Progress In Electromagnetics Research B, Vol. 111, 99–110, 2025

(Received 16 February 2025, Accepted 1 April 2025, Scheduled 15 April 2025)

Precision Measurement of Thin Dielectric Coatings on CFRP Composites Using Microwave-Based CSRR Sensors for Aerospace Applications

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ABSTRACT: This project proposal addresses the critical need for precise measurement of thin dielectric coatings, which are essential in industries such as aviation, aerospace, and automotive for enhancing structural integrity and protecting against environmental factors. Manual application of these coatings often results in uneven thickness, necessitating a streamlined measurement method. Leveraging advancements in microwave technology, particularly the use of complementary split ring resonators (CSRR), this project introduces a novel measurement approach for coatings on Carbon Fiber Reinforced Polymer (CFRP) composites. By employing electric field coupling of a leaky wave antenna between a cylindrical dielectric-loaded sensor and the coatings on CFRP through a double circular ring slot, the method identifies a correlation between resonance frequency and coating thickness. The cavity is integrated with a Vector Network Analyzer (VNA) to detect S_{11} peaks at the resonance frequency, enabling precise measurement. Initial design comparisons using CST software resulted in a sensor antenna with optimal impedance matching and sensitivity, which was subsequently fabricated and tested in a microwave lab. Remaining objectives include developing a 4th-order regression model to predict coating thickness ranging from 0 to 2 mm for Polyethylene Terephthalate (PET) on CFRP composites and validating the method for industrial applications in aero-engine parts, gas turbines, and automotive structures. Future enhancements will focus on refining the technique for very thin coatings and exploring drone-based inspection methods for comprehensive aircraft analysis. This innovative approach promises a reliable solution for measuring coating thickness, which is crucial for maintaining the performance and safety of advanced composite materials.

1. INTRODUCTION

The precise assessment of thin dielectric coating thickness is of paramount importance across industries such as aviation, aerospace, and automotive engineering. In aircraft, the average thickness of these coatings typically varies between 50 and 500 μm. Due to complex geometries, painting is often done by hand, leading to variations in coating thickness, which are quite normal. Maintaining the coating within a specific thickness range is essential: coatings that are too thick raise fuel consumption, while coatings that are too thin compromise necessary functionalities. Therefore, accurate measurement of coating thickness is economically important. While current non-destructive testing (NDT) techniques show limitations in terms of accuracy, applicability, and efficiency, conventional techniques, such as weighing, are time-intensive [1]. The transition from aluminum to carbon fiber-reinforced polymer (CFRP) composites in modern aircraft introduces additional challenges in thickness measurement [2]. Aluminum exhibits high conductivity, enabling techniques like eddy current testing [3]. In contrast, CFRP composites, due to their lower conductivity and non-magnetic properties, make these methods ineffective [4]. Ref. [5] explored the millimeter wave technology for assessing the CFRP thickness of thermal barrier coatings (TBCs) with open-ended waveguide probes for precise measurements. Ref. [6] presents an overview of microwave NDT techniques specifically for fiber-reinforced polymer composites, emphasizing their applicability in modern engineering. Ref. [7] introduced an SLSR-based microwave NDT array sensor designed for inspecting surface cracks on coated CFRP structures, illustrating advancements in sensor technology for enhanced defect detection. The aerospace sector and automotive industry along with aviation need exact measurements of thin dielectric coatings on CFRP composites for safety purposes, performance optimization, and structural integrity evaluation. Two major obstacles prevent proper thickness measurement of these materials:

1. Quantitative and structural challenges caused by manual application methods combined with surface complexity produce uneven coating distribution that affects aircraft aerodynamic performance alongside corrosion protection and material reliability.
2. Multiple Non-Destructive Testing approaches including eddy current testing and X-ray fluorescence and terahertz scanning and ultrasonic methods demonstrate insufficient accuracy for measuring thin coverings at high operational

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costs and through need for coupling agents which limits their industrial application capabilities.

A microwave-based complementary split ring resonator (CSRR) sensor represents the proposed solution to address accuracy, non-contact operations, and cost-effectiveness challenges in precise coating thickness measurement. This technique strengthens sensor response and stability and enables manufacturers to conduct automated inspections through industrial systems. Eddy current testing (ECT) detection methods for CFRP composites encounter limitations during depth detection of flaws because of the low electrical conductivity and signal weakening effects. Soft computing together with fuzzy logic enables new NDT techniques which improve system accuracy for defect detection. Ref. [8] implemented a fuzzy model that enhances ECT depth detection accuracy. Ref. [9] integrated soft computing methods with eddy currents to effectively detect delaminations in CFRP plates and obtained better results. The development of AI-based defect recognition methods enhances NDT technology by improving both its speed and accuracy while increasing automation capabilities. The recent technological developments establish a solid structure which enables microwave-based NDT systems to operate with enhanced accuracy in continuous industrial processes.

The use of ECT as an electromagnetic testing method fails to work effectively for conducting fiber glass reinforced plastics because of their low electrical conductivity levels [10]. This measurement technique presents poor spatial resolution that generates inaccurate results when assessing thickness [11]. The small penetration depth of thin dielectric coatings causes readings to become unreliable because of incorrect data [12]. X-ray fluorescence (XRF) technology represents both complex operations and high costs and demands trained professionals while being unsuitable for industrial applications [13]. The promising technology of terahertz scanning requires significant financial investment and complicated calibration procedures according to [14]. Population analysis through XRF depends on material content though microwave methods present adjustable characteristics and yet need additional improvement protocols [15]. Ultrasonic testing (UT) experiences weak signal strength when measuring coatings that have little thickness [16]. The accuracy of this method becomes unreliable in different CFRP thicknesses because it needs to use a coupling medium [17]. The interpretation of non-contact UT results leads to frequent predictions that are wrong [18]. Real-time evaluation of weight-based techniques encounters accuracy issues according to research in [19]. The testing requires stabilized conditions for measurement which leads to longer lengths of time than microwave techniques operation [20]. Environmental fluctuations further reduce precision [21]. While advanced technologies, such as X-ray fluorescence and terahertz scanning, are often limited to laboratory environments due to high costs and equipment complexity, ultrasonic approaches are better suited for thicker coatings [22]. Thus, there is a significant need for new, low-cost, and effective sensors, especially for thin dielectric coatings on CFRP substrates.

The precise measurement of coating thickness is essential for aerospace applications because it ensures both structural integrity and corrosion resistance as well as component durability. The application of standard Non-Destructive Testing (NDT) methods including eddy current testing and ultrasonic testing with X-ray fluorescence technology does not result in suitable non-contact and real-time solutions at cost-effective prices for aircraft components. The proposed CSRR sensor provides accurate and sensitive measurements of thin coatings that exist on CFRP structures.

