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Non-Destructive Detection of Composite Defects Using Millimeter Continuous Wave by Analyzing Critical Change of Amplitude for S_{11}

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Abstract

Artificially engineered defects were intentionally embedded into planar composite specimens, which were subsequently characterized using a vector network analyzer in conjunction with a custom-built two-dimensional scanning platform. The spatial locations of these pre-implanted defects were determined by analyzing consistence in the reflected S_{11} scattering parameters, demonstrating that sub-terahertz wave responses are sensitive to structural irregularities within layered media. Furthermore, the critical interfaces were determined by coordinated analysis of amplitude local maxima and the deviation local maxima. The proposed methodology was validated through comparative assessments across multiple aeronautical-grade composite materials, confirming the efficacy of both the experimental hardware configuration and the developed imaging algorithm. This work contributes to the advancement of sub-terahertz inspection techniques and associated non-destructive testing (NDT) methodologies, offering potential improvements in aviation safety through enhanced defect detection capabilities.

Keywords

Millimeter wave; Non-destructive testing; Composite; Deviation analysis.

1. INTRODUCTION

The abundant applications of composite materials in modern aircrafts are foreseeable owing to their advantages in mass density, specific strength, resistance to corrosion, fatigue bearing capacity over metals and alloys. For instance, carbon fiber reinforced polymer (CFRP) is widely employed in load bearing structures of latest products from industry giants like Boeing and Air Bus. The hatch, wing cover and tail plane made of CFPR contribute to weight control of aircrafts significantly, implying substantial cost saving for every flight. As another example, honeycomb sandwich structures are superb in stiffness weight ratio and noise proof, which is a good solution to floor and bulkhead. However, the integrity and reliability of aerospace structures made of composite materials are critically dependent on their working conditions. Components exposed to airflow are routinely subjected to extreme mechanical, thermal, and environmental stresses during service. Undetected flaws—such as delaminations, voids could significantly compromise structural performance, potentially leading to catastrophic failure. Given the stringent safety standards and high operational costs associated with aviation, it is imperative to implement robust, non-invasive inspection methodologies that enable early and accurate defect identification without impairing material functionality. Non-destructive testing (NDT)

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aimed at composite materials not only ensures compliance with airworthiness regulations but also supports predictive maintenance strategies, extends service life, and enhances overall flight safety. Consequently, the development and refinement of advanced NDT techniques for aerospace composites and multi-layered materials remain a vital research priority in modern aeronautical engineering.

Millimeter wave is categorized as an extension of microwave that is more prominent in corpuscular property due to shorter wavelength. Meanwhile, it is competitive to achieve narrower beam width with the same aperture, which facilitates better resolution at wavelength level. According to previous studies, multiple materials exhibit moderate attenuation per unit distance, making it possible to acquire internal information of a complex structure. Given that ionization is not produced during irradiation, millimeter wave is friendly to operating personnels and is a promising EM wave band for non-destructive test (NDT). A number of researchers reported their work targeting at CFRP, glass fiber reenforced polymer (GFRP), aramid fiber reenforced polymer (AFRP), honeycomb sandwich panels, camouflage coatings. Rahman et al. reviewed the advance of NDT based on microwave, offering succinct tabular representation of studies and progress [1]. The critical structures examined include honeycomb-based aerospace radome composites, flight control surfaces, and myriads of Glass Fiber-Reinforced Polyester/Epoxy (GRP/GRE) composites. Vasagar V et al. addressed the significance of corrosion test by overviewing researches regarding non-destructive technique and pointed out the potential of millimeter wave [2]. Ding et al. reported their work on millimeter wave imaging, combining near-field synthetic aperture radar algorithm with L2 regularized unwrapping algorithm to obtain denoised image [3]. Sun et al. investigated the effect of lenses and made quasi-optic analysis of the image resolution of proposed linear frequency continuous wave (LFCW) detection system [4]. In 2024, Mohammadzadeh S, et al. employed a frequency modulated continuous wave (FMCW) radar to detect GFRP whose modulation bandwidth reached 1.65THz [5]. In this work, multilayer thickness measurements with volumetric imaging for defect detection purposes were carried out. Yee TS applied k-medoids clustering algorithm to process Gaussian filtered data acquired by VNA from 18 GHz to 26.5GHz, demonstrating that the quality of manufactured GFRP could be well supervised [6]. Fang, et al. focused on delamination occurred to GFRP and detect the flaw by monitoring reflective signal [7]. It turned out that the reflection signal varied with the defect thickness and depth. She also developed a sophisticated algorithm to overcome conventional limitations on scanning speed [8]. In this work, a rapid sparse imaging method integrating wave spectrum reconstruction and com-pressed sensing (CS) is creatively proposed and validated. Navagato MD, et al. verified that the features of EM wave enhanced by principal component analysis (PCA) and stacked sparse autoencoders (SSAEs) and an autoencoder network facilitate detection of hidden defects [9]. Apart from ones employed in aerospace field, other materials or even environment may also be investigated by millimeter wave techniques on condition that the defect size is at the level of wavelength or larger and that EM wave is capable of travelling through the medium without being attenuated massively. Fauquet F, et al. conducted NDT experiment on ancient enamel plate [10]. It was reported that the system revealed subsurface features such as fractures, as well as surface-level textural variations owing to the ornamental glazes. Stavros V, et al. investigated the interferometric imaging of defects in building walls and shielded structures by capturing the transmission of 5G millimeter-wave signals [11]. A 24-element interferometric receiving array was employed to conduct the experiment. Zeng et al. explored the potential of millimeter wave radar in detection of water surface acoustic wave (WSAW) [12]. According to simulations and experiment conducted, continuous wavelet transform contributed to fine WSAW detection, which may promote military applications involving underwater object detection.

