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Enhanced sensitivity of microwave inspection of thin composites at resonance

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Abstract

In this paper, the resonance behavior of layered dielectric media is exploited for microwave non-destructive testing (NDT) of thin composite. Ultra wide band excitation over 1-20 GHz coupled to the composite using open ended coaxial probe was used to identify sample resonance in the absence of the defect. The time gated reflection coefficient (S11) of the sample measured at resonance was used to record the spatial variation in S11 for an insert with low dielectric contrast embedded in the thin composite. The proposed technique was validated using 3.5 mm thick glass fiber epoxy composite of 6 layers for 10 mm × 10 mm × 0.4 mm inclusion with low dielectric contrast ($|\Delta\varepsilon_r| \leq 2$) in between the composite layers. The measurements indicate enhanced sensitivity for the low dielectric contrast at sample resonance which is lost when inspected off resonance in agreement with the simulations.

Keywords: coaxial probe, composites, resonance, non-destructive testing

1. Introduction

Composite materials have been extensively employed in automobile, aircraft, defense and medical fields owing to its light weight, durability, and mechanical stability. Specific applications of composites include automobile fenders and body parts, aircraft radome and fuselage, battle tank heat resistant layers, external and internal prosthetics. All these applications require non-destructive testing for material inspection. Various NDT methods proposed for thin composites include induction thermography [1], ultrasound method [2], eddy current method [3] and microwave and millimeter wave [4] techniques. Among these, microwave techniques can be used to carry out evaluation of material properties like dielectric constant and loss tangent as well as the detection of defects, delamination or voids [5].

Microwave imaging using open ended waveguide on composites has been carried out in [6]. The open ended waveguide operating in the fundamental mode will have more energy concentration in the inspection area. This technique is well suitable for the thin and thick composites at the price of low spatial resolution. Free space microwave NDT is yet another method for thin composite evaluation but requires precision measurement setup for measurement calibration [7]. A couple spiral sensor has been developed in [8].This operates in the microwave high frequency range. These systems have larger foot print and relatively poor spatial resolution. Comparing these methods, we can identify that the requirements are higher spatial resolution and increased sensitivity. To achieve the higher sensitivity, the ability to identify the resonant frequency prior to testing is also required. The open ended coaxial probe techniques for inspection of thin composites has increased spatial resolution and higher sensitivity if operated at resonance.

2. Probe schematic

Figure 1 shows the coaxial probe deployed for the NDT. This probe was fabricated using SMA receptacles, where the protruded inner conductor is machined and polished such that the inner and outer conductors terminated in the same plane and will come in contact with the surface of the material under test (MUT). The cut off frequency of the probe can be determined by Eqn. (1).

$$f_{cut\ off} = \frac{190.85}{\sqrt{\varepsilon_r \mu_r}\,.(a+b)} \quad (1)$$

Here a is the diameter of the inner conductor and b is the diameter of the outer conductor of the coaxial probe. Also ε_r and μ_r are the dielectric permittivity and permeability of the dielectric spacer used between the coaxial conductors.

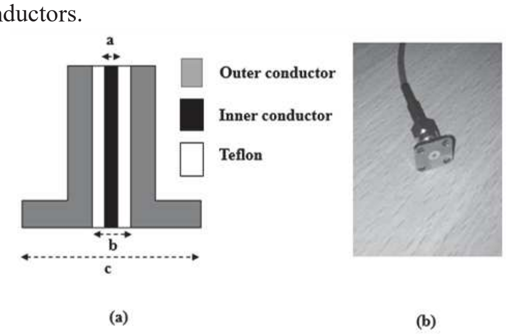

Figure 1. (a) The schematic of the coax probe; a=1.2. mm, b= 3.6 mm and c=12 mm. **(b)** Photograph of the fabricated probe.

The coaxial probe has a footprint of 3.6 mm which is very less compared to the k band open ended waveguide. Hence the spatial resolution for the probe will be higher. Also the wider operating bandwidth makes it a desired candidate over the open ended waveguide.

