Terahertz Amplitude Polynomial Principle Component Regression for Aramid-Basalt Hybrid Composite Laminate Inspection

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Abstract—As an emerging non-destructive diagnostic and monitoring technique, terahertz time-domain spectroscopy (THz-TDS) imagery is attracting more attention. In this regard, new THz image processing algorithms based on infrared thermography (IRT) concepts are greatly needed, since most IRT imagery modalities are fast for in-line industrial inspection. However, this scenario is difficult due to some physical constraints to be reached, although this idea should be followed to avoid the loss of useful information during image processing. In this paper, a novel THz amplitude polynomial principle component regression (APPCR) algorithm is proposed for the inspection of aramid-basalt hybrid composite laminates. This algorithm segments THz amplitude-frequency curves to simulate heating-up and cooling-down behaviors as in IRT; in addition, it uses an empirical orthogonal functions-based principle component regression modality to simplify the THz image analysis procedure. This experimental and analytical study shows that APPCR can: 1) simplify the THz image analysis procedure, and 2) enhance image contrast and spatial resolution. A theoretical analysis was conducted as experimental explanation, while the IRT imagery results were used for comparative purposes. In addition, signal-to-noise ratio analysis was used to evaluate quantitatively the image enhancement. Finally, it is possible to conclude that THz is more suitable to inspect transparent or semi-transparent materials. Advantages and disadvantages of THz-TDS and IRT are summarized into the text.

Index Terms—Terahertz, Infrared, Polynomial, Composite.

I. INTRODUCTION

NOWADAYS, non-destructive diagnostic and monitoring techniques are playing an important role in the modern industry. As an established non-destructive testing (NDT) technique, infrared thermography (IRT) has a wide use due to its fast imaging and data processing superiority. Moreover, the development of various IRT imagery algorithms expands its use towards fast in-line industrial inspection [1]–[7].

Although IRT has many advantages for industrial inspection, it also has limitations derived from its physical background. For example, IRT does not work well on transparent or semi-transparent materials, since most infrared radiation will pass through the materials and only a small part of them will actually heat material surface or near-surface layers. In addition, IRT has a limited penetration capability for most materials. This makes a depth detection impossible using IRT [8].

Recently, an emerging terahertz time-domain spectroscopy (THz-TDS) imagery technique is attracting more attention as a new NDT method [9]. THz is considered as the last gap in the electromagnetic spectrum. This invisible light bridges the gap between microwave electronics (RF) and infrared photonics (IR). Human-safe (i.e. non-ionizing), the THz frequency range (300-3,000GHz) enables a wealth of applications that promise to radically transform our world since it is safer than X-Ray and penetrates better than IR, while at the same time can uniquely reconfigure water and gases. In this respect, THz can be applied in many fields such as cultural heritage [10], quality control [11], physics study [12], material evaluation [13] etc.

A few THz-TDS imagery algorithms have been proposed [14], [15], although the development of new algorithms requires a large amount of time and some of them are not fast enough for in-line industrial inspection. Similar to IRT, THz-TDS is also a time-domain imagery technique. Therefore, the development of THz image processing algorithms based on infrared image processing concepts for fast in-line inspection can be considered as an attractive and smart idea. However,
this is not simple due to their different physical mechanisms and, therefore, an in-depth theoretical analysis considering THz physical mechanism is necessary in order to avoid the loss of useful information.

An available infrared image processing modality is thermographic signal reconstruction, which was proposed by Shepard et al. [16]. This method uses a polynomial fitting concept to provide a significant infrared image improvement and a good sensitivity to smaller and deeper defects by only storing polynomial coefficients [17]. Polynomial fitting has the advantages to be easy to use and accurate. The processed data have an enhanced temporal-spatial resolution and have a reduced noise level. Therefore, polynomial fitting is considered as a potential image optimization algorithm for the new THz-TDS imagery modality.

Another available infrared imagery modality is principal component thermography, which was proposed by Rajic [18]. This method offers an appealing alternative instead of relying on a prescribed set of basis functions as Fourier transform. It constructs a set of orthogonal statistical modes that provide the strongest projection for the data. The approach tends to provide compact representations for complex signals, like those that often arise in geophysics, where this type of analysis is commonly applied [19]. This method shows evidence of excellent noise-rejection qualities which manifest high levels of flaw contrast relative to that present in the unprocessed data. More interestingly being, this method is available for extensive external algorithm integration [20]–[22].

