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Time Segmented Image Fusion Based Multi-Depth Defects Imaging Method in Composites With Pulsed Terahertz

QIANG WANG, HONGBIN ZHOU, RUICONG XIA, QIUHAN LIU, AND BO YAN ZHAO
Air Force Engineering University, Xi'an 710051, China

Corresponding author: Hongbin Zhou (hbzhou990@126.com)

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ABSTRACT Recently, terahertz (THz) nondestructive testing technology has prevailed in the defect detection of composite materials yet is limited by identifying deeper flaws. To solve this problem, a time-domain piecewise imaging method based on terahertz signal extraction is proposed in this article. First, the surface reflection echo signal is removed by applying a time correction, and the time-domain signal is then segmented according to the thickness of the sample. Finally, high-quality terahertz images are obtained by image fusion technology. All imaging methods, including traditional ones, are utilized to detect defects in glass fiber reinforced plastic (GFRP) sample then the signal-to-noise ratio (SNR) and defect edge contrast of each method are calculated. The experimental results show that the proposed method can effectively improve the terahertz imaging of deeper defects in GFRP sample especially for multi-depth defects and possesses the highest SNR and defect edge contrast.

INDEX TERMS Imaging method, image fusion, defect detection, composite material.

I. INTRODUCTION

Terahertz waves are broadly adopted in biomedical testing, non- destructive testing (NDT), communication, radar and security inspection for the capability of penetrating almost all kinds of insulating materials, such as paper, coatings, foam, plastic, and glass [1]. However, applying THz as a NDT method has been delayed for many years because of the inefficiency of THz emission and the limitation of detection devices, which usually referred to the so-called ''THz gap'' in this period. Whereas, this gap has been addressed by the fast development of semiconductors and ultrafast electronics, promoting the NDT application of THz in many fields over the last two decades [2]. In practical situations, the power limitation of terahertz-source devices and the influence of environmental background noise result in the uneven distribution of background grayscale in terahertz images poor edge resolution, and unsatisfactory image quality. In particular, defects at different depths are almost indistinguishable. These issues seriously affected the detection of deeper defects in composites. The most effective yet expensive way to improve terahertz image quality is to update the related hardware conditions. Economically, the terahertz imaging method with a postprocessing algorithm can effectively improve the quality of terahertz images at a low cost. Therefore, research on terahertz imaging methods has great significance in engineering of image SNR enhancement and detectability improvement of terahertz technology.

In order to solve above problems, many image processing algorithms are proposed for higher image quality and multi-depth defects detection. Liang *et al.* studied impact damages detection in carbon-fiber reinforced plasatic (CFRP) using eddy current pulsed thermography. In their work, the multi-resolution statistical analysis method combining wavelet transform and principal component analysis (PCA) was presented improving the information of thermal image to distinguish defects, and the detectability of damage caused by different impact energy was discussed [3]. Fan *et al.* proposed a noise-robust phase-shift based method to enhance measurements of paper basis weight, the result shows that is superior to the others [4]. Wang *et al.* used advanced thermal image algorithms processing thermal data obtained by three different thermographic methods, they found that principal component analysis applied to long pulse thermography

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provides accurate imaging results over traditional pulsed thermography and step heating thermography [5]. Xiong *et al.* proposed a multi-feature parameter imaging method, which could improve the overall imaging effect [6]. M.I.B. Shams proposed a terahertz imaging method based on compression sensing, which improved the imaging quality [7]. Trofimov *et al.* used a convolution function instead of a correlation function between the Fourier transform and a standard image; additionally, an edge sharpening algorithm was used to enhance terahertz image quality [8]–[10]. Schildknecht *et al.* proposed a blind deconvolution method for terahertz images and estimated the corresponding PSF values; by using a beam of 0.5-0.75 THz, they observed traces of 1 mm narrow slits in metal test structures [11]. Zhang *et al.* found that a THz image in the frequency domain contains more information than a THz image in the time domain; they also proposed an imaging algorithm based on deconvolution, which can improve the depth resolution of multilayer object detection and imaging [12]. Wang *et al.* processed three thermography such as long pulse thermography with advanced thermal image algorithms and obtained accurate imaging results over traditional images [5]. Yi *et al.* proposes an eddy current pulse-compression thermography, which combining the Barker code modulated eddy current excitation and pulse-compression technique. Additionally, they found two features, including a newly proposed crossing point of impulse responses related to defective and non-defective areas and skewness of impulse responses have a monotonic relationship with delamination depths by using a thermal pattern enhanced method based on kernel principal component analysis technique [13]. Chrysafi *et al.* examined the efficiency of various mathematical methods in thermographic data processing, with respect to the thermal excitation method and the type of artificial defect in the CFRP specimens. They found that delamination damages could be identified through 1D techniques [14].