3. Composite Sample Preparation

Figure 2 (a) shows the fabricated defective composite sample that has been used for the testing. The fabrication was carried out using plain woven glass fiber layers and epoxy. Six layers of glass fiber textile were used for fabrication. In between the last two layers, Arlon AD250 of 0.4 mm thickness (dielectric constant of 2.5) was inserted and cured. Figure 2 (b) shows the line scan for measurement over the defective region.

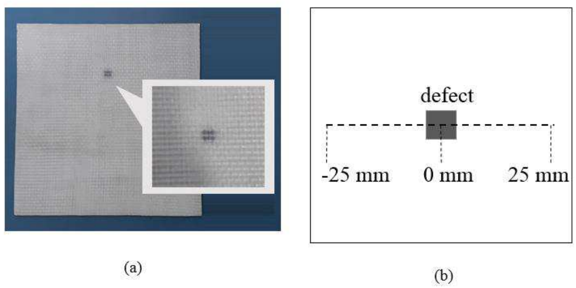

Figure 2. (a) Composite sample based on glass fiber epoxy. An Arlon 250 D sheet was inserted as defect, which is shown as an inset figure**. (b)** Line scan for probe measurement

4. Measurements

Swept frequency reflections of the coaxial probe over 1GHz to 20 GHz was gathered for a lift off of 0.2 mm between the probe and the composite. The composite was placed on a wideband microwave absorber during measurements and the time gated reflection form the composite was processed to identify resonance frequencies of the flat panel. Probe reflection measurements at resonance were recorded as the probe was scanned over defect free and defective regions of the composite.

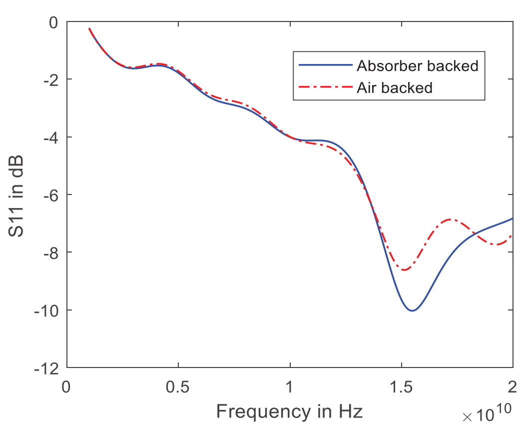

Figure 3. Reflection coefficient as a function of frequency for absorber and air backed samples.

Figure 3 shows the reflection coefficient measurements for absorber and air backed composite gathered using the open ended coaxial probe connected to Keysight E 5071C vector network analyzer (VNA).

5. Analysis and Discussions

Measurements indicate that the sample has resonance around 16 GHz. This was verified using 3D EM simulations for the measurement scenario. Figure 4 shows the simulated electric field distribution at resonance (16 GHz) and non-resonant (2 GHz) frequencies for absorber backed and air backed samples in the probe cut plane for dielectric property of the glass epoxy composite measured using free space technique [9]. At resonance, more energy is coupled to the composite compared to the non-resonant frequency. As the reflection is the least at resonance, probe sensitivity to variation in material impedance is expected to be the highest for material inspection. At the resonance, waveguide and couple spiral sensor presented in [8] can also be used for material inspection with enhanced sensitivity.

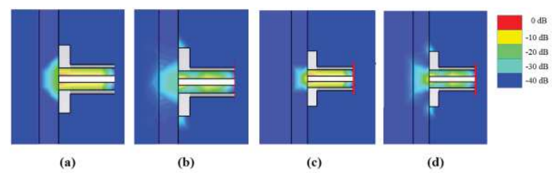

Figure 4. Electric field distribution at the probe composite interface. **(a)** 2 GHz (non resonant), absorber backed sample **(b)** 16 GHz (resonant frequency), absorber backed sample. **(c)** 2 GHz (non resonant), air backed sample **(d)** 16 GHz (resonant frequency), air backed sample.