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According to the previous studies, the difference in reflection or transmission signal underlies the probability of discovering flaws of composite materials including delamination, voids and debonding. Although received signals are subject to some artificial intelligent algorithms to depress noise, the purified amplitude or phase is mapped to the final image, displaying the position and shape of internal damage. As the general structure of material under test and the relative position of sample to the millimeter wave emitter and the receiver are already known, it is possible to highlight meaningful interval of signal for imaging by capturing meaningful change. Such assumption may simplify the complex steps to determine sample defects to a large extent.

In this work, we conducted NDT experiments on composite materials, which resembles non-ideal products owing to manufacturing limitations. The proposed simple NDT system composed of a vector network analyzer equipped with a frequency extension module, two lenses to adjust wave beam and a 2-dimensional motion stage to implement scanning. The system acquired time dependent S11 signal, which varied in amplitude and peak time. The prior knowledge attained was about the general structure of the sample, which indicated the rough temporal feature of S11 that was verified by experiment results. Moreover, a simple but feasible interval partitioning strategy is established by analyzing change in both amplitude local maxima and deviation maxima. Among the resulted slices, images with good contrast could be found to determine defect. This work would benefit development of algorithm for specialized composite structure and facilitate the application of millimeter wave technique.

2. METHOD AND INSTRUMENT

The vector network analyzer we employed is Agilent N5247A from Keysight Technologies, which operates from 10MHz to 67GHz. In order to shift its band to millimeter wave interval, frequency extension module was employed, which was purchased from Virginia Diodes Inc. The module works in pairs as a bidirectional frequency conversion front end in nature, resulting in transmitting and receiving signals from 75GHz to 110 GHz via heterodyne frequency conversion. In the experiment, 401 samplings in time domain were recorded to balance both precision and speed.

To carry out NDT experiments on materials, a system containing VNA, 2-dimensional stage, two lenses and a computer to control them both was built, illustrated by Figure 1. According to Figure 1, two lenses were inserted into the path of millimeter wave, which was employed to control the beam prior to irradiation spot. The distance between lenses is 150mm and focus length of two lenses is 75mm. The horn antenna attached to frequency extension module provides spherical wave with linear polarization that was focused by the closer lens, leading to plane wave between lenses. Furthermore, the plane wave was focused to scanning point whose reflection status was stored in its S11 signal. The 2-dimensional stage was assembled using two independent linear motion stages and controlled by a program. The graphical user interface allows convenient configuration of scanning parameters including range and steps. Above all, the acquisition of reflection wave by VNA (with help of frequency extension module) is also synchronized by home-made program. In particular, the acquiring and motion of material under test (MUT) in zigzag route is temporally alternate to avoid issues regarding positioning. Given that the precision of 2-dimensional motion stage reaches μm level, the size of spot contributed to the final resolution of imaging. Therefore, the spot size was optimized by adjusting distance between elements and the sample, leading to diameter around 6mm.

