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AN EXPLORATION OF THE UTILITIES OF TERAHERTZ WAVES FOR THE NDE OF COMPOSITES

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ABSTRACT. We report an investigation of terahertz waves for the nondestructive evaluation of composite materials and structures. The modalities of the terahertz radiation used were time domain spectroscopy (TDS) and continuous wave (CW). The composite materials and structures investigated include both non-conducting polymeric composites and carbon fiber composites. Terahertz signals in the TDS mode resembles that of ultrasound; however, unlike ultrasound, a terahertz pulse can detect a crack hidden behind a larger crack. This was demonstrated in thick GFRP laminates containing double saw slots. In carbon composites the penetration of terahertz waves is quite limited and the detection of flaws is strongly affected by the angle between the electric field vector of the terahertz waves and the intervening fiber directions. The structures tested in this study include both solid laminates and honeycomb sandwiches. The defects and anomalies investigated by terahertz waves were foreign material inclusions, simulated disbond and delamination, mechanical impact damage, heat damage, and water or hydraulic fluid ingress. The effectiveness and limitations of terahertz radiation for the NDE of composites are discussed.

Keywords: Terahertz Waves, Time Domain Spectroscopy, Continuous Wave, Non-Conducting Composites, Carbon Composites

PACS: 81.70.-g

INTRODUCTION

Recent advances of technology and instrumentation in terahertz radiation have provided a probing field on the electromagnetic spectrum that is hitherto rarely explored for materials evaluation and structural testing. We report here an investigation of terahertz radiation for the nondestructive evaluation of composite materials and structures. Terahertz radiation can readily penetrate considerable thickness of dielectric materials, so that non-conducting polymer composites reinforced with glass, quartz, or Kevlar fibers are well suited for terahertz inspection. Structures such as aircraft radomes, designed for passing radar signals, are good candidates for inspection by terahertz waves. Wind energy turbine blades, being constructed of glass fiber composites, balsa wood, and adhesive, can also be penetrated with terahertz radiation. In this work, terahertz waves are explored as an NDE tool for detecting and characterizing flaws and damage in non-conducting composites. Carbon fiber reinforced polymer composites, on the other hand, are generally too conducting for terahertz waves to penetrate. However, the degree of penetration in carbon composites by terahertz waves, especially as a function of fiber orientation, is measured quantitatively in this study. The modalities of the terahertz radiation used in this study were time domain spectroscopy (TDS) in

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the reflection and transmission modes and the continuous wave (CW) mode in transmission. The effectiveness and limitations of terahertz radiation for the NDE of composites are investigated.

TERAHERTZ INSTRUMENTATION

The terahertz instrumentation systems used in this research were provided by TeraView Limited in Cambridge, UK. The instrumentation includes a time domain spectroscopy pulsed system and a frequency domain continuous wave system. The TDS system has a frequency range of 50GHz – 4 THz and a fast delay line up to 300ps. The beam is focused to focal lengths of 50 mm and 150 mm, the full width at half maximum (FWHM) beam widths are respectively 0.8mm and 2.5mm. The TDS system can be configured for through-transmission or reflection (small angle pitch-catch) measurements. The frequency range of the CW system is 50GHz – 1.5THz, with the best resolution being 100MHz. The focal lengths of the CW system are also 50mm and 150mm. Both the TDS and the CW systems are fully fiber optics connected.

APPLICATION TO NON-CONDUCTING COMPOSITES

Terahertz waves can readily penetrate non-conducting materials and can therefore be applied to the nondestructive testing (NDT) of glass, quartz, or Kevlar fiber reinforced polymer matrix composites. Solid laminates and sandwich structures with honeycomb or foam core can all be examined with terahertz waves. In this study, terahertz radiation was explored for the NDT of a variety of non-conducting composite materials and structures. Some preliminary results are summarized below.