Another study has been carried out to identify the effect of lift off distance at the probe sample interface using paper as the coupling medium. The power reflection coefficient has been tabulated for various lift off distances in table 1.

Table 1. Reflection coefficient at resonant frequency (16 GHz)

Backing material	**Reflection coefficient, defect free region**			
	LO = 0.05 mm	LO = 0.1 mm	LO = 0.15 mm	LO = 0.2 mm
Air	-3 dB	-5 dB	-6 dB	-7dB
Microwave Absorber	-3dB	-6 dB	-7 dB	-9 dB

It can be observed that the absorber backed sample shows lower reflection coefficient between the two backing materials. Also the reflection coefficient was found to be reducing while increasing lift off distance. It can be concluded from the table that at the resonant frequency, the lift off distance between the sample and the probe will help in bringing the contrast in reflection coefficient of the sample. Which in turn will improve the sensitivity of the measurement technique.

After finding the optimum specifications in terms of the backing material, lift off distance and the resonant frequency, the scan over the defective sample has been carried out. Various trial of scans over the defective and the defect free regions for non-resonant frequency and resonant frequency for absorber backed sample with 0.2 mm lift off distance is shown in figure 5 and figure 6 respectively. It can be identified that the better contrast between defective and non-defective region is achieved at the resonant frequency as in figure 6.

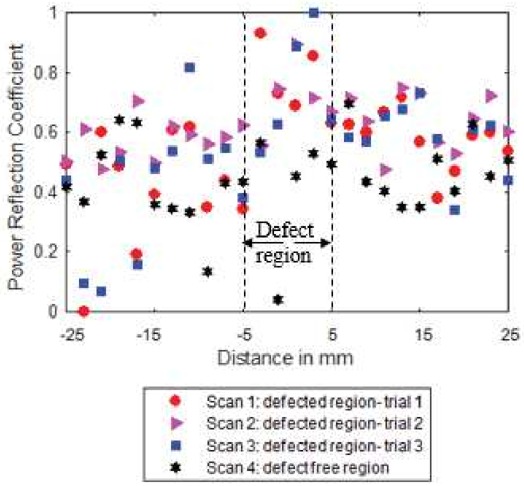

Figure 5. Reflection coefficeint meausrements across the defective and defect free regions at 2 GHz (non resonant frequency

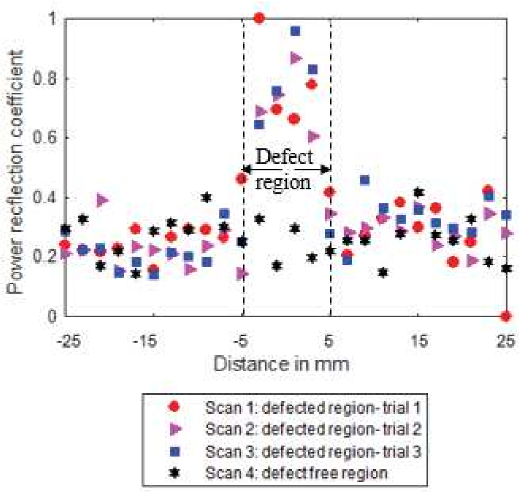

Figure 6. Reflection coefficeint meausrements across the defective and defect free regions at 16 GHz (resonant frequency)

6. Conclusion

Composite sample with spatial variation in dielectric constant has been subjected to microwave NDT deploying a coaxial probe with various backing materials and liftoff distance between sample–probe interfaces for ultra wideband excitation. The response from the composite was used to identify the sample resonant frequency. Reflection measurements on fiber glass composite gathered at resonance indicated ability to differentiate low dielectric contrast in thin composites. The measurement sensitivity improved absorber backed sample and the presence of the coupling material.

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8. References

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