Based on extensive research on different terahertz imaging methods, a time-domain piecewise imaging method with terahertz signal extraction is proposed. First, we extracted the effective signal of the defects by terahertz signal processing methods, so as to reduce the impact of noise and surface reflection echo on the imaging. Then, according to the structural characteristics of composite materials, we used the time-segmented imaging method to image the defects in each layer separately. Finally, we used the image fusion technology to fuse the images in different time periods, and the final detection imaging results are obtained. This method can effectively improve the terahertz imaging effect of deep defects in composite materials and achieve the high-quality imaging of multidepth information. This approach has good application prospects in nondestructive testing and quantita-tive depth information extraction for composite materials. In this article, the principles of terahertz signal extraction and time-domain piecewise imaging are described in detail. Then, terahertz C-scan imaging experiments are performed on glass fiber composite sample with embedded defects using this method and traditional imaging methods. The imaging results are compared and analyzed, then the SNRs and defect edge contrast of all images are calculated. The results show that the proposed method can effectively improve the terahertz image quality and defect detection rate, especially in the detection of deep defects in composite materials.

II. PRINCIPLE INFORMATION

A. EFFECTIVE SIGNAL EXTRACTION AND TIME CORRECTION

A typical pulsed terahertz detection signal is shown in Fig. 1. The figure shows that the amplitude of the initial wave signal reflected off the sample surface is much larger than other signals. This signal will play a major role in imaging using traditional characteristic parameters, such as the peak value of the signal, and a useful defect signal may be hidden, will which will have a notable impact on defect imaging. In addition, due to the uneven surface of the sample and other factors, the time delay of the signal sequence will influence the imaging effect. Therefore, it is necessary to eliminate the influence of the surface reflection signal and signal sequence delay, extract the effective signal and correct the time before imaging.

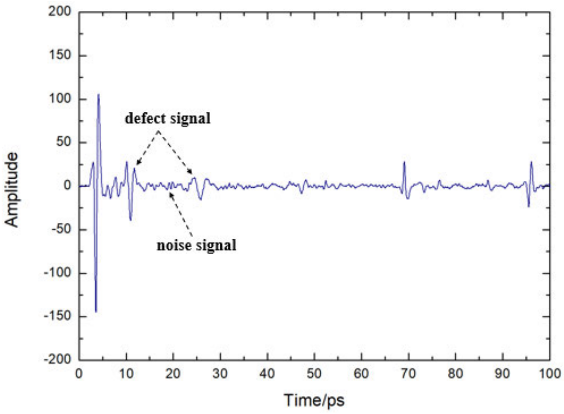


FIGURE 1. Typical terahertz time-domain signals.

The starting point of the effective signal is taken from the beginning of the first peak ($Time = t_1$) after the maximum peak (surface reflection signal) of the time-domain signal. The thickness of the sample is measured in advance, and the end point of the signal is estimated according to the thickness of the sample is $t_2 = t_1 + d/v$, where d is the sample thickness and v is the speed of the terahertz wave. Therefore, obtaining a range of effective signals from time t_1 to time t_2 is desirable. Fig. 2 is the result of extracting the effective defect signal in Fig. 1. In this case, time t_1 is set to 0 to complete the correction of the signal delay. After effective signal extraction and time delay correction, the defect signals (red ellipse frame) at different positions of the extracted signal segment are more obvious than those in the original signal because there is no interference from surface reflection and other strong signals.

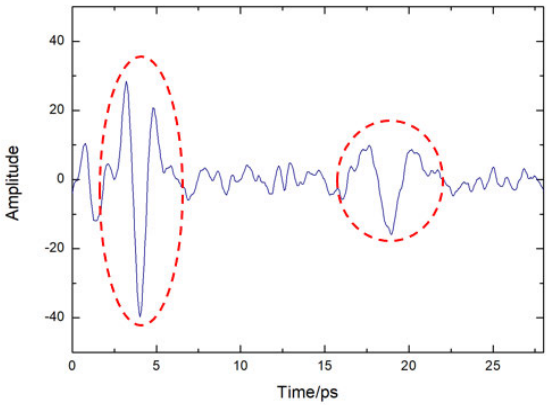


FIGURE 2. Effective signal extraction and time delay correction results.