Imaging of Multiple Delaminations

The time domain waveforms of terahertz pulses in the TDS mode bear strong resemblance to ultrasonic signals. Wave propagation concepts such as time of flight (TOF), transmission and reflection coefficients, refraction and diffraction are common to both waves. However, there are also fundamental differences when materials are probed with terahertz radiation, an electromagnetic wave, and with ultrasound, a mechanical wave. First and foremost, terahertz waves, unlike ultrasound, do not require a material medium to support it, and can therefore readily go through vacuum or air. In the ultrasonic inspection of flaws in a solid, the probing field suffers from the “shadow effect,” where a smaller crack situated behind a larger crack could not be detected. In contrast, there is no such limitation with terahertz waves. To demonstrate this effect, two semi-circular saw slots were cut into the edge of a 1/2” thick glass composite laminate, parallel to the surfaces, to serve as simulated delaminations, as shown in Fig. 1. The smaller slot (4” diameter) was located below the larger slot (5” diameter).

Using the TDS terahertz system in the through transmission mode, a scan image was made of the sample containing the double saw slots. The image of the transmitted terahertz pulse amplitude, also shown in Fig. 1, clearly revealed both saw slots. The right half of the sample contained a single saw slot and some resin-starved region nearby, which appeared in the image above it. The sample was also scanned from the top surface with reflection mode TDS terahertz pulse, and the double saw slots were again imaged. A model of the transmitted signal of a terahertz pulse through the double slot is reported by C. Thomas Chiou, et al [1].

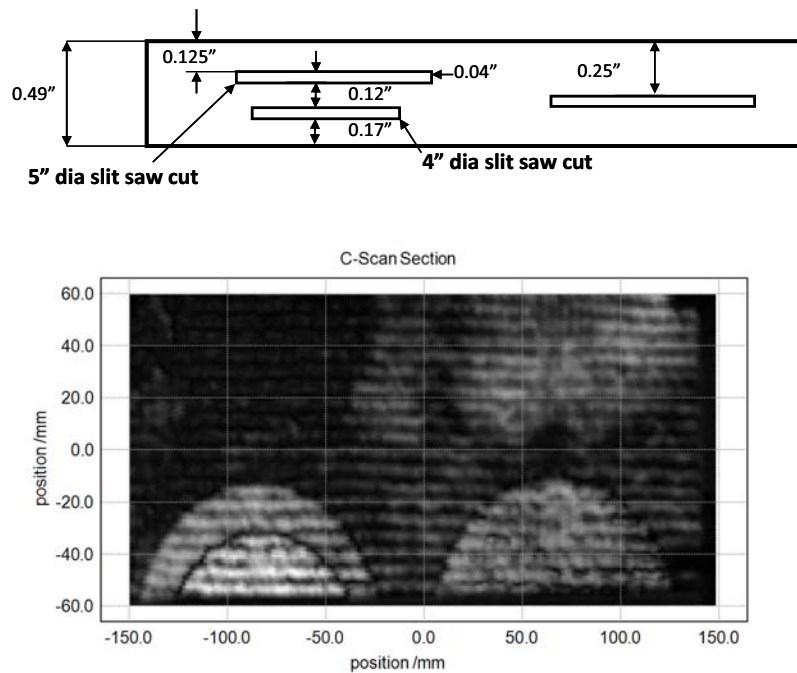


FIGURE 1. Terahertz TDS through-transmission scan image of double and single saw slots in a glass composite solid laminate. The results demonstrated that terahertz waves do not suffer from “shadow effect.”

Imaging of Impact Damage in Solid Laminates

Based on the capability described above, the multiple delaminations in solid composite laminates were imaged with reflection mode TDS terahertz waves. The specimen was a 24-ply woven glass epoxy solid laminate and the impact was made with a 2” diameter tup with an impact energy of 16.6 Joules. The reflection mode TDS scan was made on the back side of the sample so that the smaller delaminations were shadowed by the larger delaminations. Figure 2 shows the time domain signal (terahertz A-scan trace), where the two prominent pulses were reflections from the top and bottom surfaces of the specimen. To produce the images of the impact-induced delaminations, a time gate was imposed on the A-scan signal and the peak amplitude within the time gate was used to generate the images. Figure 2 shows four of such images with the time gates placed at 43-69 ps, 47-69 ps, 51-69 ps, and 56-69 ps, respectively. The series of images clearly showed the decreasing size of the delaminations toward the impact side.

