Microwave Nondestructive Evaluation Using Spiral Inductor Probe

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Abstract. Non-Destructive Testing (NDT) techniques are crucial in various civil and military applications for detecting and characterizing defects. The NDT methods contribute to the sustainability, operational readiness, and overall success of civil and military engineering. However, conventional NDT methods need improvement to detect delamination in carbon fibre reinforced polymer (CFRP) composite. The Microwave NDT method using a spiral inductor probe has the potential to detect a hidden or subsurface defect in CFRP. Unlike conven-tional eddy current NDT method that mainly detects surface and near-surface defects. Thus, the sensor can penetrate deeper into CFRP, increasing the chance of detecting concealed delamination defects. The probe is analyzed using CST Microwave Studio's computer simulation software. The designed spiral inductor exhibits a return loss of -24dB and resonates at 419 MHz. The spatial resolution and sensitivity of the proposed probe are assessed using line scans and regression analysis. The probe demonstrates high spatial resolution and sensitivity in detecting defects at depths ranging from 0.5 mm to 3.0 mm. The performance of the proposed probe indicates that resonant frequencies decrease proportionally with the depth of the defect.

Keywords: Spiral inductor probe, Simulation, Delamination, and Microwave Nondestructive Evaluation

1 Introduction

With the introduction of modern composite material, such as carbon fibre reinforced polymer (CFRP), that shows remarkable ductility ad adaptability across diverse industries, it is imperative to develop an innovative nondestructive testing NDT method to inspect the structural integrity of the composite [1]. Nondestructive testing (NDT) can be defined as a set of techniques utilized to assess the integrity and quality of materials[2]. The NDT methods aim to detect and evaluate the tested sample's defects, flaws, or anomalies[3]. Contrasted destructive testing (ND) refers to a set of evaluation methods which causes physical damage to the tested sample [4].

The NDT method is intensively used in various industries, such as power plants and aerospace [5]. Consistent inspection evaluation of the structural integrity in these industries is compulsory, using NDT methods to avoid severe system failure. Implementing NDT inspections to evaluate structural damage is essential to minimize the maintenance cost and significantly enhance the safety and effectiveness of the system[6].
Various regularly utilized conventional NDT techniques such as digital image correlation, eddy current and ultrasonic[7]. The selection of the methods has relied on its benefits and drawbacks.

Nevertheless, the conventional NDT methods fell short of inspecting and evaluating CFRP composite due to the restriction of field penetration. Thus, an alternate inspection method is required to overcome the restrictions of field penetration.

Compared to conventional NDT methods, microwave NDT has surfaced as an inspiring method for assessing CFRP materials[8]. Microwave NDT methods have many benefits, such as being user-friendly, less expensive and non-contact. This research proposes a microwave NDT method using a spiral inductor probe with a square shape. The probe as a resonator allows effective miniaturization and use of lower microwave frequencies.
The SI probe was designed using CST Microwave Studio. The selection of the SI probe as the microwave NDT method to evaluate the condition of the CFRP composites was based on multiple factors. These factors include low cost and ease of design compared to other microwave NDT methods, and it has the advantage of using a single port to excite the sensor [9].

2 Theoretical Approach

Theoretical approaches to spiral inductor design provide a foundation for optimizing the sensor’s performance and achieving the desired characteristics for detecting delamination defects in CFRP composites. by utilizing electromagnetic modelling, magnetic field distributions and applying optimization algorithms to enhance the sensitivity and spatial resolution of the spiral inductor sensor enabling more accurate and reliable defect detection.

2.1 Spiral Inductor

This research utilizes a spiral inductor as a near-field imaging technique. The probe operates within a narrow frequency band and exhibits resonance. In contrast, non-resonant near-field imaging techniques operate across broader frequency ranges. The detection principle of the resonant spiral inductor is based on the interaction between the probe and the specific defect of interest in the near field. This interaction leads to variations in the probe's resonance frequency, enabling defect detection.

2.2 Inductance

when an alternating current (ac) flows through a conductor, it produces a magnetic field around it. The magnitude of this magnetic field depends on the current amplitude and the conductor’s geometry. For spiral inductors, the shape of the coil improves the magnetic field generated.
The equation can calculate the inductance L of a spiral inductor.

$$L = \frac{\mu_0 \mu_r N^2 A}{(l + 0{\cdot}5 d\pi)} \tag{1}$$

Where L is the inductance, μ_0 is the permeability in free space, μ_r is the relative permeability of the core material, N is the number of turns in the spiral, A is the cross-sectional area of the spiral coil, where π is a constant, and d is the mean diameter of the spiral coil.