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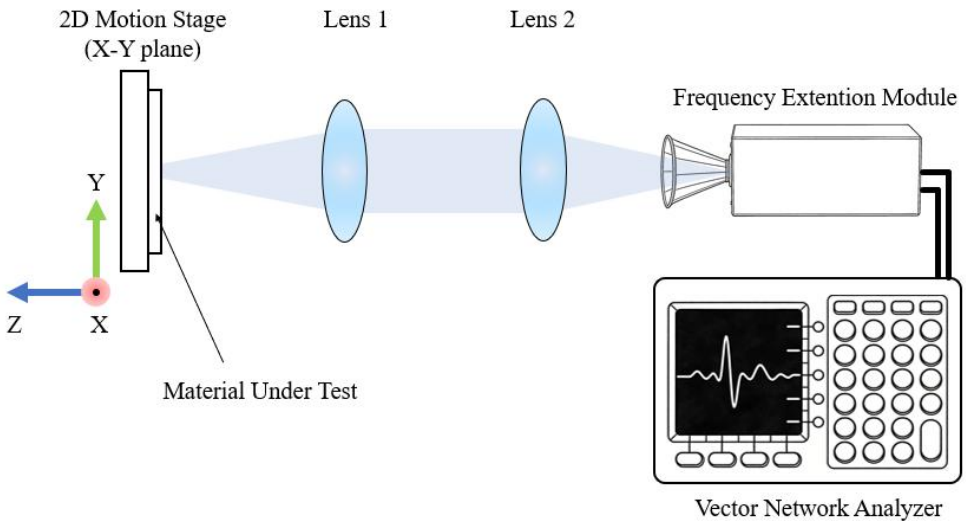


Figure 1. Schematic Diagram of the proposed NDT System for Composite Material Defect Detection

The five samples characterized in this work includes honeycomb materials, foam sandwich and GFRP. The defects pre-embedded to three kinds of samples are buried Teflon slice to simulate delamination. Though GFRP looks opaque, the outline and general position of pre-embedded Teflon slice can be identified under good light conditions. The foam between GFRP surfaces is made of polymethacrylimide (PMI). As for honeycomb materials, three layers of GFRP are separated by two layers of hexagon made of special paper. The embedded Teflon slice is buried beneath the top surface GFRP layer. The scanning regions for foam sandwich, GFRP and honeycomb materials are rectangles whose sizes are 40mm×40mm, 80mm×80mm, 140mm×40mm, respectively. The structure of samples was illustrated by Figure 2 where the fact denoted by squares are highlighted. The detailed information for five samples is listed in Table 1.