Imaging of Embedded Flaws in Kevlar/Nomex Sandwich

Both the reflection mode (small angle pitch-catch) and the transmission mode TDS terahertz scans were found effective in mapping out defects embedded between the Kevlar

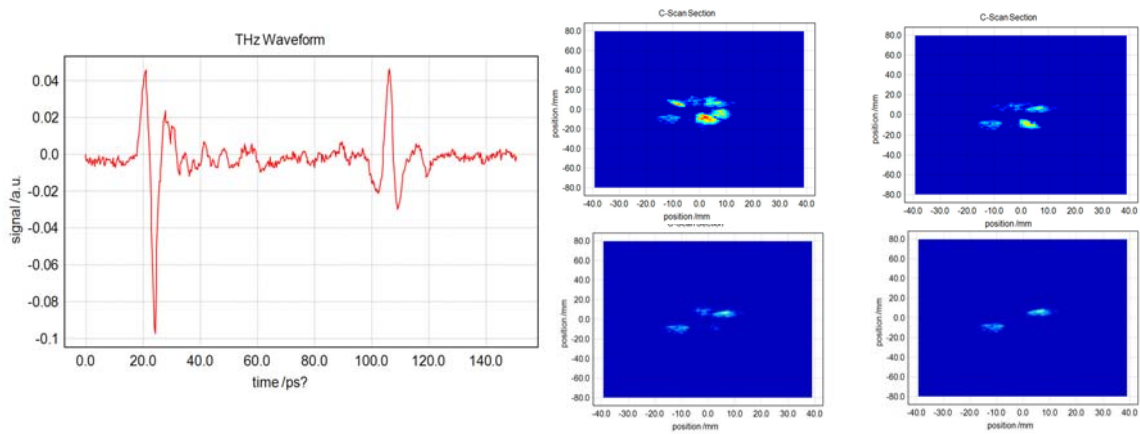


FIGURE 2. Time domain TDS waveform of glass composite laminate (left) and impact delamination images using different time gate (clockwise from upper left: 43-69 ps, 47-69 ps, 51-69 ps, and 56-69 ps).

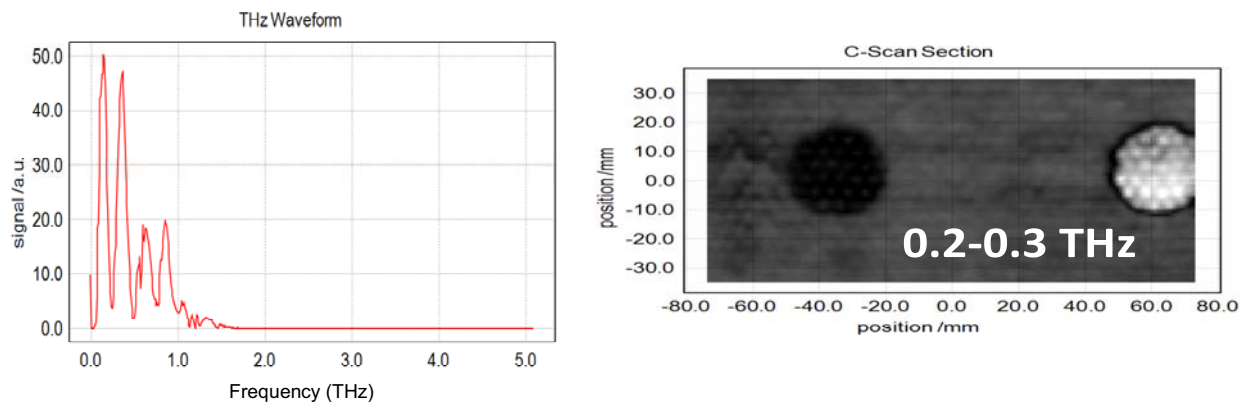


FIGURE 3. Embedded defects in Kevlar/Nomex honeycomb sandwich. FFT of TDS reflection signal (left) and image based on amplitude in the 0.2 – 0.3 THz frequency window.