The research investigates actual aerospace settings because coating condition affects both system operation and flight safety standards.

- The measurement of protective coatings on aircraft turbine blades enables erosion and performance degradation prevention by monitoring them through extreme flight environment conditions.

- The assessment of anti-corrosion protective layers through Structural Components provides essential data needed for determining maintenance effectiveness of structures alongside predicting their health level.

- The non-contact method of thickness evaluation for carbon fiber-reinforced aircraft panels helps maintain both safety levels and product durability in aerospace structures.

Real-time accurate non-contact monitoring becomes possible through the combination of CSRR sensors with microwave-based measurement technology which serves automated aircraft inspection systems.

Microwave-based methods have emerged as an effective alternative due to their minimal power consumption, ease of setup, and lack of ionizing radiation risks. For measuring coatings on CFRP composites, a variety of microwave sensors have been developed, such as cylindrical cavity resonators, open-ended rectangular waveguides, and coaxial probes [23, 24].

CFRP composites exhibit characteristics similar to metals at microwave frequencies due to their electrically conductive fibers, which facilitate the creation of a closed resonant system when an open cavity is positioned on the composite surface [25]. A novel non-destructive method for measuring the thickness of surface coatings on polymer composites uses two microwave sensors: an open cylindrical cavity resonator with a T-shaped excitation element and a flanged coaxial line sensor [26]. This sensor method relies on the dielectric properties of the coating and composite, which may vary with temperature, humidity, and frequency. Therefore, the method may not be highly accurate under different environmental conditions or for different types of coatings and composites. The method involves two different sensors and a complex signal processing algorithm, which may increase the complexity and difficulty of the measurement. A microwave material characterization technique utilizing a modified open-ended rectangular waveguide probe was implemented to assess the thickness of various coatings on carbon composite and aluminum substrates for comparative analysis. Thickness estimation errors were influenced by limited sample sizes and the small air gap among the substrates, samples, and the modified probe. Consequently, a more accurate estimation of thickness is anticipated for actual coated structures. Thus, this proposal suggests a cylindrical double-slotted sensor for detecting coating thickness applied to Carbon Fiber Reinforced Polymer (CFRP) from 0.1 to 2 mm with high resolution.

2. METHODOLOGY

This section outlines the methodologies employed to design and evaluate the proposed sensors. Each method plays a vital role in determining the accuracy and reliability of the sensors in measuring coating thickness. The methodologies involve detailed designs, simulations, and performance evaluations using various sensor structures and configurations. Below, we describe each approach and the corresponding steps taken to achieve the desired results.

2.1. Design of Proposed Slotted Sensor

The proposed slotted type sensor operates on the principle of magnetic or capacitive flux leakage, which has been widely recognized for its accuracy and reliability in non-destructive testing applications. In capacitive sensors, the measuring unit plays a critical role by sensing changes in the capacitance between two plates that are separated by a dielectric coating. The slot provides a controlled orientation and alignment of the sensor, ensuring that the measurements are accurate and repeatable. This slot serves as a guiding feature for the measurement process and ensures that the sensor is positioned correctly during testing. Magnetic flux leakage sensors, on the other hand, concentrate the magnetic field in such a way that they are able to detect minute changes in the coating thickness. This functionality is particularly useful when there are variations in the coating material or coating thickness that need to be differentiated. The slot is particularly effective in geometries like edges or cylindrical shapes, where the sloped structure provides an advantage in controlling the area measured for coating thickness. Furthermore, the sensor's ability to measure non-metallic substrate coatings using capacitive principles makes it suitable for a wide range of applications in various industries. This proposed sensor is designed to improve accuracy in situations where the slot orientation can enhance the measurement over broader areas, providing a flexible and reliable solution to coating thickness measurement.

2.2. Design of Spiral Planar Antenna Design

A novel approach is proposed with the design of the spiral sensor, which utilizes a planar printed circuit board (PCB) mounted on a low-cost FR4 substrate, measuring 3.2 mm in thickness. The sensor consists of two primary components: the top part, which is connected by a 50 Ω coaxial probe through an SMA connector, and the lower part, which includes a planar spiral structure that enhances the sensitivity of the sensor. The spiral sensor is strategically positioned on a Carbon Fiber Reinforced Polymer (CFRP) material, which is coated with Polyethylene Terephthalate (PET), as depicted in Figure 1. In the simulation setup, the CFRP material is 3 mm thick, while the PET coating thickness varies from 0.1 mm to 2 mm, offering a comprehensive range for testing coating thickness variations. Additionally, a protective cover with a thickness of 0.025 mm is applied to the lower section of the sensor to ensure durability and improve the longevity of the sensor during testing and field use. Electromagnetic simulations are conducted to analyze the sensor's performance and behavior under different conditions. The simulations help assess the sensor's response to various coating thicknesses and material compositions, allowing for the optimization of the sensor's design. This simulation-driven approach plays a crucial role in evaluating the sensor's sensitivity, accuracy, and reliability. Through these detailed analyses, the design can be fine-tuned and enhanced, ensuring that the sensor meets the desired specifications and performs effectively in real-world coating thickness measurement applications.

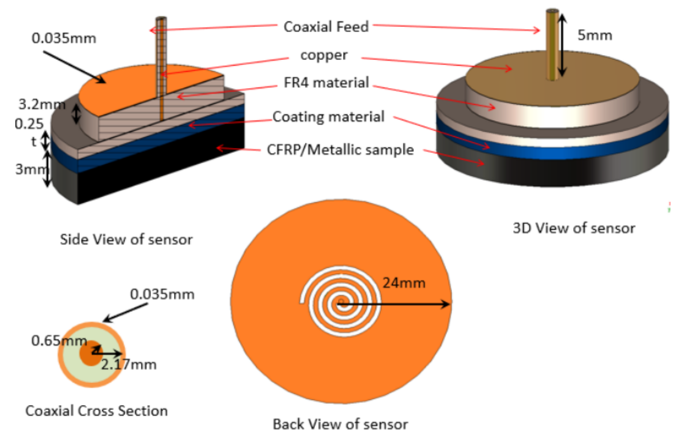


FIGURE 1. Design details of proposed spiral sensor.

The scattering parameters of the proposed spiral sensor for varying coating thicknesses of CFRP are depicted in Figure 2. The simulation reveals that the sensor is able to detect coating thicknesses up to 0.9 mm effectively. The data shows a strong correlation between the sensor's performance and coating thickness, allowing for precise measurements up to this threshold. However, once the coating thickness exceeds this value, the sensor begins to fail in distinguishing between different levels of coating thickness. This limitation is clearly evidenced by the overlapping curves in the graph, which indicate that the sensor's ability to differentiate between coating thicknesses diminishes as the thickness increases beyond 0.9 mm.