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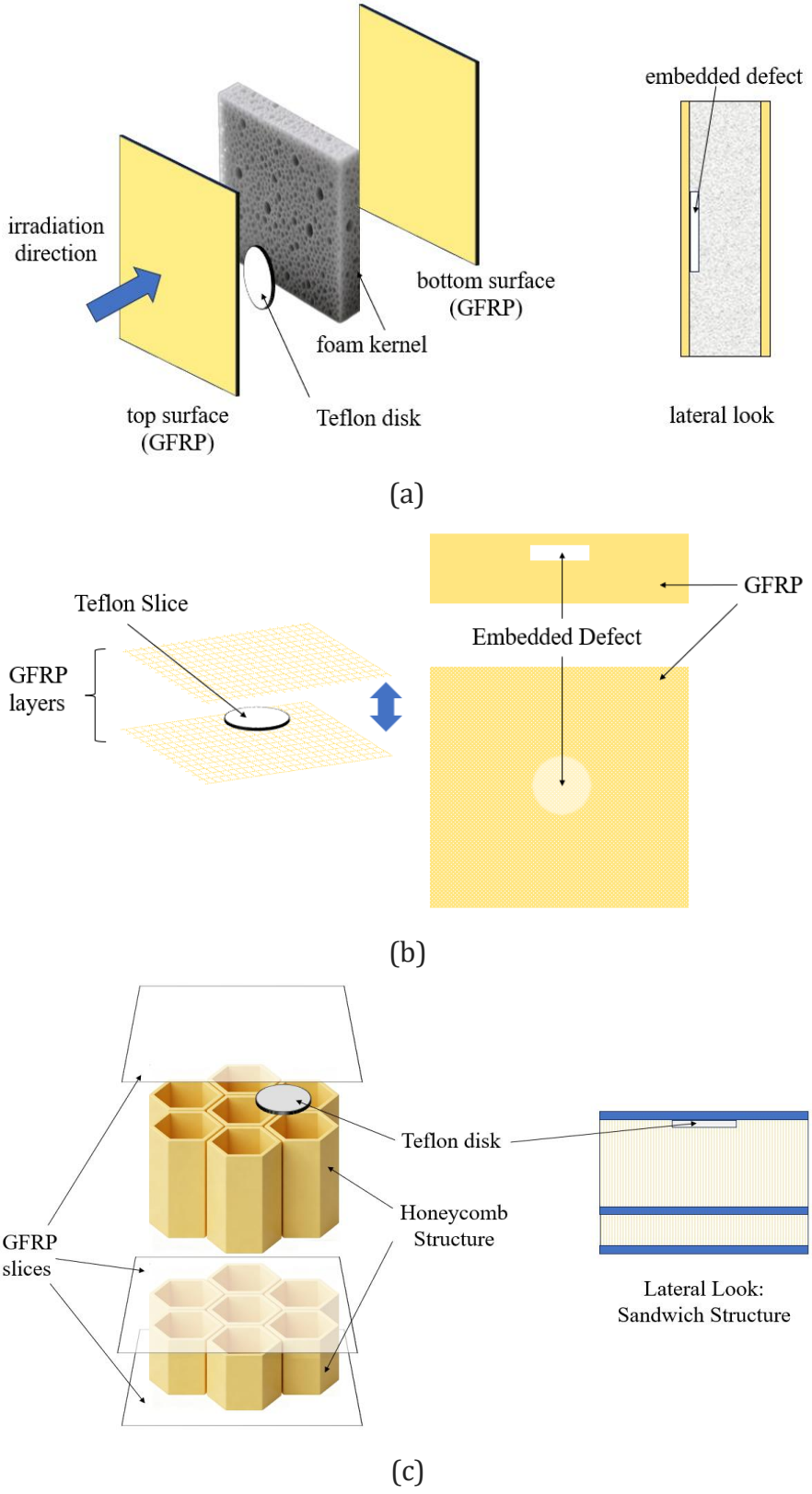


Figure 2. The structure of the tested samples: (a) foam sandwich (b) GFRP (c) honeycomb material

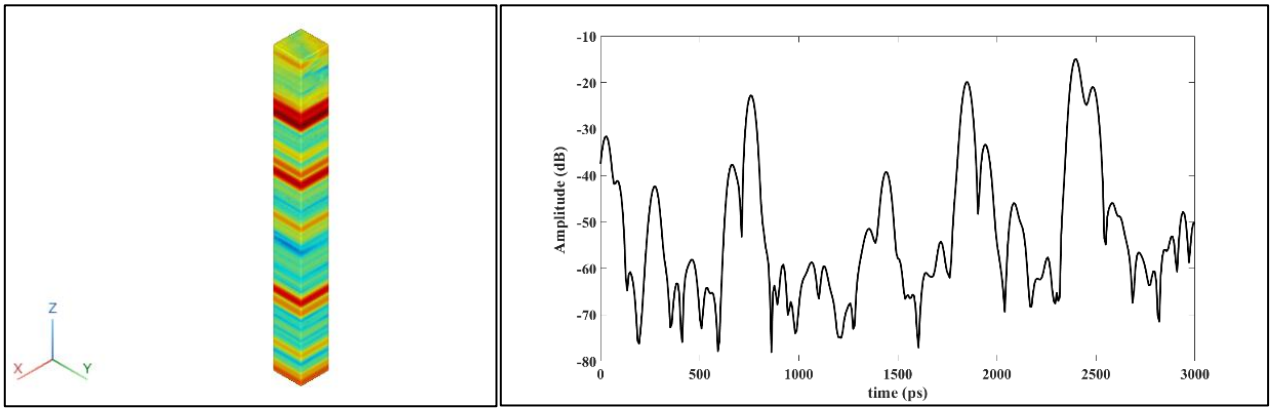
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Table 1. The detailed information for five samples is listed in Table 1

Sample number	Dimension/mm	Scanning Range/mm	Embedded Defect
#1: Foam sandwich	68×116×9	40×40	Teflon Slice (debonding)
#2: GFRP1	102×102×1.96	80×80	Teflon Slice (delamination)
#3: GFRP2	100×101×0.87	80×80	Teflon Slice (delamination)
#4: GFRP3	101×101×1.04	80×80	Teflon Slice (delamination)
#5: Honeycomb	100×198×34	140×140	Teflon Slice (debonding)

