An Infrared-Induced Terahertz Imaging Modality for Foreign Object Detection in A Lightweight Honeycomb Structure

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Abstract—In this paper, terahertz time-domain spectroscopy (THz-TDS) is used for the first time to detect fabricated defects in a glass fiber-skinned lightweight honeycomb composite panel. A novel amplitude polynomial regression (APR) algorithm is proposed as a pre-processing method. This method segments the amplitude-frequency curves to simulate the heating and the cooling monotonic behavior as in infrared thermography. Then, the method of empirical orthogonal function (EOF) imaging is applied on the APR pre-processed data as a post-processing algorithm. Signal-to-noise ratio analysis is performed to verify the image improvement of the proposed APR-EOF modality from a quantitative point of view. Finally, the experimental results and the physical analysis show that THz is more suitable with respect to the detection of defects in glass fiber lightweight honeycomb composites.

Index Terms—Terahertz, Polynomial fitting, Fourier transform, Empirical orthogonal function, Lightweight honeycomb.

I. INTRODUCTION

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In the aeronautical industry, there is an increasing need for lightweight composites above all for the internal design. In particular, it is the use of glass fiber-skinned honeycomb panels which is attracting attention. In this regard, the final products should not contain any inclusion of foreign material in order to not compromise both the aesthetic beauty and the mechanical properties subjected to vibrational loads [1].

Composites can be analyzed using established non-destructive testing (NDT) methods, such as X-ray [2], ultrasound [3], acoustics [4] or thermographic [5] techniques, but alternative methods are sought to meet the demands of new materials such as lightweight honeycomb composites. So far, the most common technique for puncture examination in composites is X-ray computed tomography (CT). This method provides clear images of the internal features and enables deep penetration. However, this method uses harmful ionizing radiation and the price of scanners is relatively high [6]. Ultrasound C-scan is another well-established NDT technique which has been widely used for defect detection in composites. Different from CT, this method is safe and cheap, but high-frequency ultrasound requires a coupling medium such as water [7]. This makes ultrasound unsuitable for non-waterproof materials.

Infrared thermography (IRT) is a more recent technique and it has the advantages of fast inspection rate, absence of contact, excellent spatial resolution and acquisition rate [8]. Recently various IRT modalities have been developed such as optical and ultrasonic excitation thermography [9], eddy current excitation thermography [10], laser spot and laser line excitation thermography [11] etc. However, IRT is not suitable for transparent or semi-transparent materials such as glass fiber composites. This is due to the fact that some infrared radiations pass through these materials and another part actually heats the surface. In addition, glass fiber is a poor conductor of heat, so heat propagates itself inside with great difficulty. Therefore, an alternatively new NDT technique is in need for the detection of subsurface defects present inside new materials such as glass fiber honeycomb composites. In this aspect, the challenging emerging terahertz time-domain imaging (THz-TDI) technique is attracting particular attention [12].

The terahertz (THz) region of the electromagnetic spectrum is defined between 100 GHz to 10 THz. It lies in the gap between electronic and optical signal generation schemes, or in other words, between microwave and infrared. THz radiation has the capability of penetrating most non-metallic materials and allows its spectroscopy for imaging the interior structures.
THz radiation is non-ionizing and thus it is not only safe for humans with respect to ionizing techniques such as X-ray or gamma inspections, but also non-destructive for specimens [13]. In this respect, THz systems can be applied in many fields such as food security [14], authentication of artworks [15], [16], packaged integrated circuits [17], [18], concealed weapons [19], biomedical diagnosis [20]–[23] and material characterization [24]–[27] etc. However, the THz imaging system is still in the research stage and its advanced image processing techniques are yet to be developed [28], [29]. Table I shows the comparison of THz-TDS and other established NDT methods.

Similarly to IRT, terahertz time-domain spectroscopy (THz-TDS) is also a time-domain imaging technique. Therefore, the application of the infrared image processing algorithms in the THz-TDS field may be considered as an attractive idea. However, this is not a simple task to be satisfied due to the absolutely different physical basis.

