NEAR-FIELD MICROWAVE IMAGING OF SUBSURFACE INCLUSIONS IN LAMINATED COMPOSITE STRUCTURES

M. AbouKhousa[1] and N. Qaddoumi[2]
[1]Department of Electrical & Computer Engineering, Concordia University, Montreal, Quebec, Canada
[2]Electrical Engineering Program, American University of Sharjah, Sharjah, U.A.E

Abstract: Laminated composite materials are becoming one of the most prominent engineering materials in wide range of applications. For most of the critical applications, these materials are engineered to have specific attributes. Accidental variations in these attributes, practically, are not tolerable. Catastrophic failures may occur to the parts manufactured form theses composites if subsurface inclusions are introduced within their layers. Hence, there is an increasing demand for a nondestructive testing (NDT) technique that is capable of evaluating the integrity of the composite structures and consequently preventing deployment failures. To this end, it is required that the NDT technique provides quantitative measures about the type, location, and orientation of the subsurface inclusions. Such information can be extracted from 2-D images captured for theses inclusions.

Introduction: Near-Field microwave imaging systems with open-ended rectangular waveguides as imaging probes have shown promising results in detecting subsurface defects in such opaque media. The quality of the experimental images captured with these systems has demonstrated the potential of the technique for material NDT purposes. Basically, these systems utilize an antenna to illuminate the composite with electromagnetic (EM) waves and monitor the reflected waves. The EM waves penetrate deep into the dielectric material where they interact with its interior and reflect back to the antenna. The properties of the reflected wave will convey the needed information about the composite at hand. In this paper, the impact of the theoretical image formation on optimizing the imaging systems will be highlighted. It will be shown that the sensitivity and resolution of the waveguide sensor can be optimized to capture images of high fidelity even for concurrent inclusions, and hence this will assure independent detection for each one.

Discussion: In general, the laminated composite structure can be modeled as a stratified dielectric structure consisting of N number of planner dielectric layers. Each layer has certain relative, to air, complex dielectric constant ($\square_r$) and thickness. The relative complex dielectric constant (εr) is a measure of the material's ability to absorb and store the incident electric energy. From the microwave NDT point of view, a subsurface inclusion is announced by a change in the complex dielectric constant of the layer in which the inclusion exists. The purpose of the microwave imaging system is to map this change spatially into 2-D image.

A typical near-field waveguide-based microwave imager is shown in figure 1. The Imaging mechanism is based on the basic idea that microwaves, once they are launched into a media, are very sensitive to discontinuities in the material space. In our case, the discontinuity is realized as foreign inclusion in composite structure. The discontinuity causes some of the incident waves to reflect back toward the transmitter, and the remaining portion will be transmitted forward into the composite. The power and the phase properties of the forward and backward travelling waves bear valuable information about the inclusion the incident wave experienced. The phase and power properties are inferred from the measured complex reflection coefficient. An open-ended rectangular waveguide probe is utilized to measure the reflection coefficient in a certain imaging plane as a function of the spatial coordinates and outputs that as 2-D intensity image.

To form and optimize a theoretical image, it is crucial to have the mathematical model that describes the interaction between the microwaves and the laminated composite structures. The model is used to calculate the phase and magnitude of the reflection coefficient at each point in the imaging plane. The model was developed and analyzed in previous investigations [4].

The developed model is applied to capture images of subsurface inclusions in a 5-layer laminated composite structure described below.

Layer 1: Skin, $\varepsilon_r = 4.5\text{-}j0.045$, thickness: 2.5 mm

Layer 2: Adhesive, $\varepsilon_r = 3.1\text{-}j0.01$, thickness: 0.3 mm

Layer 3: Inner Core, $\varepsilon_r = 1.1\text{-}j0.0026$, thickness: 40 mm

Layer 4: Adhesive, $\varepsilon_r = 3.1\text{-}j0.01$, thickness: 0.3 mm

Layer 5: Skin, $\varepsilon_r = 4.5\text{-}j0.045$, thickness: 2.5 mm

The structure is backed by conducting sheet.