3. RESULTS AND DISCUSSIONS

Considering the principles the system follows during sampling, the VNA outputs a 3-dimensional matrix, whose indices in three directions corresponded to X displacement, Y displacement and amplitude with respect to time. VNA works in a linear sweeping way where continuous wave with linear increased frequency is emitted and received. By implementing Fast Fourier Transform (FFT), data in time domain is obtained and its fluctuations reflects surface reflection due to discontinuity in dielectric property [3]. The typical measure of the amplitude in time domain is exhibited in figure 3. As is seen, the time-dependent amplitude for the scanned area is mapped and rendered in JET configuration in Figure1(a), where the coordinate indicates the directions for scanning (X and Y) and time indexing (Z), respectively. JET mapping is conducted so as to improve the visual effect that can be numerically analyzed according to Figure 1(b). According to the principle of step-frequency continuous wave and the principle of heterodyne measurement, the impedance discontinuity contributes to local maxima that can be inferred as the connection of rectangle waveguide and horn, the front of and rear surfaces of lenses, and above all the external and internal surfaces of composite structure. As the millimeter wave would reflect between two surfaces, attenuated, scattered and partially received, multiple local maxima with small values in amplitude form simultaneously.



(a) (b)

Figure 3. The typical measure of the amplitude in time domain (#1): (a) 3D amplitude mapping (b) time-dependent amplitude for pixel indexed by (1, 1)

Furthermore, the curves regarding amplitude with respect to time for all scanning points of the tested materials are displayed in Figure 4. It is noticed that the trends of curves are consistent considering the dielectric and structure of material is alike but areas with embedded defects. Besides, the trends of curves for five samples are also alike because the majority of light

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path is exactly same for all tests. It is reasonable that all curves may overlap regardless of randomness in noise if the detected material is an ideal cuboid, homogeneous in space and mounted in a way that the top surface is perpendicular to the scanning beam. However, the actual material is not even in both dielectric and structure. The material is not perfectly mounted either, which would cause extra amplitude modulation and phase change during scanning. Therefore, the irregular deviation from the mean of curves occurs to every sampling location. Moreover, a positive correlation between the extent of deviation and the amplitude value is found. This phenomenon is more noteworthy when time is large enough to obtain information regarding solid sample, indicating that the interaction between solid material and EM wave is more complex.