composite facesheet and the Nomex honeycomb core of a sandwich panel. In addition to using the peak amplitude of the terahertz pulse reflected from or transmitted through the panel, images can also be generated using the frequency domain FFT signal. Figure 3 shows the FFT of the reflected signal from the top facesheet of the Kevlar/Nomex panel, together with the image based on the peak amplitude of the FFT signal in the frequency window of 0.2 to 0.3 THz. The circle on the right was a 1" diameter double Teflon film beneath the facesheet, and the circle on the left was a 1" diameter single Teflon film.

Penetration through Wind Turbine Trailing Edge

Wind turbines typically contain three different materials: glass composite, balsa wood, and adhesive. Since all three materials are electrically non-conducting, terahertz waves can be used for the inspection of wind turbines. To assess the penetration of terahertz waves through wind turbine materials, a sample cut from a turbine blade trailing edge was used in a TDS mode transmission test. The sample is wedge-shaped and contains two balsa-cored glass composite skins. The two merging skins were joined with a thick layer of epoxy adhesive, as shown in Fig. 4. The thickness was approximately 95 mm at the large end of the wedge and 45 mm at the small end. Before testing the trailing edge sample, the refractive index of each of the constituent was measured using 6 mm thick slabs of each material machined from other

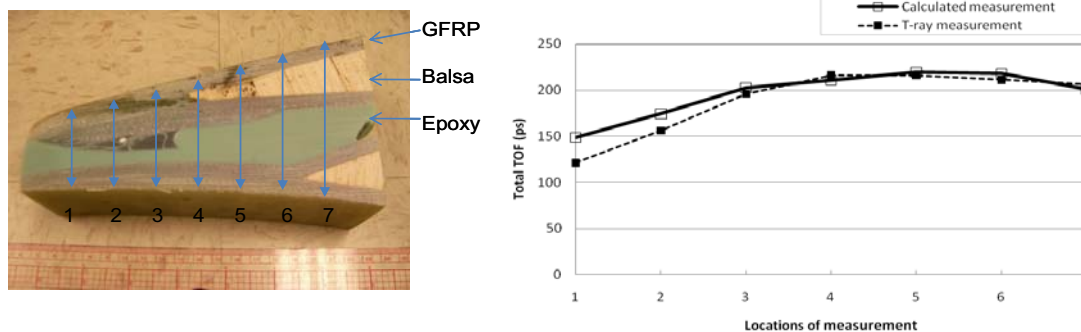


FIGURE 4. Transmission of terahertz pulse through the trailing edge of a wind turbine blade.

locations of the blade. The refractive index was measured to be 1.18 for the balsa core, 1.76 for the adhesive, and 2.17 for the glass composite. Through transmission time-of-flight (TOF) was measured at seven locations across the trailing edge. At each location the total TOF value was calculated using the measured refractive index and estimated thickness of each constituent. Since the thickness of the different layers varied considerably in the length direction, an average of the layer thickness on the two exposed ends was used. In addition, some voids also existed in the thick adhesive layer. Considering the complexity of the material, the agreement of the measured and calculated TOF values, also shown in Fig. 4, seemed quite reasonable.

Detection of Heat Damage and Fluid Ingression

Using the terahertz waves, we have explored the detection of heat damage in solid laminates of glass composite and water and hydraulic fluid ingression in honeycomb sandwich.

Both have met some success. The reflection mode TDS imaging was able to reveal the heat damaged region on a glass composite. Both reflection and transmission TDS signals were able to image water and hydraulic fluid injected into the honeycomb cells of a radome skin panel. More experiments in these areas are currently underway.

