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exchanged when $c_B[n]$ is a logical one. The $B+1$ bit GCN functions identically. It is easily seen that a one bit GCN and a one bit BTN are equivalent. Thus, by induction, the B bit GCN and the B bit BTN are equivalent when the high impedance output of the BTN is set to the LSB ('0') of the input of the GCN.

Conclusions: For a MOS implementation of a B bit DEM DAC, the FRDEM network, the GCN, and the BTN require $2^{B+3} - 4B - 8$, $B2^{B+1}$, and $2^{B+1} + B2^B - 2B - 2$ TGs, respectively. The FRDEM and the BTN implementations require fewer TGs than the GCN. The BTN requires fewer TGs than the FRDEM network when $B < 5.67$. However, the physical layout of a six bit BTN has more geometric regularity, simpler routing, and is more compact than the physical layout of a six bit FRDEM network [1]. Thus, of the three networks, the BTN is the most efficient implementation of a GCN DEM network for DACs with six or fewer bits.

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Modal transmission-line calculation of shielding effectiveness of composite structures

S.V. Savov and M.H.A.J. Herben

A novel modal transmission-line (MTL) method for the calculation of the shielding effectiveness of composite structures is presented. The MTL results are compared with the results obtained by another numerical technique. The new model is characterised by simplicity and accuracy and provides an opportunity for easy extension to laminated composite structures.

Introduction: Composite materials are used for spacecraft and aircraft structures because of their light weight, high strength, and ease of fabrication. They are generally constituted by a binding resin (e.g. epoxy, polyester, etc.) reinforced by high strength fibres (e.g. graphite, boron, etc.). Because the shielding properties of these composites are completely different from those of metals, their electromagnetic modelling is an important issue in electromagnetic compatibility (EMC). Early electromagnetic analyses of these structures concerned the determination of the radar cross-section [1]. In the first EMC-oriented paper an approximated filament-current model is used for investigating the shielding effectiveness of composite structures [2]. This method is based on a thin wire assumption and its application is restricted to the case of a single-layer periodic composite structure. In [3] the boundary integral equation method is used for similar structures. Later, a complicated extension of the filament-current model in cases of laminated structures was also suggested [4]. In the present Letter

we apply the modal transmission-line (MTL) method, which is simple, accurate and which can easily be extended to analyse laminated composite structures [5-7].

Fig. 1 Periodic composite structure

MTL method: Fig. 1 shows the geometry of the considered two-dimensional scattering problem. A plane electromagnetic wave is incident on a periodic lossy dielectric structure with thickness h and infinite extent in the y -direction. The incident wave with unit amplitude is y -polarised, has a time dependence $\exp(-j\omega t)$, which is assumed and suppressed, and its angle of incidence is θ . The problem space is divided into five regions ($l = 0-4$ as shown in Fig. 1). In region 0 (air) there are two types of solutions, i.e. incident and reflected waves, in region 4 (air) there are only transmitted waves (reflection is absent, because of infinite extent), while in finite regions 1 to 3 (composite material) there are two kinds of solutions, i.e. forward and backward propagating waves. Because of the periodicity in the x -direction with a period d , one can write the periodic tangential fields $\{E_y, H_x\}$ in every region in terms of Floquet space-harmonics [7]:

$$\begin{aligned} E_{y,l}(x, z_l) &= \sum_{n=-\infty}^{\infty} \left\{ f_{l,n} e^{jk_{l,n} z_l} + b_{l,n} e^{jk_{l,n} (h_l - z_l)} \right\} \\ &\times \sum_{m=-\infty}^{\infty} a_{l,mn} e^{jk_{x,m} x} \\ -H_{x,l}(x, z_l) &= \sum_{n=-\infty}^{\infty} y_{l,n} \left\{ f_{l,n} e^{jk_{l,n} z_l} - b_{l,n} e^{jk_{l,n} (h_l - z_l)} \right\} \\ &\times \sum_{m=-\infty}^{\infty} a_{l,mn} e^{jk_{x,m} x} \end{aligned} \quad (1)$$

where $k_{x,n} = k_0 \sin \theta + n2\pi/d$ with $n = 0, \pm 1, \pm 2, \dots$, $k_0 = 2\pi/\lambda$ is the free-space wavenumber, and (x, z_l) are the local co-ordinates of the l th layer with thickness h_l ($l = 0, 1, 2, 3, 4$). The complex dielectric constants $\epsilon_{r,l}(x)$ of the l th layer, is a periodic function, which means that it can be written in terms of a complex Fourier series:

$$\begin{aligned} \epsilon_{r,l}(x) &= \sum_{n=-\infty}^{\infty} g_{l,n} e^{jn \frac{2\pi}{d} x} \\ \text{with } g_{l,n} &= \frac{1}{d} \int_0^d \epsilon_{r,l}(x) e^{-jn \frac{2\pi}{d} x} dx \end{aligned} \quad (2)$$