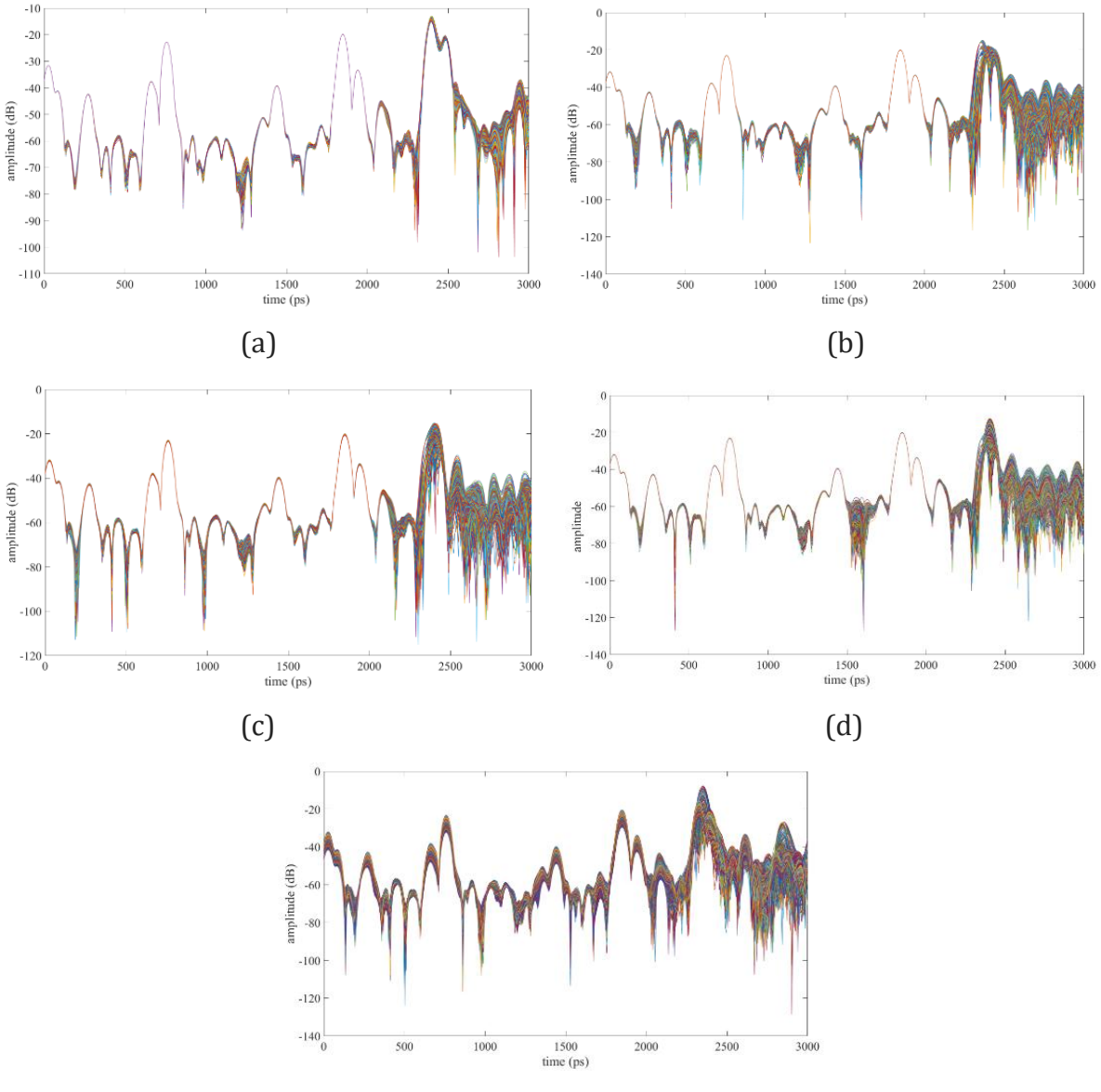


Figure 4. The time dependent amplitude for all scanning points of the tested composite material: (a) sample #1; (b) sample #2; (c) sample #3; (d) sample#4; (e) sample #5

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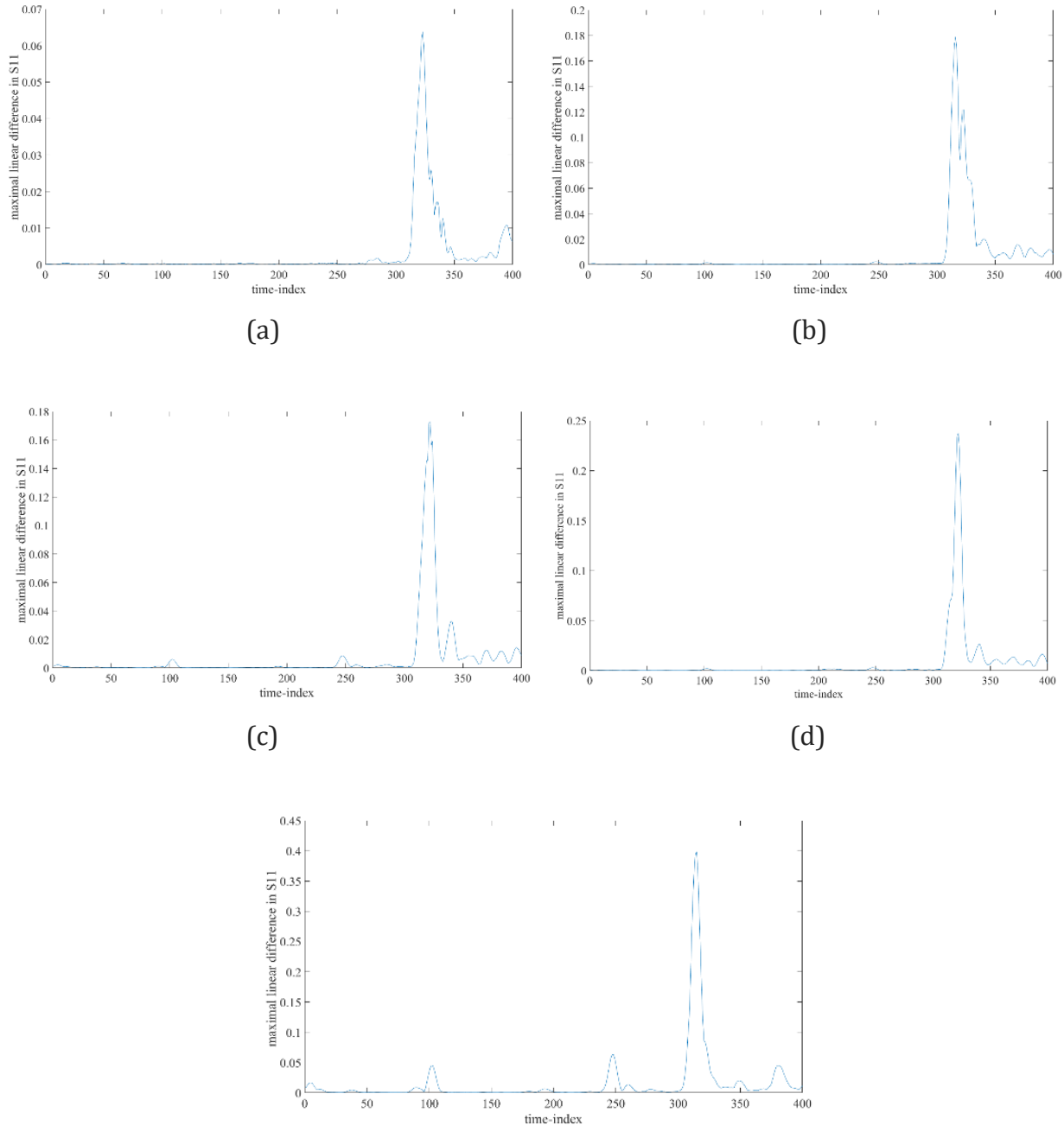