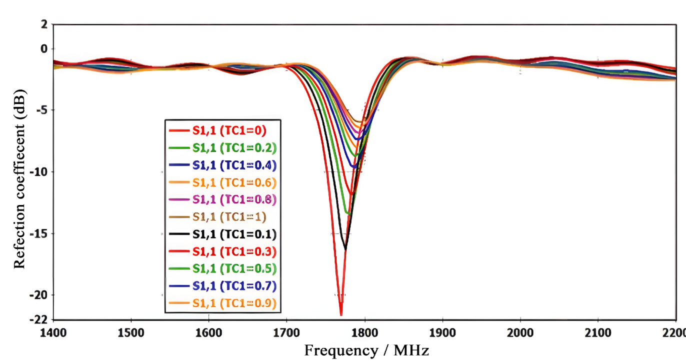


FIGURE 2. S_{11} parameters of sensor for coating thickness testing from 0 to 1 mm on CFRP.

The overlapping curves present a significant challenge in terms of the sensor's resolution. When the curves converge, it suggests that the sensor is unable to resolve the small differences in coating thickness beyond this point. This means that the sensor's sensitivity and accuracy degrade as the coating becomes thicker, which is a crucial issue for applications requiring precise measurements of thicker coatings. This performance limitation is an important factor to consider, particularly in industries where accurate coating thickness measurement is essential for product quality and performance.

The diminishing resolution, as highlighted by the overlapping curves, points to the need for design improvements to enhance the sensor's ability to measure thicker coatings with high precision. It is clear that as the coating thickness increases, the sensor struggles to maintain its ability to distinguish subtle variations, which could result in inaccurate readings and potentially lead to measurement errors. To address this issue, modifications to the sensor design are required. These changes may include adjustments to the sensor's structure, the introduction of new materials, or the optimization of electromagnetic parameters. By improving the sensor's resolution, it will be possible to ensure that it can effectively measure thicker coatings while maintaining high accuracy, reliability, and precision in real-world applications. Therefore, the observed limitations provide valuable insights that can be used to guide further design iterations and improvements in sensor performance, ultimately leading to a more robust and reliable solution for coating thickness measurement.

Possible modifications may include adjusting the sensor's structure, refining its parameters, or even incorporating new sensing techniques to improve its performance beyond the current threshold.

2.3. Design of Circular Symmetrical Slot Based Cylindrical Shape Antenna Design

The next sensor design employs a circular symmetrical slot-based cylindrical shape that is also mounted on a planar PCB, constructed using a low-cost FR4 substrate with a thickness of 3.2 mm. As with the previous sensor, this design also incorporates two primary components. The upper portion of the sensor is connected via a 50 Ω coaxial probe through an SMA connector, which facilitates the signal transfer between the sensor and external measurement system. The lower planar section of the sensor is where the unique design element comes into play: it features a circular symmetrical slot structure that is carefully engineered to provide efficient and accurate measurement of coating thickness. This design is optimized for measuring non-metallic substrate coatings, such as Polyethylene Terephthalate (PET), which are commonly used in various industries. The sensor is placed atop Carbon Fiber Reinforced Polymer (CFRP) material, which is coated with PET, as illustrated in Figure 3. This configuration is intended to ensure accurate measurement of the coating thickness, especially in materials like PET, which require precise monitoring.

In the simulation setup, the CFRP substrate is uniformly 3 mm thick, providing a consistent base for testing different coating thicknesses. The PET coating thickness ranges from 0.1 mm to 2 mm, offering a broad spectrum of thicknesses to be tested and analyzed. The wide range of coating thicknesses provides valuable insights into the sensor's performance across varying conditions. To further improve the durability and longevity of the sensor, a protective cover with a thickness of 0.025 mm is applied to the lower section of the sensor. This additional layer helps ensure that the sensor maintains its performance, even with repeated use over time. By protecting the lower section of the sensor from external elements and potential physical damage, the protective cover contributes to the sensor's reliability, allowing it to maintain high-quality measurements consistently over an extended period of usage.

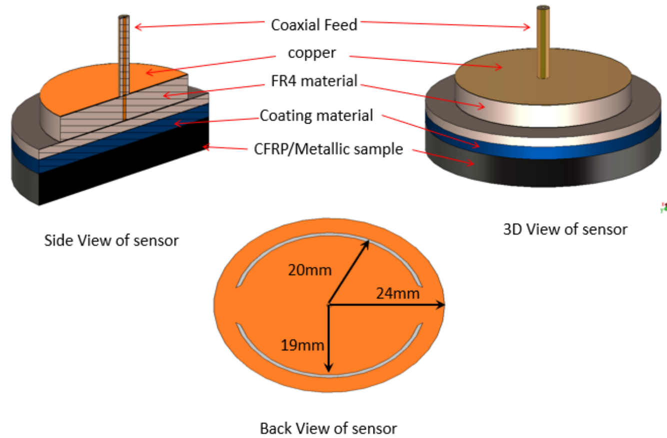


FIGURE 3. Design details of proposed circular symmetrical slot based cylindrical shape sensor.

The scattering parameters for the proposed sensor, which show its performance with varying coating thicknesses of CFRP, are illustrated in Figure 4. These simulations indicate that the sensor is capable of effectively measuring coating thicknesses up to 1.2 mm. This threshold demonstrates that the sensor can maintain high levels of accuracy and sensitivity within this range. However, beyond this range, the sensor's performance begins to diminish significantly, as evidenced by the overlapping curves in the graph. This suggests that the sensor's ability to distinguish between different levels of coating thickness becomes compromised beyond the 1.2 mm threshold. The overlapping curves indicate that the sensor is unable to resolve finer distinctions in coating thickness as the thickness increases beyond this point, which highlights a critical limitation in the sensor's resolution. This decrease in resolution needs to be addressed in future iterations to enhance the sensor's ability to measure thicker coatings with the same level of precision.