Although there are also some other complex infrared image processing algorithms recently proposed such as in [23]–[25], the above-mentioned two algorithms have the advantages to be easy to use and simple, which is particularly important for in-line industrial inspection. In addition, they are also easy to be applied into the THz spectrum. Therefore, these algorithms were chosen for the development of new infrared-induced THz-TDS imagery modality. Moreover, new aramid-basalt hybrid materials having internal damage were chosen as materials to be inspected. These new materials have different ply architectures including sandwich-like and intercalated stacking sequence. The purpose of hybridization is to acquire average mechanical properties in order to fit different industrial needs [26].

In particular, it is widely known that an improvement in the impact properties of polymer composites with high stiffness reinforcements can be obtained by mixing them with more ductile organic fibers, based on aramid or polyamide polymers. Aramid fibers show a unique combination of high stiffness, strength, low density and high elongation at fracture that leads to excellent impact resistance though they are much more expensive than basalt fibers. Therefore the design of hybrid composites based on these two fibres can reasonably result in a convenient balance of tensile, flexural and impact properties. In addition, basalt fibers are natural fibers of mineral origin, thus providing a lower environmental impact.

In this paper, a novel THz amplitude polynomial principle component regression (APPCR) algorithm is proposed. In APPCR, the time-domain image sequence is transformed as the first step into the frequency-domain by Fourier transform. The amplitude-frequency curve is segmented into two separate sequences in order to simulate heating-up and cooling-down near-linear phases as in IRT. Polynomial fitting is performed for two new image sequences after segmentation, respectively. Then, the post-processed sequences are combined into a new image sequence. The method of empirical orthogonal functions (EOFs)-based principle component regression (PCR) is applied on the fitted data for the final APPCR processing. In addition, IRT was also used in this work as a referenced technique to validate and compare the results obtained to the THz imagery results. In order to evaluate the APPCR technique quantitatively, a signal-to-noise ratio (SNR) analysis was also performed. This experimental and analytical study shows that APPCR can: 1) simplify the THz-TDS image analysis procedure, since only a few images (EOFs) are needed for analysis; 2) enhance image contrast and spatial resolution, which is particularly useful for aging-induced damage. Finally, it is possible to conclude that THz-TDS is more suitable for transparent or semi-transparent materials, and the reasons are explained in-depth from a physical point of view.

II. THEORETICAL BACKGROUND

A. THz-TDS 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:

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

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 THz spectrum. The attenuation and time delay can be used for distinguishing the layers made up of different materials.

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

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

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

The attenuation coefficient $\alpha$ [dB] can be expressed as [27]:

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

where $\mu_\alpha$ is considered as the amplitude attenuation factor and it can be calculated by [27]:

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

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:

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

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.
The complete schematic diagram of the proposed APPCR algorithm is shown in Fig. 1. The detailed processing procedure and physical mechanism will be discussed in this section.

In THz-TDS, a time-domain curve is more complex, and it is difficult for polynomial regression because it is not monotonic. Therefore, frequency-domain polynomial regression is considered alternatively in this paper. After THz Fourier transform, a frequency-domain curve can be segmented into two separate monotonic curves from their inflection point, and this process is similar to a heating-cooling behavior as in IRT (see Fig. 2).

![Fig. 2](image)

In Fig. 2, the logarithmic behavior of the frequency evolution exhibits a remarkable consistency in pixels. More specifically, the defect-free areas are near-linear, while the defective areas depart from the near-straight-line behavior at particular frequencies. The logarithmic frequency dependence can be approximated by orthogonal functions, which is shown as follows [16]:

\[
\ln[A(f)] = \sum_{n=0}^{N} a_n [\ln(f)]^n
\]

where \( A \) (or \( a_n \) as the dispersion values) is the amplitude intensity and \( f \) is the frequency.

