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Nondestructive evaluation of GFRP composite including multi-delamination using THz spectroscopy and imaging

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A B S T R A C T

We utilize a fiber-coupled terahertz time-domain spectroscopy system (THz-TDS) based on photoconductive antennas to visualize multi-delamination and their thickness in a glass-fiber-reinforced polymer (GFRP) composite plate. We simulate a hidden multi-delamination by inserting a Teflon film in the GFRP composite plate that is fabricated using the vacuum-assisted resin transfer molding (VARTM) process. Reflected or transmitted terahertz (THz) waves are recorded from GFRP samples mounted on the x–y linear motorized stage during the investigation. The x–y linear motorized stage is driven in steps of 0.2 mm, thereby allowing us to scan the sample. We examine and compare the performances of the THz time-domain visualization (TTV) and THz frequency-domain visualization (TFV) algorithms to evaluate their characteristics for the visualization of defects. The thickness of the GFRP sample and multi-delamination is estimated using the reflection geometry method. Finally, we confirm that the hidden multi-delamination of the GFRP sample has been successfully visualized in the B- and C-scans. In addition, the thicknesses of the GFRP sample and the simulated delamination as compared with the experimental values exhibit a close consistency.

1. Introduction

Composite materials are widely used in fields such as aerospace, wind-energy technology, automobile industry, civil engineering, and ship maintenance due to their mechanical strength, stiffness, corrosion resistance, and low weight. However, the manufacturing of composite structures involves a complex procedure [1–3] in which different types of defects can be generated, for example, delamination, voids, cracks, dry fibers, etc. [4] In addition, defects are also generated and “grown” during the material’s lifecycle. Therefore, irregular characteristics that can predictably lead to defects during a composite material’s lifecycle should also be considered as defects. Moreover, as the usage of composite materials continues to increase and their application fields continue to extend, their quality and performance specifications are becoming more and more stringent. The main defect in composite materials is delamination, which is the separation of layers due to various stresses [5]. Therefore, it is very important to detect, locate, and visualize hidden delaminations in composite materials.

Many research groups have investigated and developed nondestructive evaluation (NDE) or nondestructive testing (NDT) methods [4], such as computed tomography (CT) [6,7], X-ray testing [8], liquid penetrant testing (PT) [9], magnetic particle testing (MT) [10], electromagnetic testing (ET), thermal infrared testing (IR) [11], and ultrasound testing (UT) [12,13] in order to detect hidden delaminations. Each technique has its own advantages and disadvantages. CT is limited to small-sized test specimen due to the structural limitations of the equipment and high cost of installation and maintenance. Meanwhile, during X-ray testing, composite specimens may be damaged, and operator safety may be compromised due to high radiation energy. Further, PT and MT can only detect surface cracks. While IR requires a thermal source to improve performance, composite materials will undergo thermal deformation when exposed to heat sources over long periods of time. UT requires a liquid couplant to efficiently transmit ultrasound signals to the specimen. In addition, UT can estimate the location of a defect, but the depth of the defect from the surface is difficult to detect, because ultrasonic waves are largely attenuated in air, including internal air layers formed due to delamination.

Recently, terahertz (THz) imaging technology has become the most promising technique for NDT [14]. The THz part of the electromagnetic spectrum extends from 100 GHz to 10 THz, lying between the microwave and infrared regions, and the wavelength range in this region spans from 3 mm down to 30 μm, as shown in Fig. 1. THz waves are not harmful to biological tissue, and they can provide high spatial resolution due to their shorter wavelengths. Previously, it was difficult to