Additionally, the electric field distribution, as shown in Figure 5, illustrates how the sensor interacts with the coating material. The electric fields are coupled from the sensor to the coating material through the circular ring slots, facilitating the transfer of electromagnetic energy between the sensor and the coating. This electromagnetic coupling mechanism is crucial for the sensor's ability to measure the coating thickness accurately. As the electromagnetic energy is transferred through the circular slots, it interacts with the coating material in a way that changes the intensity of the electric field within the coating. This change in electric field intensity is directly related to

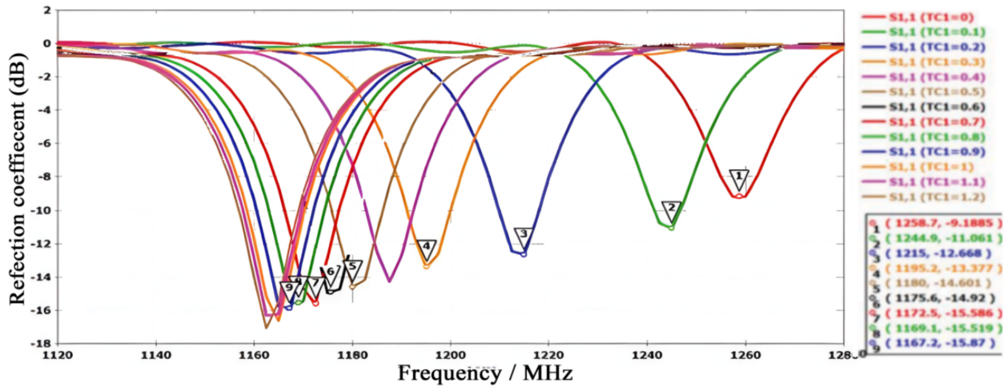


FIGURE 4. Coating thickness testing from 0 to 1.2 mm on CFRP.

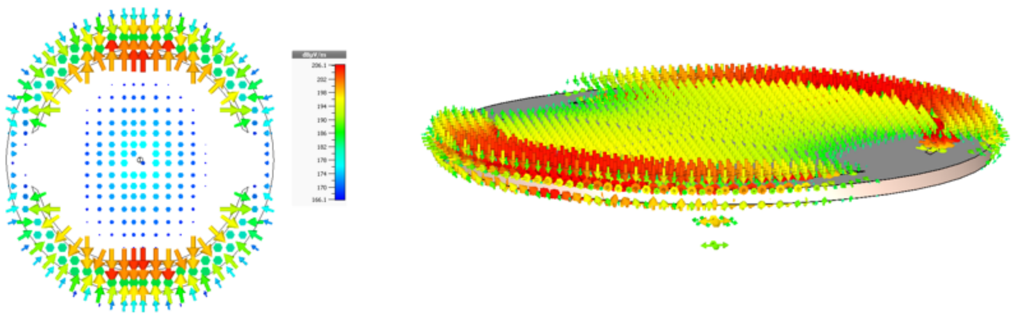


FIGURE 5. E-field distribution of sensor.

the coating's thickness, as different materials and varying thicknesses cause the electric field intensity to fluctuate in different ways. By monitoring the variations in the electric field intensity within the coating, the sensor can precisely determine the coating's thickness. The principle behind this is rooted in the behavior of electromagnetic waves as they propagate through different materials, where the interaction between the waves and material causes measurable changes in the wave's characteristics, such as intensity. Therefore, changes in the electric field intensity can be effectively correlated with variations in coating thickness, providing a reliable and accurate method for measuring and analyzing the coating material's thickness.

2.4. Design of Double Circular Slot Based Cylindrical Shape Sensor Antenna

The final proposed sensor for detecting the thickness of the coating applied to Carbon Fiber Reinforced Polymer (CFRP), ranging from 0.1 mm to 2 mm with high resolution, is introduced and elaborated upon in detail. This sensor design is carefully crafted to provide high-precision measurement, and its innovative features and capabilities are thoroughly showcased. The sensor is ingeniously engineered, utilizing a planar PCB mounted on a cost-effective FR4 substrate, which is 3.2 mm thick. This low-cost yet reliable material choice ensures that the sensor remains affordable while maintaining its performance. Its construction comprises two primary components: the upper portion, which is connected via a 50 Ω coaxial probe through an SMA connector, allowing for efficient signal transmission between the sensor and external system. The lower planar section of the sensor is where the design's uniqueness is evident, featuring a structure of double circular symmetrical slots. This thoughtful and well-executed design plays a crucial role in facilitating efficient and precise measurement of the coating thickness. Positioned atop the CFRP material that is coated with Polyethylene Terephthalate (PET), the sensor's ability to measure coating thickness is clearly demonstrated in Figure 6. The sensor's design ensures that it can effectively measure the coating thickness across a wide range, from 0.1 mm to 2 mm, offering versatility for various applications.

In the simulation setup, the CFRP substrate maintains a uniform thickness of 3 mm, providing a consistent base for testing. The PET coating thickness varies from 0.1 mm to 2 mm, which allows for a comprehensive evaluation of how the sensor performs when being subjected to different coating thicknesses. This broad range of coating thicknesses offers valuable insights into the sensor's performance across diverse scenarios, ensuring that it is capable of handling various coating applications. To evaluate the sensor's performance and behavior comprehensively, electromagnetic simulations are executed using the CST Studio Suite. This powerful software is widely recognized for its precision and versatility in electromagnetic analysis, enabling a detailed examination of how the sensor interacts with diverse coating thicknesses and material compositions. Through these simulations, engineers are provided with an opportunity to refine and optimize the sensor design iteratively, enhancing its sensitivity, accuracy, and reliability. The ability to simulate the sensor's response to varying conditions

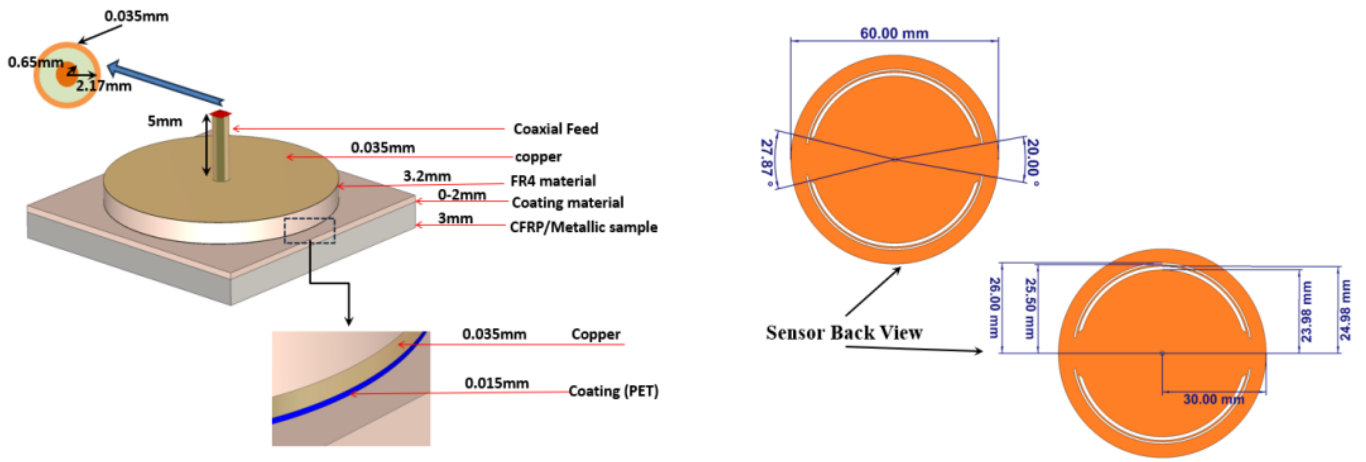


FIGURE 6. Front and back views of sensor design part.