A low-order expansion is used as a low-pass filter. In the logarithmic domain, high orders only replicate noise. Once the frequency evolution has been approximated by Eq. 6, the original data can be regressed as follows [16]:

\[
A(f) = \exp\left(\sum_{n=0}^{N} a_n [\ln(f)]^n\right)
\]

The regressed amplitude-frequency sequence is differential, and a low-order or a high-order derivative image can be created. On this basis, it only needs polynomial coefficients disregarding image sequence length. In Fig. 2, rising and falling sequences are regressed separately, and then they are combined into a new image sequence. The regressed image sequence and its derivative images can represent any point in the frequency-domain.

Then, the combined amplitude polynomial regressed (APR) image sequence is processed using the EOFs-based principle component reconstruction (PCR) technique. This technique applies singular value decomposition (SVD) on the combined APR sequence. In detail, an \( N \times M \) matrix \( A \) can be decomposed as follows [18]:

\[
A = U \Gamma V^T
\]

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

If \( A \) is arranged, time variations will be column-wise and spatial variations will be row-wise. It can be observed that the columns of \( U \) comprise a set of EOFs, which describe the spatial variations in the data.

SVD compacts the spatial and temporal data from \( A \) by projecting original data onto EOFs. The benefit is that the raw image sequence can be represented by a few EOFs, so it is unnecessary to analyze the entire sequence. Finally, a few EOFs can be obtained by the above-mentioned APPCR algorithm to analyze the complex THz-TDS data.

### III. Experimental set-up

#### A. Configurations

Fig. 3 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 the 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 [28].

Optical excitation thermography (OET), as the most often used IRT technique, was used as a referenced technique in this paper. More specifically, a photographic flashes-based transient pulsed thermography (PT) system was applied. In PT, an external heat source is used as an active heating modality to create infrared radiation. The surface temperature decreases uniformly for an area without any defect, and a sub-surface discontinuity can be considered as the resistance to heat diffusion. Accordingly, a defective location shows an abnormal temperature distribution [29]. The employed IRT system is shown in Fig. 4.

**B. Specimens**

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Aramid</th>
<th>Basalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ([g/cm^3])</td>
<td>1.44</td>
<td>2.60</td>
</tr>
<tr>
<td>Linear density ([dtex])</td>
<td>1100</td>
<td>1500</td>
</tr>
<tr>
<td>Tensile strength ([MPa])</td>
<td>2400-3600</td>
<td>2500-3000</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>2.2-3.0</td>
<td>3.30</td>
</tr>
<tr>
<td>Young’s modulus ([GPa])</td>
<td>100-120</td>
<td>80-90</td>
</tr>
<tr>
<td>Specific heat ([J/kgK])</td>
<td>1420</td>
<td>860</td>
</tr>
<tr>
<td>Maximum temperature for long-term use in air (\degree C)</td>
<td>175</td>
<td>650</td>
</tr>
</tbody>
</table>

The aramid (KK 130P, Twaron HM) and basalt (BAS 220.1270.P) fabrics were plain woven with a density of 130\(g/m^2\) and 220\(g/m^2\), respectively (see Table I for the physical and mechanical properties of the aramid and basalt fibers). The matrix material is a bi-component epoxy resin. The laminates were manufactured by resin transfer molding (RTM), and they were cured for 12 hours at room temperature and 4 hours at 70 \(\degree C\). All of the laminates have a similar 13-layer volume fraction of 0.33±0.01. Therefore, they have a similar thickness of 3.50±0.15 mm. The dimensions of the specimens are 180 mm×60 mm. Fig. 5 shows the impacted specimens, while Fig. 6 shows their schematic structures. It is worth mentioning that aramid fibers have a commercial name Kevlar\textsuperscript{®}, which is commonly used in the industry.
C. Defects

These laminates were impacted using a falling weight tower at an energy of 12.5 J by keeping constant the mass (6.929 kg) of a hemispherical head indenter with a diameter of 12.7 mm. This impact energy can create an appreciable damage with a damage degree (defined as the ratio between the absorbed energy and the impact energy) higher than 0.55, even if the damage is far from penetration.

After the impact loading procedure, the specimens were placed in an environmental chamber operating in inert atmosphere to create accelerated environmental aging. The environmental aging procedure is shown in Fig. 7. The chamber temperature was increased by 1–2 °C/min until a plateau temperature of +164 °C was reached. The specimens remained at this temperature for 1 hour. Then, the temperature decreased by 1–2 °C/min until a minimum temperature of −160 °C was reached and it was also maintained for an additional hour.