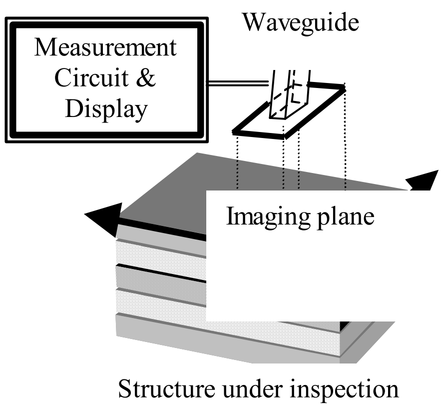

Figure 1: Near-field waveguide-based imager

An air ($\varepsilon_r = 1$) inclusion of dimensions $2\times3\times0.3$ mm³ (x,y,z) may exist in the first or second adhesive layers. In order to detect and assess the effect of each inclusion independently, we need to visualize them with acceptable non-overlapping dynamic ranges. So, the frequency of operation, liftoff (standoff) distance, and the waveguide band, which yield the required images, must be determined before application.

Using the developed model, we found that operating at 32 GHz in the Ka band at standoff distance of 1 mm meets the detection requirements. Figure 2 shows the raster phase image when the inclusion is present in the first adhesive layer. The spatial extent of the inclusion is apparent from the image with a dynamic range of 40 degrees.

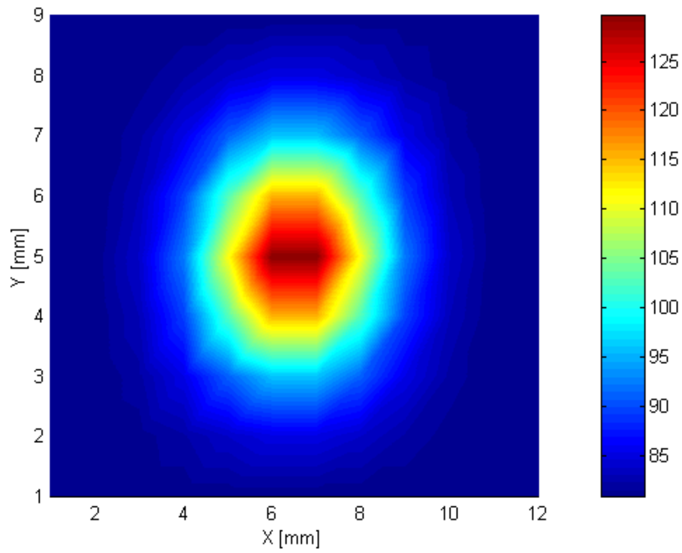

Figure 1 Phase image for an inclusion in the 1st adhesive layer.

In Figure 3, the inclusion extent in second adhesive layer is also evident with a narrower, yet still acceptable, dynamic range (25 degrees). Given that both dynamic ranges are not overlapping, we can distinguish between the two locations of the inclusion at the same frequency.

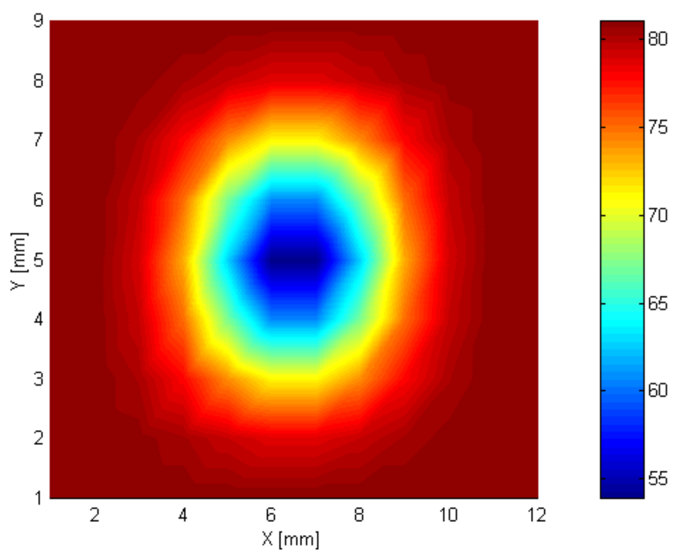

Figure 3: Phase image for an inclusion in the 2nd adhesive layer

Conclusions: Near-field waveguide-based microwave imagers constitute competent candidate to detect and assess the existence and extent of foreign inclusions in the laminated composite materials. Imaging of various inclusions can be achieved reliably through model-based optimization procedures. These procedures result in theoretical images to be used in conjunction with the practical images to extract the properties of the subsurface inclusion.

References:

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