APPLICATION TO CARBON COMPOSITES

Terahertz waves can penetrate dielectric materials quite easily but not electrically conducting materials. The application of terahertz waves to the inspection of carbon composites is mentioned in the literature [2] but there has not been in depth studies. In this work, quantitative measurements were made for the penetration of terahertz radiation through solid laminates of carbon fiber composites. Special attention was given to the orientation of the carbon fibers in the plies of the laminate with respect to the electric field direction of the terahertz radiation. The flaws embedded under the top few plies of a carbon composite laminate were imaged with pulsed terahertz waves in the reflection mode.

Electrical Conductivity and Penetration through Carbon Composites

Carbon fiber reinforced polymer composites (CFRP) are poor conductors for electricity and the conductivity is anisotropic, so it is worthwhile to quantify the penetration of terahertz waves in carbon composites. The carbon fibers used in the manufacturing of CFRP are highly anisotropic microscopically; the electrical conductivity along the fiber axis is about three orders of magnitude greater than that in the radial direction. In a unidirectional laminate of carbon fiber composite, the transverse electrical conductivity is further impeded by the lack of continuity. The conduction mechanism in the transverse direction (perpendicular to the fiber

axis) is a percolation process that relies on the random contact between adjacent fibers. In the literature, the electrical conductivity data for carbon composites are somewhat sparse [3, 4]. The reported values of longitudinal conductivity (σ_l) varied from 1×10^4 S/m to 6×10^4 S/m. The range of reported data on the transverse conductivity (σ_t) is particularly large; from 2 S/m to as high as 600 S/m. The value of transverse conductivity in a unidirectional laminate is highly dependent on the manufacturing process and the quality of the composite. In a unidirectional carbon composite, the in-plane conductivity with the electrical current flowing at an angle θ from the fiber axis is given by [5]:

$$\sigma = \sigma_l \cos^2 \theta + \sigma_t \sin^2 \theta \quad (1)$$

Because of the highly anisotropic electrical conductivity ($\sigma_l \gg \sigma_t$), the penetration of terahertz waves through a unidirectional carbon composite depends on the relative angle between the electrical field vector and the fiber axis. When the electric field of the terahertz wave is parallel to the axial direction of the carbon fibers, the conductivity is the highest and the penetration is the lowest. When the electric field vector is perpendicular to the fiber axis, the conductivity is the lowest and the penetration is the highest. Using a value of $\sigma_t = 10$ S/m, the skin depth of a unidirectional carbon composite for a terahertz wave, with the electric field oriented normal to the fiber axis, is approximately 0.2 mm at 1 THz and 0.5 mm at 0.1 THz. Experimentally, we have measured the angular dependence of the power transmission through a 24-ply unidirectional carbon composite laminate using the CW terahertz system. Near the low end of the frequency spectrum ($f \sim 0.1$ THz), the transmitted power is more than 30 dB above the noise floor. The angular dependence of the transmitted power at 0.1 THz is shown in Fig. 5. When compared to the theoretical prediction based on the angular dependent conductivity, the measured power transmission at angles away from 90° is much higher than predicted. The prediction, under the assumptions that the incident terahertz radiation is precisely linearly polarized and that the fiber axes in the laminate are all parallel, would have the unidirectional carbon composite behaving like a polarizer with a sharp cut-off. The discrepancy between the expected and observed results is yet to be reconciled.

Detection of Shallow Flaws in Carbon Composite

Based on the electrical conductivity in carbon composites, we tried to understand the detectability of shallow embedded flaws in a carbon composite laminate. Tedlar (polyvinylidene fluoride) films, 0.001" thick and measuring $\frac{1}{2}$ " and $\frac{1}{4}$ " squares, were embedded in a quasi-isotropic carbon composite laminate at depths of 1 ply, 2 plies, 3 plies, and 4 plies, respectively. The fiber orientations in the first four plies of the laminate are respectively -45° , 0° , 45° , and 90° . Using TDS terahertz waves in the reflection mode, the flaws were scanned