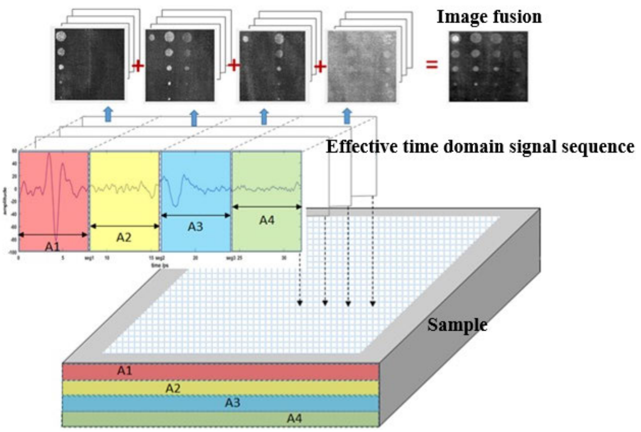


FIGURE 3. Principle of time-domain segmented imaging.

B. TIME-DOMAIN PIECEWISE IMAGING

At present, using the amplitude or time information of the time-domain signal is the most common approach in terahertz nondestructive testing and imaging methods. In addition to directly using time-domain signals for imaging, frequency-domain signals can also be imaged. These signals are transformed from time-domain signals through fast Fourier transform. All time-domain signals are one-pass signals used in traditional terahertz time-domain imaging methods. However, according to the distribution characteristics of the terahertz time-domain signal in Fig. 2, both the noise and defect signals weaken with time. Notably, as the detection depth increases, the optical path becomes longer and the signal received by the receiver becomes weaker. Therefore, the amplitude of a deep defect signal is often smaller than the amplitude of a noise signal in the initial stage. As a result, it is easy to lose deep defect information using traditional imaging methods. In addition, when there are overlapping defects at different depths at the same position, only the shallowest defect can be displayed, which results in the loss of deep defects or poor imaging quality in imaging results.

To solve this problem, an improved time-domain signal imaging method based on effective signal extraction and segmented imaging for terahertz detection is proposed in this article. As shown in Fig. 3, the obtained terahertz signal is divided into N segments (A_1 to A_4) at all positions corresponding to the different depth ranges of the sample. The defect signal is relatively obvious in each time period. Then, the characteristic parameters related to the effective time signal sequence in each time period are selected for imaging, such as the peak value and maximum values of the signal; at this time, high-quality planar imaging results in N different depth ranges can be obtained. However, due to the redundancy and complementarity of information among multiple planar images in the same region obtained by imaging in different time segments, it is necessary to obtain a combined terahertz planar image with all defect information from multiple terahertz planar images in the same region obtained by the relevant time-segment imaging technology. Thus, the problem of deep defect information loss can be avoided to a large extent, and the final imaging quality can be improved.

III. EXPERIMENTS AND ANALYSIS

A. EQUIPMENT AND SAMPLE

A terahertz time-domain spectrograph FICO REV 2.0 from Zomega Terahertz Corporation was used for the experiments. The spectrograph consisted of three main parts: the FICO base unit, the transmitters and receivers and the electronic control box. The instrument incorporated two measurement modes: a high dynamic mode and a wide-band mode. In the high dynamic mode, the frequency range was 0.1 THz-2.0 THz, the power peak was 0.75 THz, and the dynamic range reached 70 dB. In the wide-band mode, the frequency range was 0.1 THz-4.0 THz, the power peak was 0.75 THz, and the dynamic range reached 58 dB. The instrument had a frequency resolution of 11 GHz, a waveform sampling rate of 500 Hz, a time delay of 100 ps, an imaging resolution of 0.2 mm, a two-dimensional x-y scanning range of 150 mm*150 mm, and a minimum step of 0.05 mm. In this experimental study, the high dynamic mode was used, and the step setting was 0.5 mm. The experiment was conducted at room temperature (approximately 292 K) to improve the SNR. Additionally, to reduce the influence of water vapor on the absorption of terahertz waves, the experimental instrument was placed in an airtight plexiglass cover, and dry air was continuously charged to maintain a humidity of 0∼1%.

The sample used in this experiment was aeronautical glass fiber composites that consisted of glass fiber and epoxy resin; sample had 8 layers, was 5.2 mm thick and was 180*180 mm in size. Artificially embedded polytetrafluoroethylene (PTFE) was used to create delamination and inclusion defects in the sample. Using such sample in the experiments has practical engineering application value. Sample photos and design drawings are shown in Fig. 5.