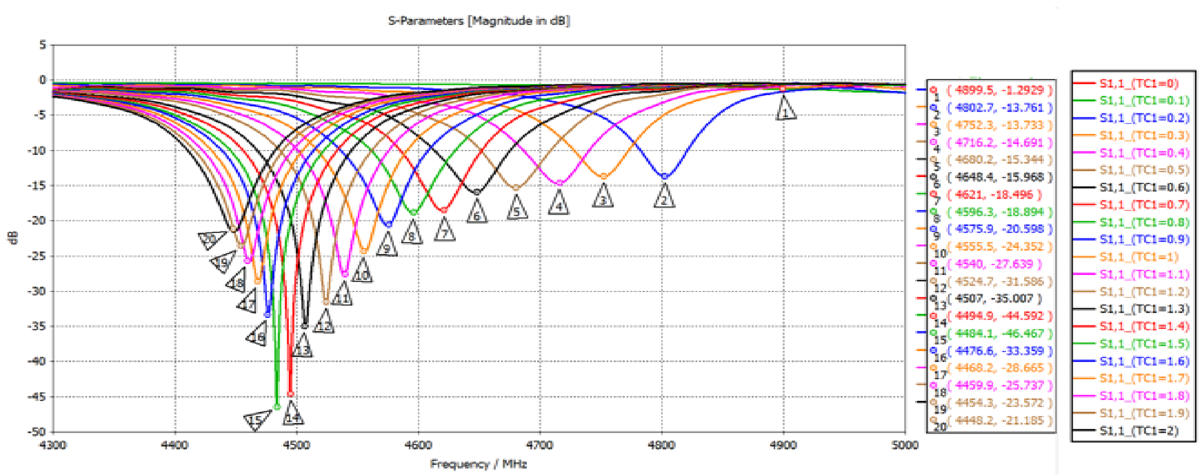


FIGURE 7. Coating thickness testing from 0 to 1.2 mm on CFRP.

ensures that the final design is robust, offering precise measurements in real-world applications.

The front and back views of the sensor design are shown in Figure 6, which illustrates the physical appearance and structural layout of the sensor. These views help provide a clearer understanding of how the sensor is constructed, as well as how the various components work together to enable accurate coating thickness measurement.

The scattering parameters of the proposed sensor, which depict its response to varying coating thicknesses of CFRP, are illustrated in Figure 7. These parameters show how the sensor's signal changes with respect to the different coating thicknesses, providing valuable data on its performance across various conditions.

Figure 7 presents the results from coating thickness testing, where the thickness is varied from 0 to 1.2 mm on CFRP. The simulation results offer a clear view of how the sensor responds as the coating thickness changes, highlighting the sensor's ability to measure small variations in thickness with high precision.

The simulation provides comprehensive coverage for coating thicknesses up to 2 mm, maintaining high resolution throughout this range. However, beyond this point, the sensor's ability to differentiate between different levels of coating thickness begins to diminish. This is clearly indicated by the overlapping curves in the scattering parameter plots. The overlapping curves suggest that the sensor's resolution becomes compromised beyond the 2 mm threshold, and it becomes less effective at distinguishing subtle differences in thickness. This observation highlights a significant limitation in the sensor's performance, pointing to a reduced capability in accurately measuring coating thickness beyond this range.

The overlapping curves in the scattering parameter plots also indicate a saturation effect, where the sensor's response reaches a plateau beyond a certain thickness limit. This phenomenon occurs due to the interaction between the electromagnetic waves and thicker coating layers. As the coating thickness increases, the sensor's sensitivity to small variations in thickness diminishes, leading to a reduced ability to distinguish between coatings with subtle differences in thickness. This limitation is an important consideration when the sensor is used for applications that require highly accurate measurement of thicker coatings. The design may need further adjustments or improvements to address this limitation and extend the sensor's range of effective measurements.

3. SIMULATED AND MEASURED RESULTS

3.1. Prediction Model of Sensor Sensitivity Using Regression Analysis

The simulation provides coverage for coating thicknesses up to 2 mm with high resolution. However, beyond this range, the sensor's ability to differentiate between different levels of coating thickness becomes compromised, as evidenced by the overlapping curves. This observation highlights a significant limitation in the sensor's performance, indicating a diminished capability beyond the 2 mm threshold. The overlapping curves in the scattering parameter plots suggest a saturation effect, where the sensor's response reaches a plateau beyond a certain thickness limit. This phenomenon occurs due to the interaction between the electromagnetic waves and thicker coating layers, resulting in a reduced sensitivity of the sensor to distinguish subtle variations in thickness.

The sensor's ability to detect changes in coating thickness becomes increasingly less effective as the coating reaches thicker layers, which can be attributed to the fact that electromagnetic wave penetration diminishes with increased thickness. As the coating layer increases, it becomes harder for the sensor to discern differences between various thickness levels, ultimately limiting its application in thicker materials.

Figure 8 displays the regression analysis of the proposed sensor with simulated data for PET coating samples. The sensor demonstrates excellent performance, exhibiting high accuracy, particularly evident in the 4th order regression model. This indicates a robust predictive capability of the sensor across a range of data points. The model's success is attributed to its sensitivity and precision in accurately reflecting the coating thickness. Additionally, the model can be adjusted or refined further to improve its accuracy in real-world applications where more complex variables may be involved.

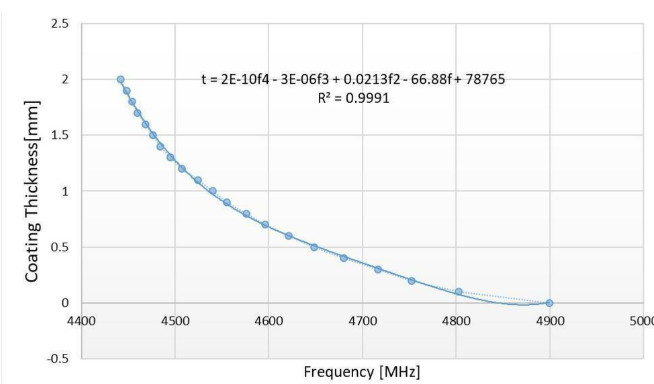


FIGURE 8. Regression analysis of proposed sensor with coating.