![Fig. 7. Schematic environmental aging procedure.](image)

IV. RESULT ANALYSIS

Fig. 8 shows the IRT imagery results applying Fourier transform. When a thermal pulse is transformed by PPT in the frequency domain, an image sequence representing its disperse frequencies can be obtained. Fig. 8 shows the post-processed images from the first four frequencies.

In Fig. 8, no significant difference with the exception of contrast change can be observed along with the increase of the frequencies. This is because IRT imagery is based on thermophotonic absorption of different infrared spectra. Infrared radiation has a weak penetration capability, and its energy is increasingly absorbed and diffused during the increase of the radiation depth. Accordingly, IRT has a limited probing depth, especially for composite materials which have more absorption and diffusion modulus due to their complex structures.

On the contrary, THz does not have the above-mentioned disadvantage, because THz radiation has a powerful penetration capability. Fig. 9 shows the imagery results applying Fourier transform in THz-TDS. It can be observed that no defect was detected at the frequency of 0.1 THz. From 0.2 to 0.8 THz, different features and defects can be reached. In Fig. 9, a higher spatial resolution can be obtained at a higher frequency. However, more noise also is present during the increase of the spatial resolution at a higher frequency.

![Fig. 8. IRT imagery results applying Fourier transform.](image)

This phenomenon can be explained by the frequency-domain curves, as shown in Fig. 10. When the THz frequency is higher, a large amount of noise is present along the amplitude axis.

In addition, the amplitude of the K specimen is higher than the hybrid specimens at the same frequency, while the amplitude of the B specimen shows the lowest value. This is because the physical properties of the hybrid specimens are between the K and B specimens.

In the THz imagery results (see Fig. 9), the impact-induced damage in the K specimen can be inspected more clearly. This is because THz radiation can pass through semi-transparent material more easily. On the contrary, the same feature becomes a disadvantage for IRT, since most of the infrared radiation passes through the material so it only heats the surface and the near-surface layer.

In Fig. 11, it is possible to see that the THz beams pass through the K specimen in a shorter time. Accordingly, the THz amplitude intensity in the K specimen is the highest. This observation validates the above-mentioned discussion. Overall, THz-TDS is more suitable for transparent or semi-transparent materials than IRT, since most infrared radiation passes through the specimen and only a small part heats the surface as discussed previously.

In Fig. 9, abnormal features can be observed. These features exist neither on the specimen surfaces nor in the near-surface layers, which can be validated by the IRT imagery results that show surface and near-surface thermophotonic images (see Fig. 8). These features are considered as aging-induced damage which was caused by the environmental aging process (see Fig. 7). More specifically, different THz amplitude intensities in the form of color difference correspond to different aging-induced damage resistance.

For the hybrid specimens, the images from the frequencies of 0.2-0.4 THz show different features from those at the higher frequencies. This is caused by the THz beams reflection and attenuation at the interfaces of different K-B layers.
The images from the higher frequencies are less affected by unexpected reflection. This is because these reflection signals correspond to the lower frequencies if time-domain signal evolution is taken into account. On this basis, it is possible to conclude that a higher frequency corresponds to a shallow depth, while a lower frequency corresponds to a deeper depth in the present THz-TDS set-up.

In Fig. 9, phase images show a better identification for impact-induced damage, while amplitude images show more damaged features induced by environmental aging. This is because phase transform considered the aging-induced damage as noise, while phase images are less affected by noise. Fourier transform can provide useful information, although an image sequence needs to be analyzed. Indeed, it needs a large amount of time and experience to perform an analysis procedure, which limits its potential in-line industrial applications. Therefore, the development of fast THz-TDS imagery and analysis technique is useful such as APPCR algorithm.

As a referenced technique, Fig. 12 shows the IRT imagery results applying PCR and polynomial regression algorithms. The post-processed images have a comparatively optimized contrast if compared to the Fourier transform results (see Fig. 8). As previously discussed, on the one hand, IRT can only show the surface and near-surface features for the semi-transparent materials which are made of aramid fibers. On the other hand, it can show deeper-depth information for the B specimen which is opaque. This is because heat shows a slower diffusion compared with materials made of aramid fibers (see Fig. 13). Therefore, the slower cooling-down phase provides more internal damage information for the B specimen.