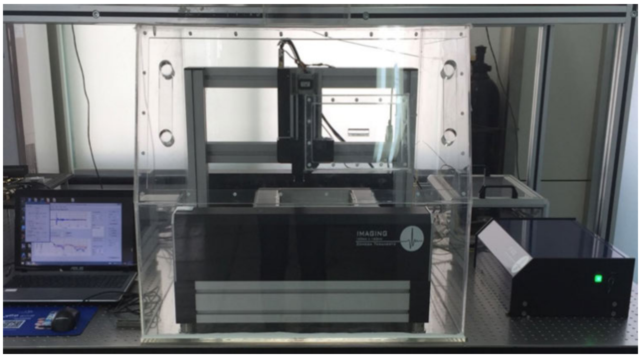
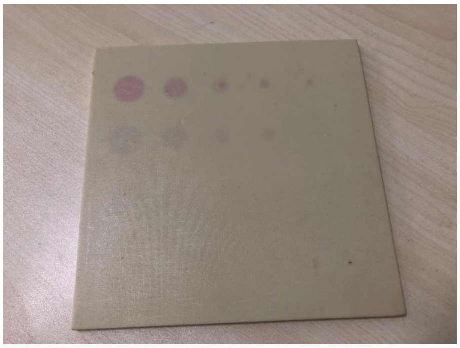
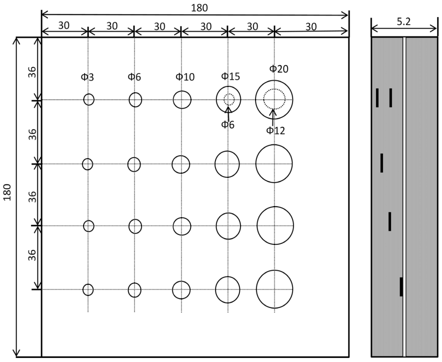


FIGURE 4. The main components of the FICO fiber coupled time-domain spectrometer.

(a) Front view of sample

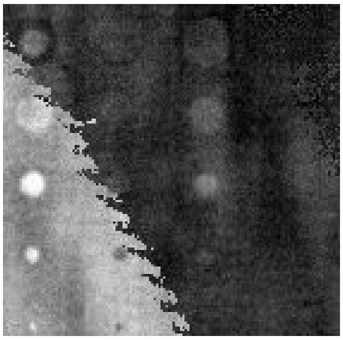


(b) Bottom view of sample

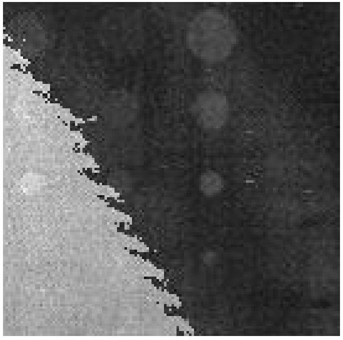


(c) Sample design drawing

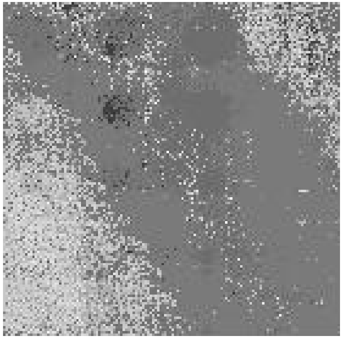
FIGURE 5. Sample photo and design drawings.



(a) Peak to peak



(b) Max amplitude



(c) Max amplitude time

FIGURE 6. Results of traditional terahertz time-domain imaging methods.

B. IMAGING RESULTS

As shown in Fig. 6, the terahertz imaging results for the experimental sample were obtained by traditional terahertz time-domain imaging methods. These adopt the peak, maximum amplitude and maximum amplitude time imaging of the time-domain signal, respectively. From the results of Fig. 6 (a) and Fig. 6 (b), we can see that defects with depth of 0.5mm-1.5mm and diameter of more than 6mm can be identified in the imaging results for the peak and maximum values, but the image contrast ratio and SNR are not high and noise interference is serious. The SNR of the maximum-amplitude time imaging results, as Fig. 6 (c) shown, is too low to recognize any defects.