Furthermore, Table 1 presents the regression constants and coefficients, offering a comprehensive insight into the predictive model's parameters. Understanding these coefficients is crucial for interpreting the sensor's response and fine-tuning its performance in real-world applications. These coefficients serve as a foundation for improving the sensor's predictive capabilities, allowing researchers and engineers to refine the sensor for specific use cases. By understanding the relationships between each coefficient and the sensor's response, adjustments can be made to enhance the overall measurement accuracy, ensuring more reliable and precise results.

TABLE 1. Regression constants and coefficients.

Coefficient	Values
$k4$	2E-10
$k3$	3E-06
$k2$	0.0213
$k1$	-66.88
ko	78765
R^2 (Correlation Coefficient)	0.9991

This regression model provides a high degree of accuracy in predicting coating thickness based on sensor data. The R^2 value of 0.9991 indicates an excellent fit of the data to the model, reinforcing the reliability and precision of the sensor's performance for thickness measurement.

3.2. Field Distribution of the Proposed Sensor

The double circular ring slot structure in the sensor design plays a pivotal role in ensuring efficient coupling of the electric fields from the sensor to the coating, allowing for optimal interaction and delivering precise measurements. This design significantly enhances the sensitivity of the sensor by effectively channeling the electric fields, which in turn leads to an improved detection of variations in the coating. By leveraging the unique properties of this structure, the sensor can detect even subtle changes in thickness, ensuring high accuracy for industrial applications.

Leaky wave antennas, known for their ability to produce directed radiation patterns and controlled beam steering, are strategically utilized in this sensor design to improve its precision in sensing applications. The dynamic adjustment of beam direction not only enhances the accuracy of the measurements but also increases the reliability of the sensor, making it ideal for targeted sensing and high-resolution measurement tasks. The ability to adjust the beam direction allows for enhanced adaptability across varying environments, contributing to a more versatile and reliable sensor.

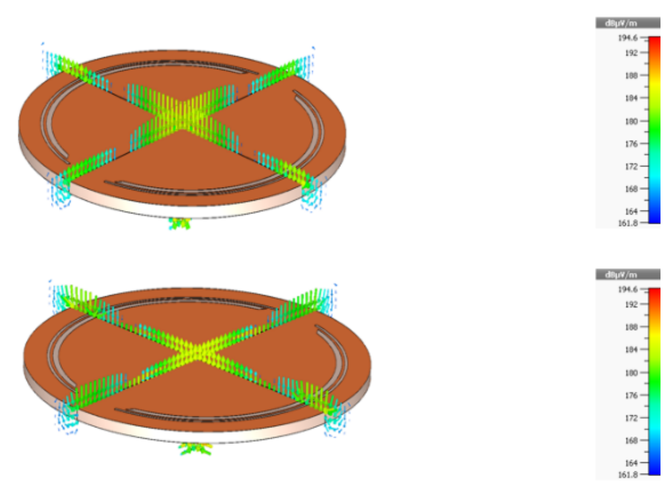


FIGURE 9. The intensity and spatial distribution of the electric fields depicted.

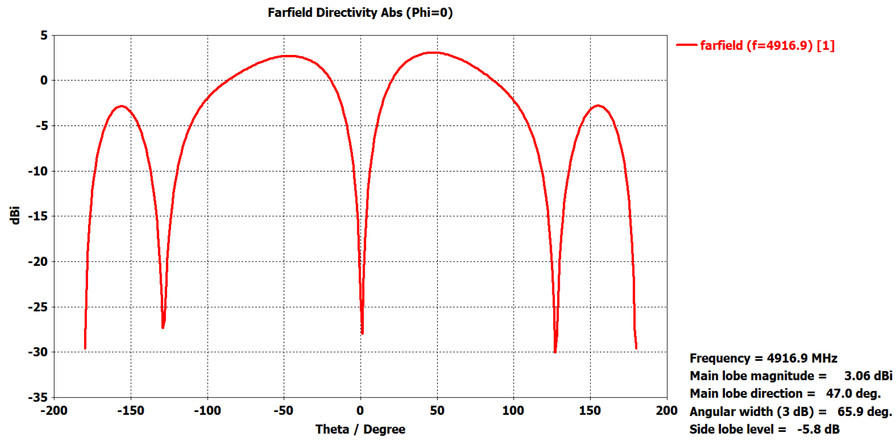


FIGURE 10. Far field analysis at phi = 0 deg.

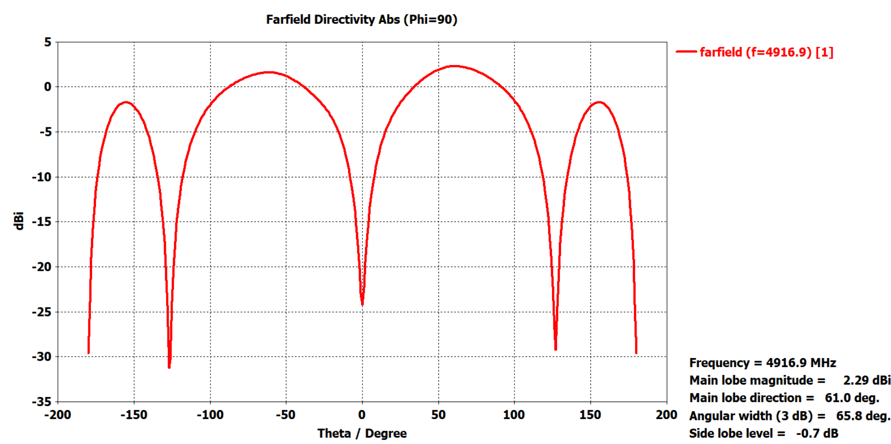


FIGURE 11. Far field analysis at phi = 90 deg.

The intensity and spatial distribution of the electric fields, illustrated in Figure 9, offer valuable insights into the sensor's performance. These field distributions are essential for understanding the sensor's accuracy and resolution, as they directly inform the optimization of sensor parameters. By analyzing these distributions, engineers can fine-tune the sensor to ensure that it operates at its best across different environments and conditions. This visualization also highlights the symmetrical properties of the electromagnetic field, which are critical for designing sensing systems that are both robust and adaptable.