3 Methodology

3.1 Design of the Spiral Inductor Sensor

The lower microwave range probe's design is depicted in Figure 1 with an 8-turn square SI sensor and a 7.1mm side length. A small loop is created around the SI to stimulate it, and both the SI and loop are built from 0.035mm copper strips on a 1.6mm thick FR4 4.3 substrate. The proposed SI sensor was simulated using CST Microwave Studio.

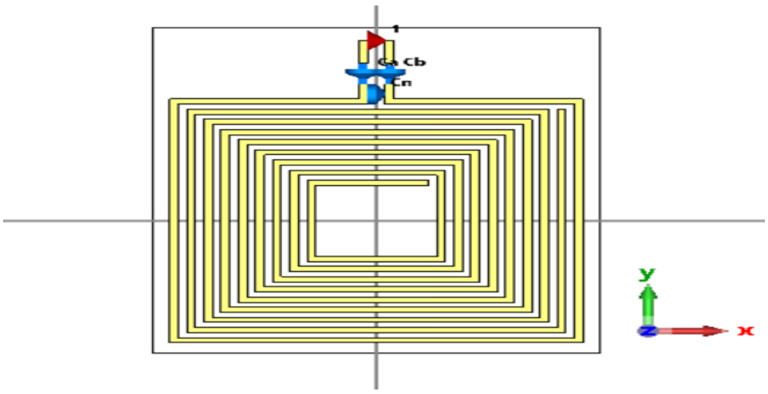

Fig. 1. Shows the proposed design spiral inductor probe.

The proposed probe incorporates a loop for feeding the SI while utilizing a matching network consisting of a 12pF capacitor (C_n) and two equivalent 2pF capacitors (C_a and C_b) to ensure a 50-ohm match. This study's main objective was achieved by simulating the spiral inductor sensor and found to resonate at 419 MHz with a return loss of S_{11} of (-24 dB), as shown in Figure 1&2.

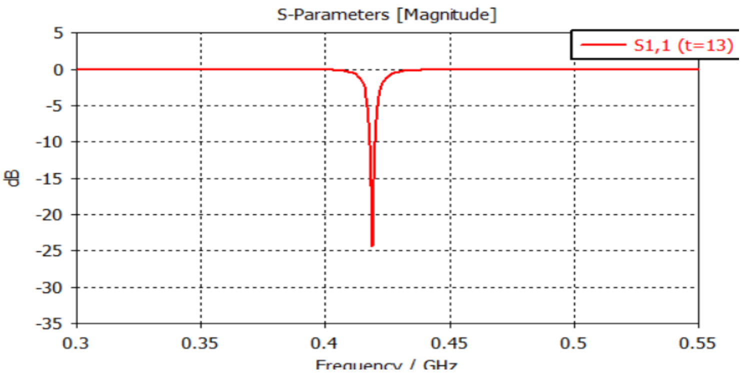

Fig. 2. Shows the return loss (S_{11}) in dB of the 3D simulated result of the probe.

3.2 CFRP Sample

This study employed a CFRP sample in a rectangular plate with 50mm x 50mm x 6mm (length, width, and thickness). Defects were created on the sample, and the proposed probe in Fig. 1 was utilized to examine the depths of the defects, which varied from 0.5mm to 3.0mm. A line scan was performed from -15mm to 15mm in length with a step size of 2.5mm to assess the probe's sensitivity.

4 Result and Discussion

4.1 Resolution and Sensitivity of Proposed Spiral Inductor Probe

Specific features of imaging systems are determined by their ability to detect defects. The image probe's near-field sensing region affects its spatial resolution and is influenced by the SI sensor's geometry. The near-field region of the probe is used to assess the magnitude of the surface current and examine the sensing region. Figure. 3 illustrates the surface current distribution over the x, y, and z planes in the near-field probes.

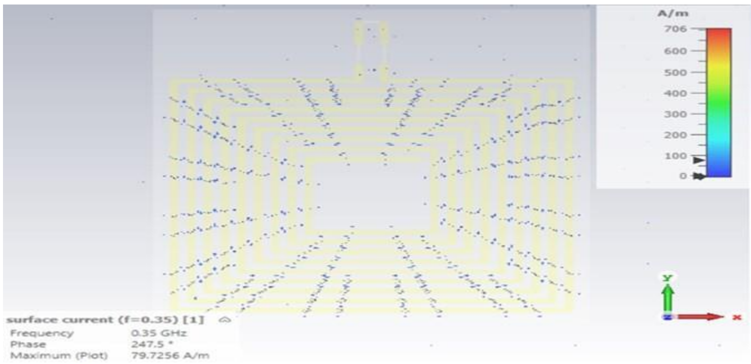

Fig. 3. Simulation of the near-field probe's surface current distribution in the x, y plane.