As shown in Fig. 7, a typical terahertz spectrum signal with defect positions is shown. The spectrum of the defect signal in the defective area increases obviously in a certain frequency range compared with that in nondefective areas. Terahertz imaging can also be performed using this corresponding amplitude of the frequency range. Fig. 8 shows the imaging results for 0.16 THz, 0.29 THz and 0.32 THz, corresponding to the amplitudes of the frequency spectrum signal from the time-domain signal of the glass fiber composite sample

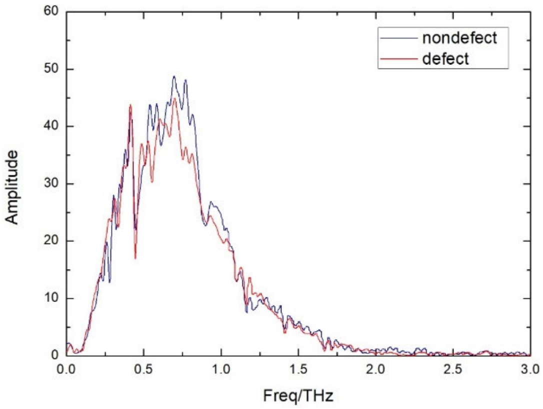
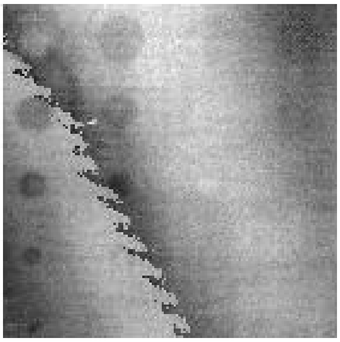
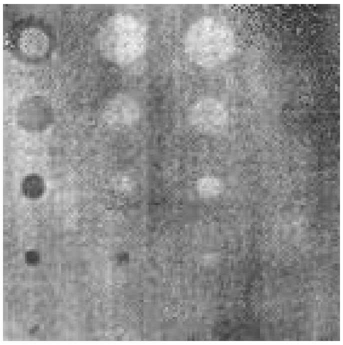


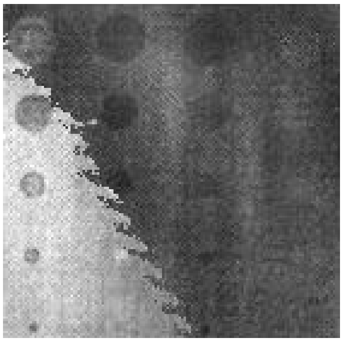
FIGURE 7. Typical frequency spectrum of the THz signal in defect areas.



(a) 0.16 THz



(b) 0.29 THz



(c) 0.32 THz

FIGURE 8. Frequency amplitude imaging results.

obtained by Fourier transform. From the results, we can see that 0.29 THz has the best imaging effect. It can not only see the defects at 1.5mm depth, but also have small gray difference for the defects at different depths at the same location.In contrast, 0.16 THz and 0.32 THz have poor imaging results, only defects deep within 1 mm can be seen.Similarly, no defects are visible deep within 2mm.

Figs. 9-11 show the results of terahertz time-domain segmented-signal imaging for fiberglass composite samples. After tring times of N value, setting $N = 4$ could get the best result. Figs. 9-11 show the peak to peak, maximum-amplitude and maximum-amplitude time imaging results corresponding to the 4-segment signals (A_1-A_4). The peak-to-peak and maximum-amplitude results are better than the maximum-amplitude time result because the latter includes more noise. In general,all defects at different depths can be imaged very well, and the SNR and contrast ratio of the image are significantly improved. not ideal due to the large depth. After the effective signal extraction, the noise is reduced, the defects imaging in last column are better than traditional imaging methods.

C. IMAGE FUSION BASED ON WAVELET DECOMPOSITION

The above experimental results indicates that the terahertz imaging method based on effective signal extraction can greatly improve the imaging quality of defects and the SNR. However, many images are obtained by the time-domain segmented-signal imaging method. A single image generally contains incomplete detection information. In addition, the information redundancy and complementarity among images are considerable. It is necessary to combine multiple images in the same region obtained by different time-domain segmented signals into a terahertz detection image containing all the defect information through image fusion technology. Compared with other image fusion methods, the image fusion method based on wavelet decomposition has the following inherent advantages: 1) excellent reconstruction ability to ensure that there is no information loss or redundant information in the process of image or signal decomposition and 2) image decomposition into a combination of an average image (low frequency coefficient) and a detailed image (high frequency coefficient), which represent different structures of the image. By selecting the wavelet coefficients in the combined image, it is easier to extract and highlight the structural information and detailed information in the original image and retain the image edges and other features than in traditional methods. Therefore, this article chooses image fusion technology based on wavelet decomposition to fuse the time-domain segmented-signal terahertz images and obtain a complete terahertz image.

Figs. 9 shows that the peak-to-peak imaging results are the clearest and contain relatively complete information. Therefore, image fusion is performed using the peak-to-peak imaging results for each signal segment. The complete terahertz image is obtained as shown in Figs. 12-14.