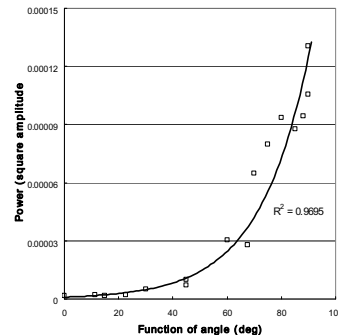


FIGURE 5. Angular dependence of transmitted power of 0.1 THz terahertz waves through a 24-ply unidirectional carbon composite laminate. At 90° the electric field vector is normal to the fibers.

and imaged. It was found that only flaws embedded below the first two plies were detectable and that the detectability of the flaws (or signal-to-noise ratio S/N) depended on the direction of the electric field vector of the terahertz waves with respect to the fiber directions in the first two plies. A series of scan images were obtained with the composite sample rotated every 22.5 degrees with respect to the electric field. Figure 6 shows the scan images of 1/2" and 1/4" square brass foils embedded below the first ply and the second ply respectively. Scan images were also obtained for the nylon and tedlar film flaws; the trends of the detectability or S/N for the three types of flaws were quite similar.

We then correlated the S/N of the flaw images to the conductivity of the first two plies. Since $\sigma_f \gg \sigma_c$, Eq. (1) may be written as $\sigma \approx \sigma_f \cos^2 \theta$. To interpret the terahertz scan images of the flaws under the 1st and 2nd plies, one must consider at least two effects. First, the penetration through the 1st ply depends on the relative angle between the electric field and the fiber direction in the 1st ply. Any radiation that is to penetrate the 2nd ply must have transmitted through the 1st ply. So the detectability of the flaw under the 2nd ply depends on the angle between the electric field and the fiber direction in both the first and the second plies. Secondly, one should consider the fact that even though the radiation is focused, the beam still interacts with the conductivity of both plies. A simple-minded argument is to consider them as two resistors in parallel so that the total resistance R is given by $(1/R) = (1/R_1 + 1/R_2)$. In this sense, a less conducting ply can be "shorted out" by a conducting ply above or below it. For this reason, we add up the conductivities of the first two plies: $\sigma_1 + \sigma_2$ and correlate its value to the

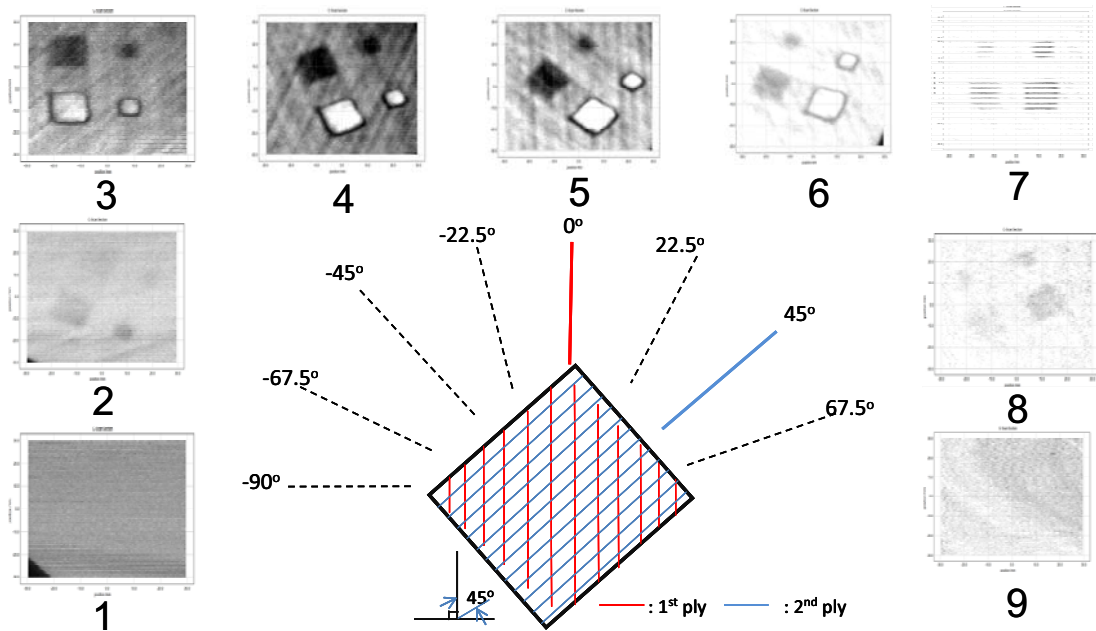


FIGURE 6. TDS reflection mode terahertz scan images of embedded brass foils in a quasi-isotropic carbon composite laminate.