Although a deeper information is available in IRT for the B specimen, it cannot probe the entire thickness. Therefore, the images of the B specimen show more features, but it is still limited if compared to the THz-TDS technique.

It is worth noting that Fig. 8 used 4th-order polynomial regression, since it was seen that 4th-order or 5th-order polyno-
mial can provide the best fit for IRT imagery [16]. However, an optimal polynomial order should be re-investigated for THz-TDS. From our experiments (see Fig. 14), it was validated that 4th-order or 5th-order polynomial is also an optimal modality for THz-TDS. A higher-order polynomial such as 8th-order or 9th-order polynomial can also provide a comparatively good result in THz-TDS, but an extreme high-order polynomial such as 20th-order shows only noise.

Fig. 14. Comparison of THz-TDS images from different polynomial orders.

Although THz-TDS shows a significant superiority for aging-induced damage detection, IRT also shows a comparative superiority for impact-induced damage detection. This is because impact-induced damage is similar to a hole, which infrared radiation can entirely pass through so that thermophotonic absorption barely occurs.

Comparing with the Fourier transform imagery results (see Fig 9), APPCR can provide a higher image contrast and a higher spatial resolution. This is helpful to reveal more damage information. Interestingly, the 1st-order derivative APPCR provides the best image performance among all the results.

SNR analysis was used herein as a means to evaluate quantitatively the APPCR image enhancement. SNR values can provide useful information for the sensitivity of each modality used in Fig. 15, if compared to the detectability of similar defects.

In this paper, SNR is expressed in decibels (dB) following the 20 log rule which is often used in imaging applications, which is described as follows:

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

where \(S_d\) represents the intensity of signals, \(S_a\) represents the intensity of sound areas, and \(\sigma_{Sa}\) is the standard deviation representing noise variability.

Fig. 16 shows the SNR values which correspond to the applied modalities in Fig. 15. The SNR values were obtained herein from the positions of the maximum intensities of each specimen. These positions indicate the weakest damage resistance locations. It is possible to see that APCR and APPCR modalities both improve greatly the image performance, when compared to peak-to-peak imaging modality. Moreover, the 1st-order derivative APPCR provides the best image performance among all the modalities. This can be licked to the imagery results in Fig. 15.

V. CONCLUSIONS

As an emerging non-destructive diagnostic and monitoring technique, THz-TDS is attracting more attention. In this regard, the development of new THz image processing algorithms based on IRT concepts is extremely attractive, since most IRT imagery modalities are fast and easy to use for simplify the image analysis procedure, which is particularly attractive to fast in-line industrial inspection.
in-line industrial inspection. However, the various physical concepts must be considered in order to avoid the loss of useful information during image processing procedure.

In this paper, a novel APPCR algorithm is proposed for THz-TDS imagery, and it was used to evaluate several aramid-basalt hybrid composite laminates. Although APPCR is based on several different IRT imagery concepts, it is a complex and new algorithm by considering the fact that it has a different physical mechanism as well as a different processing modality. This experimental and analytical study uses the features of APPCR. In addition, the established IRT technique was also used for comparative purposes to show the advantages of disadvantages of different responses to impact loading and environmental aging.

In conclusion, APPCR can: 1) simplify the THz-TDS image analysis procedure, since only a few images (EOFs) are needed for analysis; 2) enhance image contrast and spatial resolution for THz-TDS imagery, which was quantitatively evaluated via SNR analysis. In addition, a theoretical analysis was also conducted to experimentally explain the results obtained. These advantages confirm the use of APPCR and THz-TDS as an emerging new technique.

Finally, it is possible to conclude that THz-TDS is more suitable for transparent or semi-transparent materials than IRT. This is due to the fact that most infrared radiation will pass through the materials, but only a small part of them will heat the material surface and near-surface layers. This explains the impossibility of IRT for depth damage detection. On the contrary, THz does not have this problem, and it even becomes an advantage because it can provide a higher signal intensity when most THz beams can pass through semi-transparent materials. Moreover, THz radiation has a powerful penetration capability which can go through most non-metal materials, and so it can provide the entire depth information of inspected materials, especially for aging-induced damage.

REFERENCES


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