Fig. 12 shows the results obtained using the direct image superposition method. Fig. 13 and Fig. 14 show the results

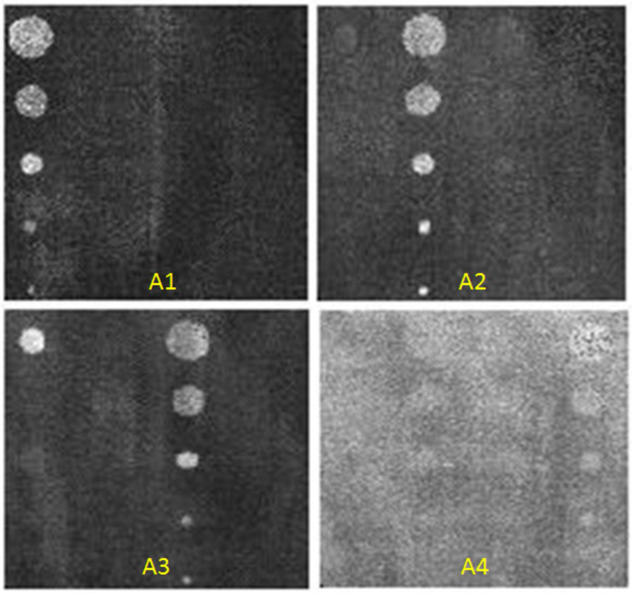


FIGURE 9. Peak-to-peak imaging results for time-domain segmented signals.

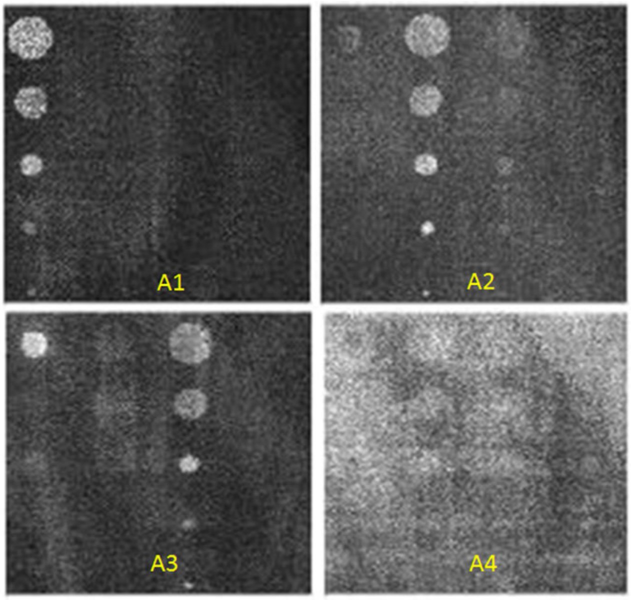


FIGURE 10. Maximum-amplitude imaging results for time-domain segmented signals.

obtained using the image fusion method based on wavelet decomposition, in which Fig. 13 adopts the method of taking a large absolute value of the coefficient and Fig. 14 adopts the weighted average method. The defects signal in A_1, A_2, and A_3 are obvious, and the defect signal in A_4 is fuzzy, so the weight coefficients of A_1, A_2, and A_3 should be similar to improve the weight coefficient of A_4. However, the value of the coefficient should not be overly large; otherwise, the SNR of the image will be reduced. From Figs. 12-14, by using the image fusion method, the defect information in the original images is completely retained in the final image, and the redundancy of the image information is eliminated. Additionally, the contrast ratio of the fused image obtained by the direct image superposition method is low, and it is

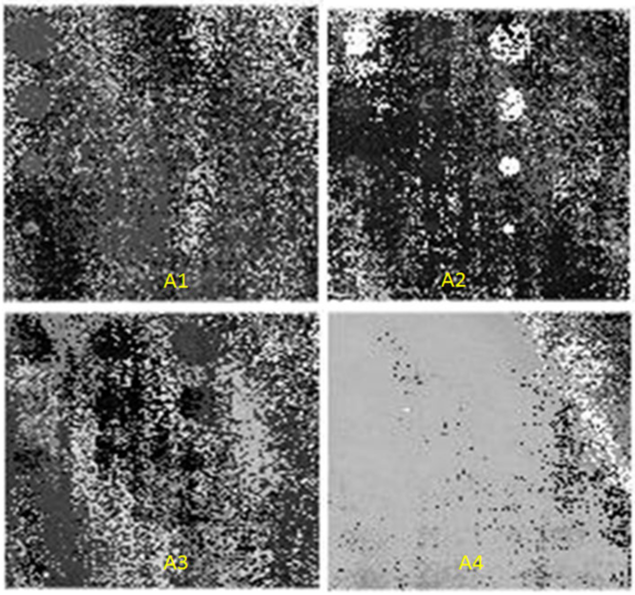


FIGURE 11. Maximum-amplitude time imaging results for time-domain segmented signals.