A balanced electromagnetic response is crucial for maintaining consistent sensor readings, which enhances the reliability of the sensor in industrial coating thickness measurement applications. This consistency ensures that the sensor provides accurate data, making it a trusted tool for quality control and precision measurement in industries that require tight tolerances.

Overall, these visualizations deepen the understanding of the sensor's electromagnetic behavior and showcase its effectiveness in real-world applications. Through continuous simulations and refinements, the sensor undergoes iterative improvements that contribute to its enhanced accuracy, stability, and adaptability. The simulation-driven approach plays a vital role in optimizing the sensor's capabilities, allowing for more effective and reliable industrial applications. This iterative process of analysis and refinement ultimately results in a robust and dependable solution for coating thickness measurement, ensuring that the sensor meets industry standards for precision, quality assurance, and overall performance.

3.3. Radiation Pattern Analysis of Proposed Antenna

The radiation patterns of a sensor are crucial for understanding its performance characteristics and determining its suitability for various sensing applications. These patterns illustrate how the sensor emits or receives electromagnetic waves in different directions, providing a visual representation of its sensitivity and coverage area.

Figures 10 and 11 present the 2D far field radiation patterns of the sensor at angles of phi $= 0°$ and phi $= 90°$. These patterns reveal the characteristics of the leaky wave antenna, where minimal radiation occurs at the center and between the circular slots. The increased radiation intensity near the slots signifies their pivotal role in radiation emission. This distribution of radiation highlights the directional nature of the antenna, crucial for targeted sensing applications. Understanding these radiation patterns aids in optimizing the sensor's performance for

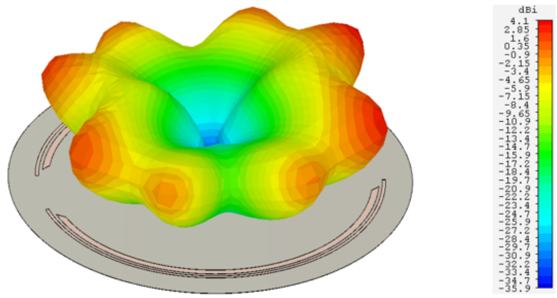
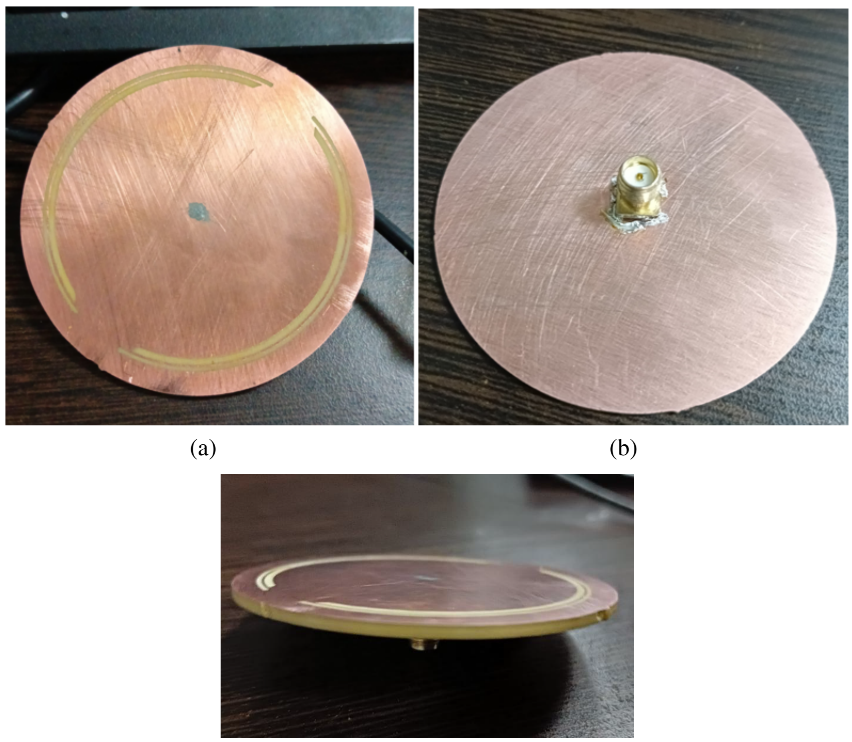


FIGURE 12. 3D radiation pattern of proposed sensor.



(a) (b) (c)

FIGURE 13. Sensor hardware, (a) back view, (b) top view, (c) 3D view.

specific detection tasks, ensuring maximum sensitivity and accuracy. Additionally, Figure 12 provides a three-dimensional representation of the radiation patterns, offering a comprehensive view of the sensor's electromagnetic behavior. This visualization captures the spatial distribution of radiation in all directions, elucidating the antenna's coverage and beam steering capabilities. By analyzing the 3D radiation patterns, researchers can fine-tune the sensor design to achieve desired sensing objectives, such as enhanced detection range or angular coverage.

By thoroughly testing the sensor with a diverse range of representative samples, researchers can comprehensively validate its effectiveness across various materials and applications. This rigorous evaluation ensures the sensor's reliability, accuracy, and adaptability, confirming its suitability for a broad spectrum of industrial and commercial uses. The selected samples serve as tangible proof of the sensor's capabilities, offering concrete evidence of its functionality and efficiency. Moreover, they highlight its versatility in different environments, demonstrating its potential to revolutionize multiple fields. By showcasing its impact across numerous applications, these tests establish the sensor as a critical innovation, paving the way for widespread adoption and integration into advanced technological systems.

3.4. Sensor Antenna Fabrication and Measurement Process

The simulated sensor antennas were fabricated and connected with a male connector for excitation of the antenna. The antenna's front and side 3D views are shown in Figure 13.

For coating analysis purposes, the CFRP material and PET samples from 0.1 to 2 mm were taken for measurement, as shown in Figure 14.

After the fabrication process was completed, the sensor antenna underwent rigorous testing using a vector network analyzer (VNA) capable of operating within a frequency range

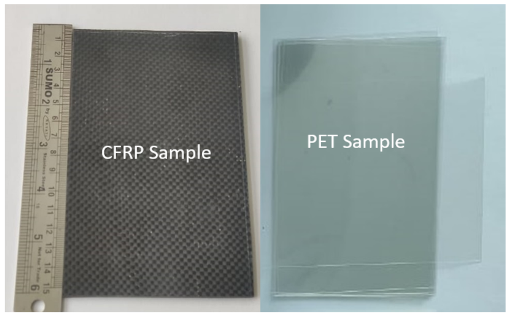


FIGURE 14. CFRP and PET sample.

FIGURE 15. VNA measurement setup.

TABLE 2. Comparison of conventional NDT techniques vs. proposed CSRR sensor.