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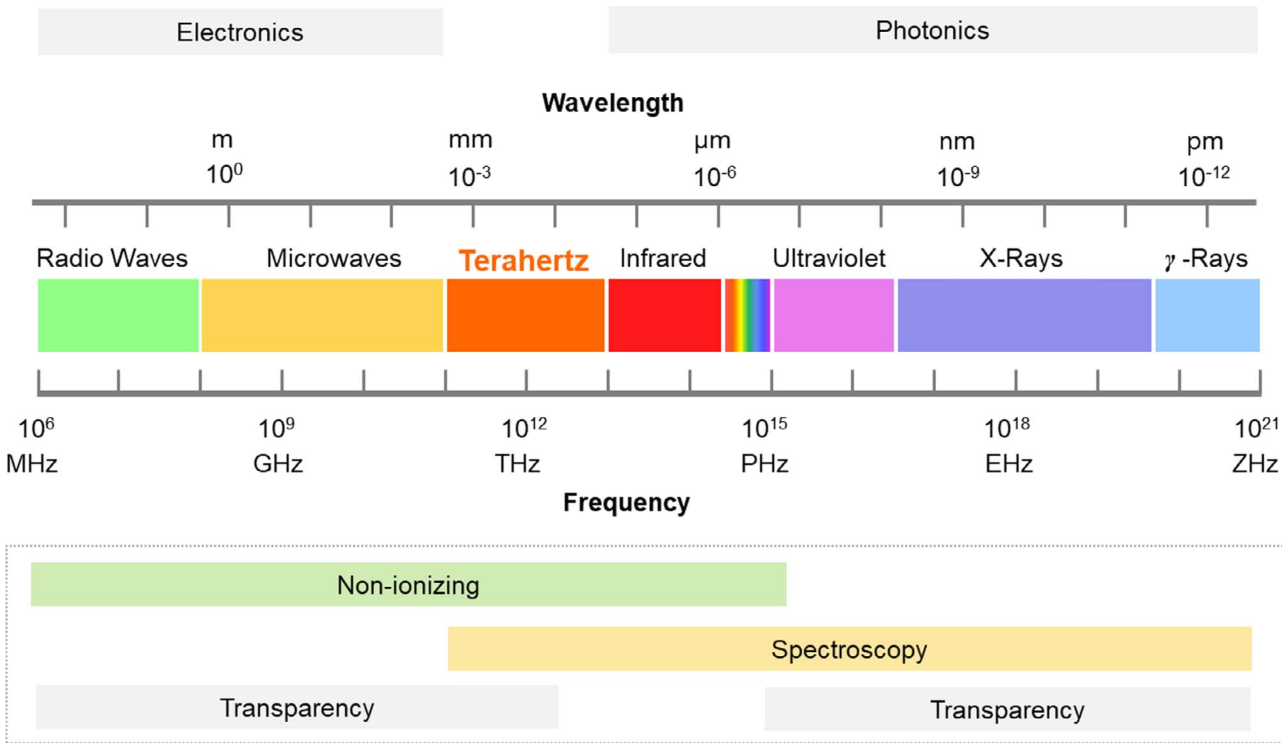

Fig. 1. THz band in the electromagnetic spectrum.

implement THz imaging due to the technical limitations of efficiently generating and detecting THz waves. However, the development of ultrafast lasers and ultra-micro machining technologies has contributed to the development of THz time-domain spectroscopy (THz-TDS). This evolution has enabled the introduction of THz-based technology to NDT, making apparent its advantages for the inspection of composite materials.

Many studies on THz-based inspection and visualization of defects in composite structures have been actively carried out to improve on the existing NDT limitations. Furthermore, THz-based inspection methods do not require a liquid couplant or any additional parts during inspection.

Table 1 summarizes the THz-based visualization methods proposed thus far. Redo-Sanchez et al. [15] demonstrated that occluded textual content could be successfully extracted from a packed stack of paper pages down to nine pages without human supervision via the use of a fiber-coupled pulsed THz-TDS system based on a photoconductive antenna (PCA). THz images were captured by mounting samples on an x–y motorized stage with 0.2-mm step size. Meanwhile, Dong et al. [16] considered reflection and transmission methods using a THz-TDS system based on PCAs to visualize a Teflon film in a glass-fiber-reinforced polymer (GFRP) plate consisting of eight glass fiber layers. Ryu et al. [17] visualized a simulated delamination in a GFRP plate by using a fiber-coupled pulsed THz-TDS system based on PCA. They set the incident angle to 25° in the reflection method. Further, Zhang et al. [18] attempted to image a Teflon film in a carbon-fiber-reinforced polymer (CFRP) plate consisting of two carbon fibers. They considered reflection methods using a THz-TDS system based on PCAs and processed the THz signals in the time domain. Sørgård et al. [19] studied a CFRP plate fabricated with twelve carbon fibers that included a simulated delamination between the carbon fiber layers. However, in all these studies, defect visualization was performed in either the time domain or the

Table 1
Summary of existing defect visualization methods.

	THz Source	THz band width (THz)	Time delay range (ps)	Scan size (mm × mm)	Scan step (mm)	Scan geometry
	Incident angle	Specimen	Defect type (Thickness)	Imaging method	Humidity	Scan method
Redo-Sanchez et al. [15]	Fiber-coupled PCA, Pulsed THz	0–2	0–100	22 × 44	0.2	Reflection
	–	9 layers paper	Text (20 µm)	Time-gated spectral, Time domain amplitude	–	Raster scan
Dong et al. [16]	PCA, Pulsed THz	0.6–3	0–45	50 × 50	0.1	Reflection, transmission
	–	8 layers GFRP	Teflon film (250 µm)	Time domain amplitude	–	Raster scan
Ryu et al. [17]	Fiber-coupled PCA, Pulsed THz	0.1–3	26–48	30 × 30	–	Reflection
	–	12 layers GFRP	Delamination (100 µm)	Time domain amplitude	1%	Raster scan
Zhang et al. [18]	PCA, Pulsed THZ	0–3.5	0–80	100 × 100	–	Reflection
	–	2 layers CFRP	Teflon film (150 µm)	Time domain amplitude	–	Raster scan
Sørgård et al. [19]	Fiber-coupled PCA, Pulsed THz	–	80–300	60 × 60	1	Reflection, transmission
	–	12 layers CFRP	Impact damage (-)	Peak-to-peak, Time domain amplitude	–	Raster scan