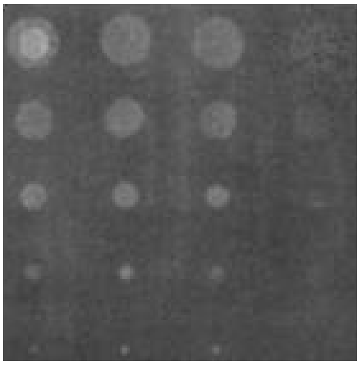


FIGURE 12. Fusion results of the direct image superposition method.

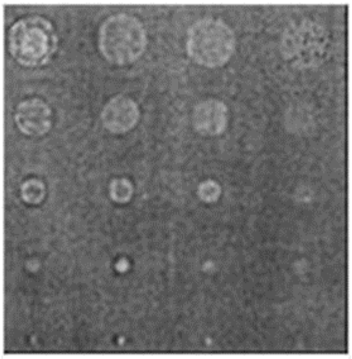
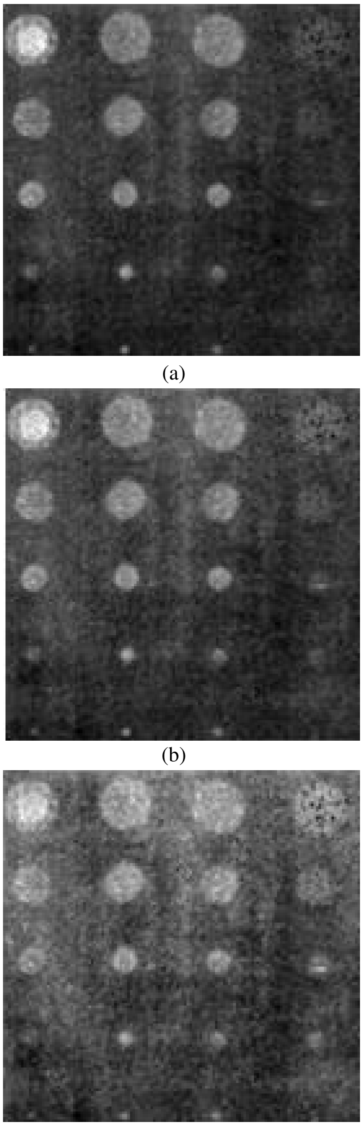


FIGURE 13. Fusion results for the method that takes a large absolute value of the coefficient.


(a)

(b)

(c)

FIGURE 14. **Image fusion results with different weighting coefficients. The coefficient values are (a) 1, 1, 1, 1; (b) 1, 1, 1, 1.5; and (c) 1, 1, 1, 2.**

difficult to distinguish the defects in the last column. The image fusion method based on wavelet decomposition with a high absolute value can obtain a high contrast ratio but also results in increased noise. The fusion rules using the image fusion method based on weighted average wavelet decomposition obtain a high SNR and contrast ratio and the best overall effect; notably, almost all defects in the sample can be identified, even the imaging resolution reaches 3 mm of the smallest defect diameter and the detection ability reaches 2mm. Suprisingly, two defects at the same location but different depths could be identified and it has high contrast. Finally, by comparing the results of the traditional terahertz detection imaging method in Fig. 6 and Fig. 8, this imaging method can greatly improve composite defect detection by combining time-domain segmented-signal imaging and image fusion technology based on wavelet decomposition.