Different from THz-TDS, many advanced infrared image processing algorithms have been introduced in the scientific context. The well-known pulsed phase thermography was proposed by Maldaugue and Marinetti in 1996. This method combines the advantages of pulsed and modulated modalities applying Fourier transform on pulsed heating [30]. Then, Shepard et al. proposed thermographic signal reconstruction in 2001, which provides a significant improvement and a good sensitivity to smaller and deeper defects by only storing polynomial coefficients [31]. In 2002, Rajic proposed an empirical orthogonal function-based principal component regression method, which enhances the image performance and characterizes the defect depth [32]. On this basis, a few enhanced principal component regression modalities have been proposed such as candid covariance-free incremental principal component thermography [33] and sparse principal component thermography [34]. In 2011, Tabatabaei et al. proposed thermophotonic radar imaging, which uses an emissivity-normalized modality with advantages over phase lock-in thermography [35]. In 2014, Lopez et al. applied partial least-squares regression on pulsed thermography [36]. In 2016, Gao et al. proposed an image processing method based on multiple physical fields for inductive thermography [37]. Moreover, many other researchers also developed various infrared image processing techniques, such as coded thermography [38], among many others [39]–[45]. These infrared image processing techniques improve the detection capability of IRT. However, it is impossible to overcome the limitations of infrared physics. Therefore, IRT is still ineligible with respect to some specific applications such as glass fiber etc.

In this paper, THz-TDS is used to inspect a glass fiber-skinned lightweight honeycomb composite panel containing a foreign insert. Interestingly, a novel amplitude polynomial regression (APR) algorithm is proposed as a pre-processing method. In APR, the time-domain image sequence is transformed into the frequency-domain by Fourier transform. The amplitude-frequency curve is segmented into two separate sequences in order to simulate the heating up and the cooling down near-linear phases as in IRT. Polynomial regression is performed for the two image sequences, respectively. The two post-processing sequences are combined into a new APR image sequence and the corresponding physical and mathematical link is supplied. Then, the method of empirical orthogonal function (EOF) imaging is applied on the pre-processed APR data as a post-processing algorithm. To the best of our knowledge, it is the first time that EOF imaging is used in THz-TDS. Finally, a signal-to-noise ratio (SNR) analysis is performed to verify the image improvement of the proposed APR-EOF THz imaging modality from a quantitative point of view.

### II. Research Aim

Fig. 1 shows a lightweight composite panel. The honeycomb core was made of 0.125 inch thick Nomex, with core cell size of 0.125 inch in diameter. In both sides, the glass fiber skins are unidirectional and impregnated with epoxy resin 290 g/m². The epoxy resin used to bond the core with the facesheet was HexPly M26, an advanced modified epoxy resin developed for aerospace and industrial applications. This panel offers unique characteristics since it combines lightweight with high mechanical properties.

![Fig. 1. Photographs of the specimen.](image)

A thin square plastic insert, simulating a sub-surface defect, was added in the panel during manufacturing. It was applied on the back face from the inner side and near a panel corner. The CT slices in Fig. 2 show the structural images.

As explained in section I, it is difficult to detect this type of material by IRT because: 1) some infrared radiations...
pass through this semi-transparent material and another part actually heats the surface; 2) glass fiber is a poor conductor of heat, so heat propagates with difficulty; 3) the honeycomb structure, which contains a large amount of air, limits the thermal diffusion. Fig. 3 shows the infrared images. It is observed that the insert cannot be detected.

![Fig. 3. Infrared post-processing results.](image)

**Fig. 3. Infrared post-processing results.**

Another alternative is ultrasonic detection. Fig. 4 shows the ultrasonic C-scan images (2.25 MHz). The insert cannot be detected in the reflection mode. This is because the insert was not placed flat when preforming. On the contrary, the insert can be detected clearly in the transmission mode. This also indicates that a THz-TDS configuration in the reflection mode will also not detect the insert because the work principles of ultrasonic C-scan and THz-TDS are similar. Therefore, a THz-TDS configuration in the transmission mode was used in this paper.

### III. METHODOLOGY

#### A. Theory

When THz pulses pass through a material, both signal attenuation and time delay are observed due to the fact that light velocity is higher in the vacuum than in the material. The refractive index $n$ in a material can be expressed as:

$$ n = \frac{c}{v} $$

(1)

where $c$ and $v$ are the fraction of light velocity in the vacuum and in the material, respectively.

Most materials have their unique refractive indices and absorption coefficients in the THz spectrum. The attenuation and time delay can be used to distinguish the layers composed of different materials.

According to Eq. 1, the refractive index $n$ in a material can be calculated by:

$$ n = \frac{c \cdot \Delta t}{d} + 1 $$

(2)

where $\Delta t$ is the time delay divergence and $d$ is the material thickness.