TABLE 1. Conductivity of the first two plies of the carbon composite laminate for the seven scans (shown in Fig. 5) of shallow flaws using terahertz pulse. θ is the angle between the electric field vector and fiber axis in the first ply, and ϕ is the angle between the electric field vector and fiber axis in the second ply.

	Scan 1	Scan 2	Scan 3	Scan 4	Scan 5	Scan 6	Scan 7	Scan 8	Scan 9
θ	0	-22.5	-45	-67.5	90	67.5	45	22.5	0
ϕ	-45	-67.5	90	67.5	45	22.5	0	-22.5	-45
σ_1	$1.0\sigma_f$	$0.85\sigma_f$	$0.5\sigma_f$	$0.15\sigma_f$	0	$0.15\sigma_f$	$0.5\sigma_f$	$0.85\sigma_f$	$1.0\sigma_f$
σ_2	$0.5\sigma_f$	$0.15\sigma_f$	0	$0.15\sigma_f$	$0.5\sigma_f$	$0.85\sigma_f$	$1.0\sigma_f$	$0.85\sigma_f$	$0.5\sigma_f$
$\sigma_1 + \sigma_2$	$1.5\sigma_f$	$1.0\sigma_f$	$0.5\sigma_f$	$0.30\sigma_f$	$0.5\sigma_f$	$1.0\sigma_f$	$1.5\sigma_f$	$1.7\sigma_f$	$1.5\sigma_f$

signal-to-noise ratio of the flaws in the scan image. The conductivities of the first two plies for all the seven scans with the sample rotated 22.5 degrees after each scan are listed in Table 1. Using $\sigma \approx \sigma_f \cos^2 \theta$, the total conductivity has the lowest value ($0.30\sigma_f$) when the electric field makes a 67.5° angle with both the 1st ply and 2nd ply fibers. The S/N of the flaw image is therefore expected to be the highest when the sample is at this angle. Scan 3 and scan 5, with the fibers in the first two plies oriented at -45° and 90° and at 90° and 45° respectively, both have a low $\sigma_1 + \sigma_2$ value of $0.5 \sigma_f$. The three scans with the lowest $\sigma_1 + \sigma_2$ value seemed to have the best S/N. In contrast, sample orientations that gave a high value of total conductivity, such as $\theta = 0^\circ$, $\phi = -45^\circ$ ($\sigma_1 + \sigma_2 = 1.5 \sigma_f$), had poor signal-to-noise ratio. An examination of the trend of flaw detectability in the scan images shows that the prediction of S/N based on combined conductivity of the two plies is in qualitative agreement with the experimental results. It should be pointed out, however, that these results only represent a qualitative trend comparison between the angular dependence of the electrical conductivity and the S/N of the experimental scans of the flaws. To properly model the interaction between the conducting CFRP plies and the electric field of the terahertz waves, a complete field-flaw interaction model would be needed.

CONCLUSION

We reported here some initial results obtained in an exploration of terahertz wave applications for the NDT of composites. The conductivity of carbon fibers will substantially limit the utility of terahertz waves in CFRP. In non-conducting composites of glass, quartz, and Kevlar fibers, terahertz can complement ultrasonic NDT, especially with its penetration ability and immunity to shadow effect. The strength of terahertz spectroscopy for materials evaluation, contamination detection, and fluid ingress is yet to be explored. As with other new technologies, the cost of instrumentation and the ease of use of terahertz radiation will improve with time. A continued exploration of terahertz applications for composite NDT should prove fruitful.

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