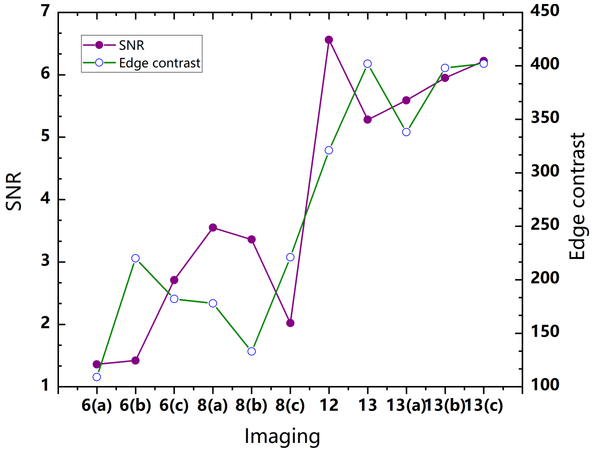


FIGURE 15. **Quantitative comparison of imaging effect.**

As shown in Fig. 15, quantitative calculation of various imaging methods are compared. The abscissa represents the image number in this article. Apparently, the SNR and edge contrast of the method in this article is significantly higher than that of the traditional imaging method. Edge contrast represents the gray difference between defect contour and background. The higher the edge contrast, the easier the eye can distinguish. The results show that the SNR and edge contrast of this imaging method are much higher than other methods. Adapting different image fusion methods lead to different image effects. Suprisingly, the result of imaging with weighting coefficients 1,1,1,2 Fig. 14 (c) is the highest. But effect of observation is inferior to Fig. 14 (a). This could be the sensitivity of the human eye to contrast differences at low spatial frequencies is high, and the sensitivity of the human eye to contrast differences related to brightness is higher than for chroma. Therefore, in most cases, the objective evaluation result will be inconsistent with the subjective feeling of the observer.

IV. CONCLUSION

Terahertz nondestructive testing technology, as a new testing technology, plays a very important role in the production and service of composite materials, and the imaging effect of such materials will directly affect the testing ability and efficiency. In this article, a time segmented image fusion based multi- depth defects imaging method is proposed. Terahertz images obtained by inspecting GFRP sample with internal PTFE inserts are compared with those images obtained using traditional imaging methods. Results show that the method proposed can effectively improve the SNR and contrast ratio of the image, especially for the detection of multi-depth defects in the same location. However, this method associates with large amount of calculation and steps, and the effect depends on the value N, which is to be improved in the next step. In addition, how to select and optimize image fusion algorithm to attain better image is also worth further research.

Terahertz detection technology has the advantage of pro- viding quantitative information for the deep and three- dimensional imaging of samples, so it is expected to become a supplement to traditional methods (e.g., X-ray imaging and ultrasonic detection imaging). The research and development of terahertz nondestructive testing technology is of great significance to the maintenance of composite materials.

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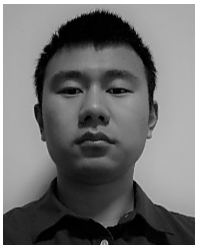
QIANG WANG was born in Nantong, Jiangsu, China, in 1976. He received the Ph.D. degree in aerospace propulsion theory and engineering from Air Force Engineering University, in 2005.

From 2005 to 2011, he was a Lecturer with the College of Aerospace Engineering, Air Force Engineering University. From 2011 to 2014, he was an Associate Professor with the Training Department, Air Force Engineering University. Since 2014, he has been a Professor with the College of Equipment Management and UAV Engineering, Air Force Engineering University. He is the author of one book, more than 60 articles, and more than four inventions. His research interests include terahertz technology, nondestructive testing, and infrared detection technology.

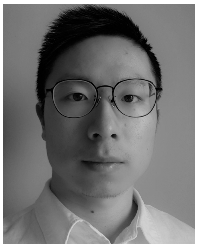
HONGBIN ZHOU received the B.S. degree in flight vehicle propulsion engineering and the M.S. degree in control science and engineering from Air Force Engineering University, China, in 2017 and 2019, respectively, where he is currently pursuing the Ph.D. degree in control science and engineering.

Since 2017, he has been a Research Assistant with the Aviation Safety and Airworthiness Laboratory, Air Force Engineering University. His research interests include the deep learning and terahertz technology.



RUICONG XIA is currently pursuing the master's degree with the College of Equipment Management and UAV Engineering, Air Force Engineering University, China.

Since 2018, he has been a Research Assistant with the Aviation Safety and Airworthiness Laboratory, Air Force Engineering University. His current research interests include the experiment and application of infrared thermography and laser ultrasound NDT.



QIUHAN LIU was born in Jurong, Jiangsu, China, in 1996. He received the B.S. degree in safety engineering from Air Force Engineering University, China, in 2018, where he is currently pursuing the degree majoring in control engineering.

His research interests include application of terahertz and infrared in non-destructive testing of carbon/glass fiber composites and defect classification using deep learning algorithm.

BO YAN ZHAO received the B.B.A. degree in management engineering from Air Force Engineering University, China, in 2019, where he is currently pursuing the master's degree in control science and engineering. He has been a member with the Aviation Safety and Airworthiness Laboratory, Air Force Engineering University, since 2019. His research interests include deep learning and NDT technology.