The attenuation coefficient $\alpha$ [dB] can be expressed as [17]:

$$ \alpha = 20 \cdot \log(e) \cdot \mu_\alpha \approx 8.7 \mu_\alpha $$

(3)

where $\mu_\alpha$ [cm$^{-1}$] is considered as the amplitude attenuation factor and it can be calculated by [17]:

$$ \mu_\alpha = \frac{1}{d} \cdot \ln \frac{A}{A_0} $$

(4)

where $A_0$ is the amplitude of the reference signals in the air, $A$ is the amplitude of the signals passing through the materials. $A$ is dependent on $d$ and it can be expressed as:

$$ A = A_0 \cdot e^{-\mu_\alpha d} $$

(5)

In this paper, the attenuation factor value of the specimen is considered as the absorption factor value due to the fact that the specimen is not preformed by layers with different refractive indexes and attenuation factors. This consideration simplifies the physical analysis.

#### B. Experiments

Fig. 5 shows the schematic configuration of the employed THz-TDS system. The pump wavelength is 1550 nm and the repetition rate is 80 MHz. The system has a 5 GHz frequency resolution. The experiments were performed in transmission mode. The specimens were located in the focus of the optical system between the Thz emitter and the receiver.

A main advantage of transmission mode is that the complex refractive index $(N = n + i \cdot k)$ and the attenuation coefficient $\alpha$ of a measured material can be easily determined [46]. In addition, the insert cannot be detected in the reflection mode (see Fig. 4).
THz frequency-domain is possible. Therefore, the use of polynomial regression in the IRT. Both thermal diffusion abnormalities and THz absorption abnormalities can be considered as curve behaviors in the IRT. Therefore, the logarithmic behavior of the THz frequency evolution also exhibits consistency in pixels. Specifically, the defect-free areas are near-linear on the THz amplitude-frequency curve, while the defective areas depart from the near-straight-line behavior at particular frequencies. The logarithmic frequency dependence of a pixel can be approximated by a function, or a set of orthogonal functions. In most cases, a polynomial provides an excellent fit to experimental data, which is shown as follows:

$$ln[A(f)] = \Sigma_{n=0}^{N} a_n [ln(f)]^n$$  \hspace{1cm} (6)

where $A$ is the amplitude intensity and $f$ is the frequency after FFT.

A low-order expansion is applied in order to act as a low-pass filter. In the logarithmic domain, high orders only replicate noise which appears in the low-amplitude data. Once the THz frequency evolution of each pixel has been approximated by Eq. 6 or a similar function, the original data can be reconstructed as follows:

$$A(f) = \exp(\Sigma_{n=0}^{N} a_n [ln(f)]^n)$$  \hspace{1cm} (7)

The reconstructed THz amplitude-frequency sequence in Eq. 7 is differentiable and, therefore, a low-order or a high-order derivative image can be created. On this basis, it is possible to only save the polynomial coefficients regardless of the length of the image sequence. The rising and the falling sequences are reconstructed and then they are combined into a new THz amplitude-frequency image evolution as shown in Fig. 6. The reconstructed or the derivative images represent any point in frequency.

The above-mentioned THz amplitude-frequency based polynomial reconstruction method is considered as a new amplitude polynomial regression (APR) pre-processing algorithm for THz-TDS. Similar to IRT, more advanced image processing techniques can be applied on the pre-processed data.

It has been found that a 4th-order or a 5th-order polynomial provides the best fit to IRT data. From our experiments, it is observed that a higher order such as a 8th-order or a 9th-order polynomial can also provide a good fit to THz.

D. Empirical Orthogonal Function Imaging

Empirical orthogonal function (EOF) imaging has been used in IRT since it provides a group of orthogonal statistical modes [32]. This method is derived from geophysics, in which this type of analysis is often used [49]. It gives the strongest

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**Fig. 5.** Experimental configuration of THz-TDS.

**Fig. 6.** Raw amplitude and APR curves in the frequency-domain.
Fig. 7. Schematic diagram of the proposed APR-EOF THz imaging modality.

projection for the thermal evolution. It can provide a few compact variations for the full thermal evolution.

The technique is based on the singular value decomposition (SVD) of the measured data and, therefore, it is also eligible with respect to both the time-domain and the frequency-domain evolution in THz-TDS.

A $N \times M$ matrix $A$ can be decomposed as follows:

$$A = U \Gamma V^T$$

where, if $M > N$, $\Gamma$ is an $N \times N$ diagonal matrix with positive or zero elements which represent the singular values of the matrix $A$, $U$ is an $M \times N$ matrix, and $V^T$ is the transpose of an $N \times N$ matrix.

If the matrix $A$ is arranged (the time variations are column-wise and spatial variations are row-wise), the columns of the matrix $U$ consist of a group of EOFs which can represent the spatial variations in the THz time-domain or frequency-domain evolution.

