make time domain processing easier

$$Z_{\rho,\varphi}(\omega) = r_0 + \sum_{n=1}^{N} \frac{k_n}{j\omega - \omega_n}, \quad (4)$$

where r_0 is the resistance, k_n the residus et ω_n the poles. The poles number should be at least $N = 3$ for a sufficient accuracy. Then, $N = 6$ poles are used in the simulation of section 3.

3 Numerical results

The problem consists in a perfectly conducting (PEC) cube covered with patterns on its three xOy inf, yOz inf and xOz inf faces. Fig. 2 represents the elementary pattern geometry of an arbitrary and non-absorbing periodic structure which has been previously simulated by the SFDTD method for several incident angles, for the TE and TM modes and on the $0^+ - 15$ GHz frequency band. The cube is submitted to an incident plane wave at incidence $\theta_i = 60°$, $\varphi = 30°$ (see Fig. 3). The three faces covered with patterns are in direct visibility of the incident rays. We compare the SIBC model with the reference FDTD scheme and the case where the cube is only a PEC to note the material effect. The PEC cube side length is $L = 37.5$ mm. Spatial discretization steps are all set to $\Delta = 0.125$ mm for the FDTD reference and 3.22 times bigger $\Delta = 0.4025$ mm for the SIBC case. Then, CFL $= 0.99$. Note that the three sides are covered with a patch of 20×20 patterns. The radar cross section (RCS) is computed in the direction $\varphi = 30°$ for all θ angles and for the TM mode. Fig. 4 shows the good agreement between the SIBC model and the standard FDTD scheme for the chosen frequency $f = 5$ GHz.

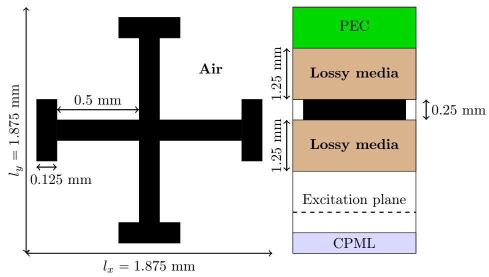

Figure 2: On the left : above view. On the right : cross section of the material composed of two lossy layers around the PEC cross. The excitation plane injects in the up direction the incident wave which is absorbed by CPML in the down direction.

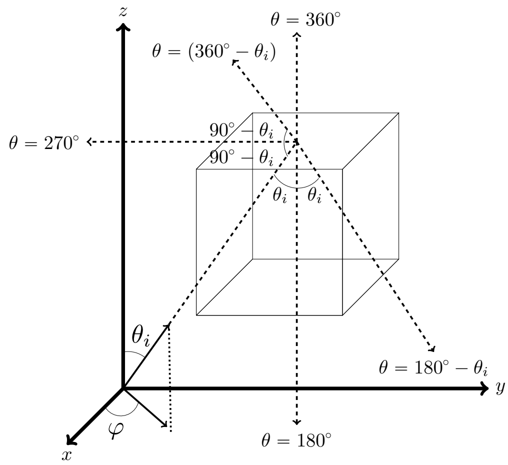

Figure 3: Geometry of the PEC cube. Three cube faces are covered with patterns. RCS direction are plot in dotted line in the yOz plane ($\varphi = 90°$).

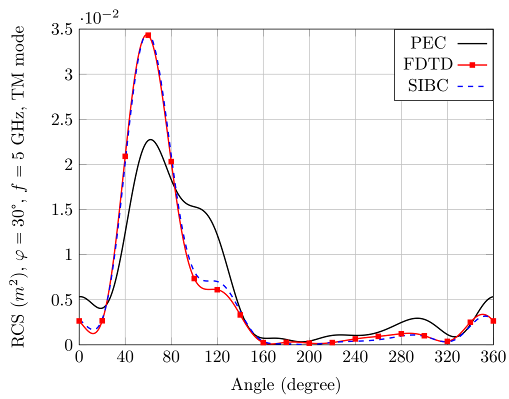

Figure 4: RCS obtained by the SIBC model and the standard FDTD Yee scheme.

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