Figure 5. Time-dependent range for all samples: (a) sample #1; (b) sample #2; (c) sample #3; (d) sample #4; (5) sample #5

According to Figure 4, the consistence of curves in time exceeds that in amplitude. For example, despite much larger deviation observed for #3 in amplitude, the time deviation of peaks for #5 is not observed, which resembles the case in #1, #2, #3 and #4. However, at period from 2300ps to 2500ps, multiple peaks are observed for #3 and they vary in both peak time and amplitude values, indicating the dielectric distribution in light path change significantly. The most probable reason is the embedded of Teflon slice, which contributes to multiple reflections at different time. Thus, it is inspired that by analyzing meaningful peak time and deviation change, one could determine the temporal interval indicating the material as well as the embedded defect. As the distance between lenses are twice the distance between lens 2 to the sample, the peaks corresponding to lenses and front surface of the sample can be determined, which lie at 757.5ps, 1852.5ps and around 2400ps (sample dependent). In Figure

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5, we plot the deviation of curves for every sample by calculating range with respect to time, which purified the temporal feature to be analyzed. The range with respect to time is about a wide peak posterior to the front surface of the material under test. Herein, we eliminate the unit of time by dividing time step to argue that the deviation view is an analysis strategy employed instead of a new, transformed signal and the range in linear form is employed. Additionally, multiple local maxima attached to profile are also found, different in both value and time-index.

The deviation is contributed in different mechanisms depending on the composite material. In GFRP, multiple glass fiber layers are stacked and solidified during manufacturing, which result in nonuniformity in dielectric [13-15]. Every layer consists of holes which would be filled by others while adding new holes distributed elsewhere which are also filled by certain layers. As for foam sandwich, the size of holes and the location of holes are diverse, which can be equivalent to a group of scattering balls. The uncertainty in structure lead to multiple scattering plane, which cause multiple local reflections within sample to change the wave form [16-19]. The macro structure of honeycomb is approximately periodic if longer wavelength is considered. However, the reflection from walls is diffuse reflection, which destroy the interference chance, forming dispersed train of waves along different directions [20,21]. We examined the imaging slice with the largest range to acquire better result in Figure 6.