SVD extracts a group of compact spatial, temporal and frequency variations from the matrix $A$ by projecting the original THz evolution onto the EOFs. Usually, the original evolution can be represented by only a few EOFs. This method shows an excellent noise-rejection capability.

In this paper, EOF imaging is used as the post-processing algorithm in the proposed APR-EOF imaging modality. It is the first time that EOF imaging is used in THz-TDS to the best of our knowledge. Although this method can be used in both the time-domain and the frequency-domain data in THz-TDS, it was only used in the frequency-domain to post-process the amplitude and the APR pre-processed data. This is because: 1) the improvement thanks to the proposed APR pre-processing algorithm can be evaluated and compared with the raw amplitude data; 2) the frequency-domain evolution may provide a group of clearer and more easily analytical EOFs if compared to the more complex THz time-domain evolution. The complete schematic diagram of the proposed APR-EOF THz imaging modality is shown in Fig. 7.

IV. RESULTS ANALYSIS

Fig. 8 shows the THz analytical curves. The attenuation coefficient has a larger value on the insert position. The

Fig. 8. THz-TDS analytical curves: (a) time-domain, (b) frequency-domain.
The refraction index of Teflon is known to be \(1.35 \sim 1.38\) [50]. The time delay caused by the insert is 0.35 ps, as shown in Fig. 8a. According to Eq. 2, the thickness of the insert is \(\sim 0.3\) mm. This value is close to the estimated thickness during manufacturing. THz-TDS has the capability of calculating the thickness of a single layer, while its B-scan imaging can show more clearly the signal abnormalities on the insert position, as shown in Fig. 9.

![Fig. 9. B-scan imaging.](image)

The noise is caused by the honeycomb structure, in which the time delays of the THz beams are different. Compared to the amplitude images, the phase images are less affected by noise. The proposed APR pre-processing algorithm reduces the low frequency noise, and it also improves the image performance, especially for the insert identification in the low frequency images. At the frequencies of 0.8 THz and 1 THz, APR does not improve the image performance as is known to occur at lower frequencies. However, APR shows a more evident enhancement at the higher frequencies (Fig. 11).

![Fig. 10. Fourier transform and APR pre-processed results at the lower frequencies.](image)

![Fig. 11. APR pre-processed results at the higher frequencies.](image)

The amplitude image at 2.5 THz is blurry. However, the APR images show a clear identification at this frequency. From 3.5 THz, the amplitude images are full of noise. The APR image without frequency derivatives shows a clear identification at 3.5 THz, but it is blurry at 4.5 THz and it is also full of noise from 5.5 THz. Interestingly, the APR images calculated using the 1st-order frequency derivative show an identification at all of the frequencies, and its contrast is better than the 2nd-order derivative images. Overall, the APR pre-processing algorithm improves the image performance and reduces noise in the high frequency images more evidently.

![Fig. 12. Peak-to-peak imaging results for the raw amplitude and the APR pre-processed data.](image)

SNR is used herein as a means to evaluate and compare the sensitivity of the applied processing modalities. The SNR is expressed in decibels (dB) following the 20 log rule often used in imaging applications, as follows:

\[
SNR = 20 \cdot \log_{10} \left| \frac{S_d - S_a}{\sigma_{S_a}} \right| \quad (9)
\]

where \(S_d\) represents the intensity of signals, \(S_a\) represents the intensity of sound areas, and \(\sigma_{S_a}\) is the standard deviation representing noise variability.
SNR values provide important information about the sensitivity of each technique when comparing the detectability of similar features or defects. The analytical SNR values in Fig. 14 show the image enhancement of the proposed APR-EOF THz imaging modality.

As can be seen, TDz-TDS shows a larger SNR value than CT. In THz-TDS, both APR and EOF imaging algorithms can significantly improve the quality of the original images. The proposed APR-EOF modality shows the largest SNR value. This indicates that this imaging modality is effective to improve the probability of detection (PoD) for THz-TDS from a quantitative point of view.

V. CONCLUSIONS

The proposed APR pre-processing algorithm can improve the image performance and the identification of the foreign insert in THz-TDS, when compared to the raw amplitude data in the frequency-domain. APR can also reduce the structural noise at the lower THz frequencies region. THz EOF imaging can be applied on the APR pre-processed data as a post-processing algorithm. The APR-EOF imaging modality can significantly improve the final image quality in THz-TDS, which is quantitatively verified by SNR analysis. Finally, it is worth mentioning that, as a new non-destructive imaging technique, THz is more suitable with respect to glass fiber-skinned lightweight honeycomb composite inspection than other established NDT techniques previously mentioned.

REFERENCES


