Full-wave model and numerical study of electromagnetic plane-wave scattering by multilayered, fiber-based periodic composites

C. Y. Li*[(1)], D. Lesselier[(1)], and Y. Zhong[(2)]
(1) Laboratoire des Signaux et Systèmes UMR8506 (CNRS-SUPELEC-Univ Paris-Sud)
(2) A*STAR, Institute of High Performance Computing, 138632 Singapore

Advanced composite materials are widely applied in aerospace, naval and automotive industries particularly due to their light weight, high stiffness and resistance to corrosion. The building block of the material is a composite slab composed of two parts, matrix and reinforcement. The reinforcement, such as graphite or glass fibers, is embedded inside the background matrix and periodically arranged while the matrix, such as epoxy, binds the reinforcement together. All fibers inside are then orientated into the same direction. Stacking up single layers yields multi-layer composite laminates, the orientations of the fibers in different layers usually differing from one to the other in order to provide strength and stiffness in all directions (C. Alexander *et al.*, *Journal of Applied Physics*, **114**, 2013, 1 – 10).

During manufacturing or service period, various damages and defects, like micro-cracks, inclusions and small delaminations, may appear. They impact the mechanical properties of the composites, shorten the service life and at worst affect the safe and effective functioning of parts involved. Therefore, non-destructive testing (NdT) methods are needed for effective inspection of these damages.

Using traditional NdT methods, including ultrasonic methods, tomography, and thermography, for NdT of composite materials remains challenging or high-cost (L. Cheng *et al.*, *Journal of Sensors*, **2012**, 2012, 1 – 7). But electromagnetic methods show good potential for inspecting low-energy impact damages at eddy-current frequencies for conductive fibers and microwave ones for dielectric fibers. However, effective imaging first requires a good understanding of the electromagnetic behavior, the one of undamaged laminates in the first step. In the present contribution, a multilayer model for a composite structure, with fibers inside each layer parallel to each other, is investigated to that effect.

The solution method, as an extension of our previous work (C. Y. Li *et al.* *Applied Physics A*, **117**, 2014, 567 – 572; C. Y. Li *et al.* in *URSI General Assembly and Scientific Symposium, 2014 XXXIth URSI, Beijing*, 2014), is based on multipole and plane wave expansions in view of their computational efficiency and accuracy, as well as analytic tractability (J.-P. Groby and D. Lesselier, *Journal of the Optical Society of America A*, **25**, 2008, 146 – 152). In each layer, the periodic problem is restricted in one unit cell by using the Floquet theorem (L. C. Botten *et al.*, *Journal of the Optical Society of America A*, **17**, 2000, 2165 – 2176). In this cell, fields in regions above and below the one occupied by the fiber are plane-wave expanded. The expansion coefficients for the two regions are related through establishing Rayleigh's identity in the vicinity of the fiber. A propagating matrix is constructed by matching the fields between two layers. Then, a linear system providing reflection and transmission coefficients is obtained by iteratively calculating the propagating matrix from the top layer to the bottom layer. Power reflection and transmission coefficients follow from time-averaged Poynting vectors.

Applicability and accuracy of the method have been validated with a number of numerical experiments led in the context of non-destructive testing of fiber-reinforced composites, under illumination by normal and obliquely incident plane waves. One has also tested the approach by comparing the results with those given by a T-matrix method (K. Yasumoto and H. Jia, Modeling of photonic crystals by multilayered periodic arrays of circular cylinders, Chapter 3, in *Electromagnetic Theory and Applications for Photonic Crystals*, K. Yasumoto ed., 2010, Taylor & Francis), and good match has been observed. At the same time, the method has the ability to provide dyadic Green's functions associated to the structure investigated via proper plane wave expansion and Fourier transformation, which more brute-force numerical or analytical-numerical methods like FDTD or FEM do not necessarily easily do.