Criteria	Eddy Current Testing	X-ray Fluorescence (XRF)	Terahertz Scanning	Ultrasonic Testing (UT)	Weight-Based Methods	Proposed CSRR Sensor
Measurement Accuracy	Low for CFRP due to poor conductivity [10]	High, but material-dependent [13]	High, but requires calibration [14]	Medium, depends on couplant [16]	Medium, sensitive to environmental variations [19]	High, precise thickness detection
Cost-Effectiveness	Medium, but probe replacements costly [11]	Expensive, requires trained personnel [13]	Very expensive, high operational costs [14]	Medium, dependent on coupling medium [17]	Low, but slow process [19]	Low-cost, scalable industrial solution
Applicability to CFRP	Poor, ineffective on non-conductive CFRP [12]	Effective, but limited by composition [13]	Good, but lab-based [14]	Moderate, relies on acoustic impedance [16]	Limited, dependent on weight stability [19]	Highly effective for all CFRP-based coatings
Sensitivity to Thin Coatings	Low, poor resolution [12]	High, but affected by surface roughness [13]	High, but costly for thin films [15]	Medium, signal attenuation issues [16]	Poor, struggles with minor thickness changes [19]	High, detects coatings as thin as 0.1 mm
Ease of Implementation	Medium, requires skilled operation [11]	Difficult, needs specialized training [13]	Difficult, requires controlled environments [14]	Moderate, requires coupling agents [17]	Easy, but slow for real-time use [20]	Easy, integrates with automated inspection

of 3 kHz to 9 GHz which is displayed in Figure 15. This advanced testing procedure was essential in evaluating the sensor antenna's overall performance and efficiency.

The analysis was conducted using S-parameters, which provided crucial insights into the antenna's behavior under varying conditions. Specifically, measurements were taken for different thicknesses of PET material layered on CFRP material to assess their impact on performance. The simulated and measured results were compared and shown in Figure 16. The measured response got slight variation with frequency due to material loss. These results offer a comprehensive understanding of the proposed sensor antenna's response to material variations, ensuring its reliability and effectiveness in practical applications.

3.5. Comparative Assessment of Existing and Proposed Techniques

The comparison between traditional inspection techniques and the created microwave-based CSRR sensor is shown in Table 2. This comparison shows how the proposed method offers better accuracy to manufacturers and lower costs while being sensitive to defects and useful for industrial applications.

Research findings show that the CSRR sensor offers better performance than typical NDT methods because it delivers precise detection along with enhanced sensitivity at reduced expenses. The CSRR sensor operates without material contact because it functions independently from couplants or physical devices as eddy current and ultrasonic sensors do. The CSRR sen-

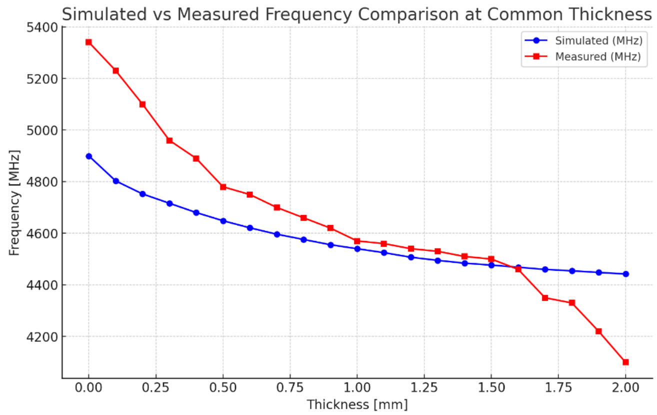


FIGURE 16. Comparison of simulated and measured frequency with varying thickness.

sor tops the measurements of XRF and Terahertz scanning with better precision at a reasonable cost and yet provides real-time monitoring capabilities. Weight-based techniques are inexpensive, but they provide no real-time measurement capability making them unreliable for precision-based industrial coating analysis. It is advantageous for aerospace applications to use the proposed CSRR sensor because it provides real-time measurements alongside high measurement precision for coating monitoring. The CSRR sensor provides automated non-contact structure evaluation of critical aircraft components compared to more expensive conventional assessment methods. Industrial applications support the practical value of the CSRR sensor through real-world implementation examples. The sensor provides turbomachinery blade coating erosion detection for maintaining both ideal engine performance and extended product lifespan. Anti-corrosion layer maintenance through regular inspections helps prevent equipment failure to save maintenance expenses. The CSRR sensor enables accurate thickness measurement of CFRP panels in aircrafts, thus allowing inspections without physical contact to verify safety compliance. Real-time adaptability and high sensitivity along with industrial process integration make the CSRR sensor provide cost-effective NDT alternative solutions in aerospace maintenance and safety assessments.

4. CONCLUSION

The research presents an innovative solution for accurately measuring CFRP composite coating thickness which provides high efficiency. A sophisticated sensor combines an electric field interacting leaky wave antenna structure with a cylindrical dielectric-loaded sensor coupled to a double circular ring slot to establish powerful interactions with CFRP coatings. Sensor frequency resonance follows a reverse pattern to coating thickness, so it functions as an excellent tool for developing accurate measurements. The resonance frequency detection becomes possible through S_{11} peak analysis when using a VNA integrated with the sensor for real-time precise measurements. A 4th order regression model serves to calculate coating thickness ranging from 0 to 2 mm when PET covers CFRP structures. This method delivers exceptional and consistent performance in addition to precise measurements which makes it appropriate for non-destructive testing applications. The proposed system functions outside laboratory boundaries due to its readiness for real-time inspection. On-site coating thickness analysis becomes quick and automated through portable instrument systems attached to drones for inspection needs specifically useful in aircraft maintenance and structural monitoring applications and quality control operations. Future research should use artificial intelligence to develop prediction models which are combined with automated data processing to enhance performance along with eliminating manual calibration requirements. By integrating drone-mounted inspection systems with CSRR sensor operators can conduct remote real-time and large-scale monitoring of coating thickness on complex surfaces that are hard to access. The research presents a ground breaking technique for non-contact coating measurement that merges beneficial properties of leaky wave antennas and VNA-based sensors with state-of-the-art regression analytics. The system delivers effective solutions for exact real-time automated industrial inspections through its adjustable execution and affordable capabilities.

ACKNOWLEDGEMENT

This work was supported by the Crescent Seed Fund Project Scheme. The authors would like to express their gratitude for the financial support provided by the B.S. Abdur Rahman Crescent Institute of Science and Technology, which made this research possible. The authors also acknowledge the facilities, technical assistance, and support provided by the Department of Electronics and Communication Engineering at B.S. Abdur Rahman Crescent Institute of Science and Technology.

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