We can now define a square matrix $[P_l]$ with elements [7]:

$$P_{l,mn} = k_0^2 g_{l,n-m} - k_{x,m}^2 \delta_{nm} \quad (3)$$

where δ_{nm} are the Kronecker-delta symbols $\{\delta_{nm} = 1, n = m; \delta_{nm} = 0, n \neq m\}$. The propagation constants $\{k_{l,n} \equiv k_{z,l,n}\}$ of the forward and backward propagating waves in eqn. 1 can then be found from the following eigenvalue equation

$$\det([P_l] - k_{l,n}^2 [I]) = 0 \quad (4)$$

In the case of a homogeneous layer they are simply $\sqrt{(k_0^2 \epsilon_{r,i} - k_{x,n}^2)}$ for propagating waves and $j\sqrt{(k_0^2 \epsilon_{r,i} - k_{x,n}^2)}$ for evanescent waves, and the characteristic admittances in both cases are

$$y_{l,n} = \frac{k_{l,n}}{k_0 \eta_0} \quad (5)$$

where η_0 is the free-space wave impedance. The eigenvectors, associated to the eigenvalues $\{k_{l,n}\}$ are columns of a square matrix with elements $\{a_{l,mn}\}$, which in a homogeneous case reduces to the identity matrix $[I]$.

After imposing the boundary conditions on the interfaces between the regions, the unknown coefficients $\{f_{l,n}, b_{l,n}\}$ are found [7]. The matrix solution for the reflection and transmission coefficients of the modes has the form ($r_n \equiv b_{0,n}$; $t_n \equiv f_{4,n}$)

$$[r] = [R][i] \quad \text{and} \quad [t] = [T][i] \quad (6)$$

where $[R] = [R_0]$, $[T_0] = [I] + [R_0]$, and $[T] = [T_3][T_2][T_1][T_0]$ are the total reflection and transmission matrices of the composite structure – the latter is a product of the transmission matrices of the layers in a reverse order (excluding the last one). Here the incidence column matrix for a singlemode excitation in the region 0 has components ($i_n \equiv f_{0,n} = \delta_{0n}$) while the absence of reflected waves in region 4 means ($b_{4,n} = 0$).

The power transmission coefficient (p_t) and the shielding effectiveness (SE) are

$$p_t = \sum_n |t_n|^2 (y_{0,n}/y_{0,0}) \quad \text{and} \quad SE = -10 \log_{10} p_t \quad (7)$$

Application of MTL model to composites: The MTL model will be applied to two composite structures, i.e. a graphite/epoxy and a copper/epoxy composite, with the geometry shown in Fig. 1. To minimise the number of layers, the circular wires are replaced with square ones. The parameters of this structure are chosen [2]: $h = d = 0.127\text{mm}$, and $2a = 0.1d$. The parameters of the materials are: dielectric constant of the dielectric matrix (epoxy) $\epsilon_r = 3.4$, conductivity of the graphite fibre $\sigma = 6.67 \times 10^4 \text{S/m}$, and conductivity of the copper wire $\sigma = 5.80 \times 10^7 \text{S/m}$. Fig. 2 shows the shielding effectiveness of the two composites in a wide frequency range ($1\text{GHz} < f < 100\text{GHz}$) for normal wave incidence. Results for the graphite/epoxy structure based on the approximated filament-current model [2] are also added to Fig. 2 (circles) and appear to agree rather well with the MTL results for the same composite (solid line). Some small discrepancies between them could be explained by the different shape of the cross-section of the fibres, viz. square in this Letter and circular in [2]. It is evident from Fig. 2 that the shielding effectiveness of the copper/epoxy composite continuously decreases with increasing frequency, while for the graphite/epoxy composite it is almost constant up to 20GHz and after that it starts decreasing, and the differences between them become smaller and smaller.

Fig. 2 Shielding effectiveness of the composites as function of frequency for normal wave incidence

Circles are results from [2]
 --- copper/epoxy
 ——— graphite/epoxy

Conclusions: The modal transmission-line (MTL) model can be used to analyse the shielding effectiveness of lightweight composite materials which are used for spacecraft and aircraft structures. Compared with other methods, the MTL method appears to be very efficient with respect to computational time: for graphite fibre reinforced materials it needs only nine modes, while in the case of copper wires (worst-case situation) 49 modes are sufficient to obtain accurate results.

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Stability criterion for radial wave equation in finite-difference time-domain method

M.E. Potter and M. Okoniewski

A relaxed time-step stability criterion is derived for the radial wave equation in Schelkunoff form approximated by a finite-difference time-domain (FDTD) method. The criterion is established by comparing with the Cartesian Laplacian operator. This is the first step in developing stability analysis for a spherical wave implementation in FDTD.

Introduction: The finite-difference time-domain (FDTD) method has been used extensively in electromagnetic field modelling owing to its ability to robustly handle interactions of fields with complex heterogeneous structures. In particular, the total/scattered field formulation [1] has allowed for efficient implementation of arbitrarily directed uniform plane waves, consequently facilitating efficient modelling of far field scattering problems. The efficient implementation of source fields on the Huygens' surface is not restricted to plane waves, however. For example, we have shown recently that an infinite line source can be implemented in a manner similar to plane waves [2].

The restriction of plane wave sources is that they inherently model the far field of an electromagnetic source. To model the antenna/object scattering problems in the near field, the standard approach is to model both the source and object in the same domain. The drawback of this approach is that the computational cost can become a burden either because of the domain size or the