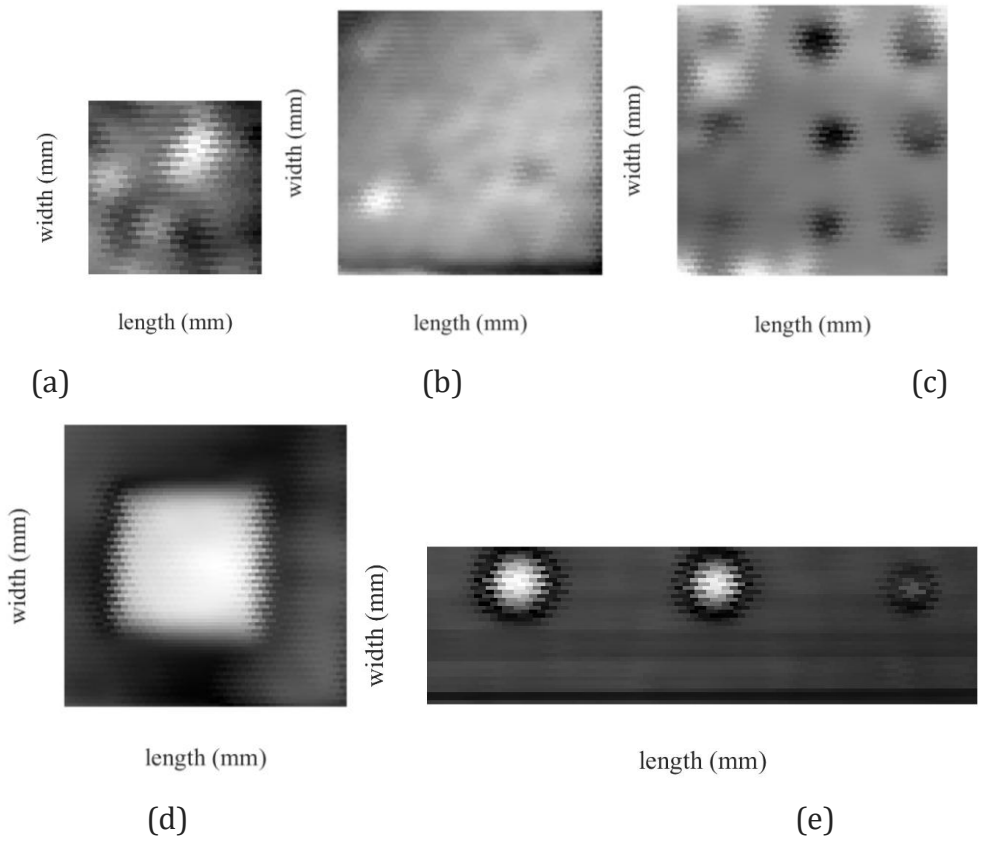


Figure 6. NDT Imaging slice of composite considering considering amplitude deviation: (a) sample #1; (b) sample #2; (c) sample #3; (d) sample #4; (5) sample #5

As is shonw in Figure6, the defect within composite can be identified whereas the gray level is not uniform because the deviation is determined by comparing all amplitude values and normalization is conducted during imaging. The images exhibite 1(circle, light), 4(form a square), 9(circle, square and triangle), 1(square), 3(circle) defects, respectively. The edge of Teflon for #3, #4, #5 sample is much clear because of good craft. It is also implied that the millimeter wave propagation within regular structure facilitates identification of abnormality. Another disadvantage to compromise the experiment lies that the surface is partially painted to

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determine scanning area containing defects under visible light. Image shown in figure 6(b) fails to obtain well-identiable edge owing to this passive operation. Besides, the information distributed along time is not fully utilized to form an integrated image, which shall be further investigated. The experiments suggest that defect including delamination and debonding occurred to composite materials for aerospace can be detected using continuous millimeter wave scanning, and that prior knowledge including general structure, position could be employed to determine appropriate imaging slice.

4. CONCLUSIONS

In this study, composite materials and structures including foam sandwich structure, GFRP, honeycomb structure were examined under a millimeter wave NDT system that contains a vector network analyzer with a frequency extender module, two lenses to adjust beam, and a 2D motion stage for scanning. By implementing zigzag scanning, the time dependent S11 was acquired, whose change and deviation among scanning area was analyzed in detail. By calculating slice with the largest range (deviation), key slices were extracted to locate the defect where prior knowledge was employed. The preset distance between sample, optical elements were employed to understand the peak. Meanwhile, the propagation principle of millimeter wave and prominent optical difference between solid material and free space underlies the deviation-based analysis. This investigation would benefit application of millimeter wave technique on NDT and development of algorithm considering prior conditions with respect to both material under test and system configuration.

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