According to the findings, the imaging probe effectively detects surface current and exhibits superior spatial resolution in the near field. The surface current distribution in the probe's plane is symmetric along the x and y axes. The maximum positions along the x, y, and z planes, as depicted in Figure 3, are 12.900, -2.100, and 0.035mm, respectively. Thus, the probe's spatial resolution performance makes it suitable for defect detection during sample scanning. Furthermore, the sensitivity of the SI probe was investigated by scanning the depth of the defect sizes, ranging from 0.5mm to 3.0mm.

Six (6) observations were made, with the corresponding resonance frequency responses of 409, 404, 401, 399, 398, and 397MHz, obtained through line scanning. A linear regression analysis technique was used to determine the relationships between the two variables. Figure. 4 illustrates the regression analysis plot result.

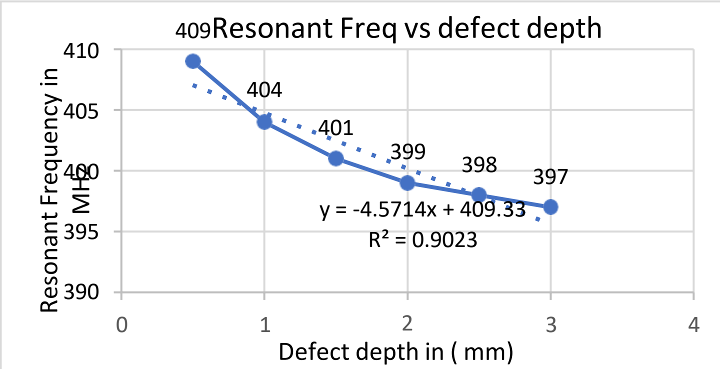

Fig. 4. Illustrates a regression analysis of resonant frequency vs depth of the defect.

The regression analysis produced an R-squared value of 0.9023 and an R-value equation of -4.571x +409.39. The R-squared value of 90.23% indicates that the defect's depth can explain variability in resonance frequency. The negative slope of the regression line (-4.517) suggests that the resonance frequency decreases as the depth of the defect increases. On the other hand, the line intercept (409.39) reveals the resonance frequency when the depth of the defect is 0.5mm. The results suggest that the SI probe used in this study demonstrates a strong sensitivity to the depth of the defect. The findings suggest that the probe can identify defects near the inspected material.

Table 1. Depth of defects and resonant frequency response.

Depth in(mm)	0.5	1.0	1.5	2.0	2.5	3.0
Resonant Frequency in MH	409	404	401	399	398	397

Matlab software was also used to plot the data in Table 1. The resonant frequency was plotted against the depth of the defect. As the depth of the defect increases, there is a decrease in resonant frequency. Therefore, it can be deduced that deeper flaws significantly impact the resonant frequency.

The result can be valuable in applications such as nondestructive testing, where the resonant frequency can indicate the defect's severity in the inspected material.

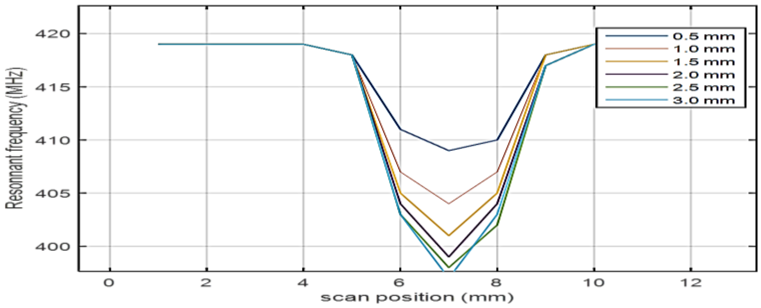

Fig. 5. Illustrates the Matlab plot of resonance frequency responses against the depth of the defect.

5 Conclusion

This research describes a novel microwave spiral inductor probe for detecting delamination in CFRP composites. The proposed probe performance shows that resonant frequencies decrease in direct proportion to the depth of the defect. This indicates that the probe is sensitive to small changes due to a material under taste (MUT) defect.

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