10.21611/qirt.2020.054

Research on the detection of delamination defect of CFRP using thermal-wave radar tomography (TWRT)

Fei WANG[1,2], Bo-yuan DONG[1,2], Jun-yan LIU[1,2,*], Yang WANG[1,2]

[1.] School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, 150001, P.R.China.

[2.] State Key Laboratory of Robotics and System (HIT), Harbin, 150001, P.R.China.

[*]correspondence author: Jun-yan LIU, e-mail: ljywlj@hit.edu.cn, tel.:0086-13845169859, address, No. 92, Xidazhi street, Nangang district, Harbin, 150001, P.R.China.

Abstract

Carbon fiber reinforced polymer (CFRP) has been widely used in modern industry due to its excellent properties. However, due to its strong anisotropy, it is easy to produce delamination defect which seriously affect the performance of the material. Therefore, for CFRP composites, how to effectively and accurately detect and identify internal defect have become a hot and difficult research field. In this paper, a new tomography method called thermal-wave radar tomography (TWRT) is introduced, and it is applied to the visualization detection of CFRP delamination defect. Firstly, the time delay correlation dual orthogonal demodulation (DOD) algorithm is used to extract the frequency domain and time domain characteristic sequence of the thermal-wave signal of the pulse radar, and the TWRT method is established, the applicability of the method is analyzed by the COMSOL simulation. Then, the correctness of the simulation analysis is verified by the experiment of detecting the flat bottom holes which used to replace the delamination defect of CFRP composites by TWRT, and the accuracy of the shape and position (depth) of the defect detected by TWRT is determined. Finally, the ultrasonic C-scan imaging method and TWRT are used to compare and analyze the delamination defect of CFRP composites, which proved the superiority of TWRT. The experimental results illustrate that TWRT technique can achieve high-quality 3D geometric reconstruction of delamination defect, which provides a new method and idea for nondestructive testing and tomography of CFRP composites.

Keywords: Carbon fiber reinforced polymer (CFRP), delamination defect, thermal-wave radar tomography

10.21611/qirt.2020.054

1. Introduction

Carbon fiber reinforced polymer (CFRP) has the advantages of light weight, high strength, high specific stiffness, corrosion resistance and adjustable anisotropy, which makes it widely used in aerospace, nuclear civil and renewable energy fields. However, such materials show strong anisotropy and internal interface effect. In the process of production or use, defects such as delamination and invisible impact damage are easy to occur between layers, which seriously affect the performance of materials or structures [1]. Therefore, for CFRP composites, how to effectively and accurately detect and identify internal delamination defects has become a hot and difficult research field.

In order to ensure the quality of CFRP composites, it is necessary to carry out effective non-destructive testing & Evaluation (NDT & E) in the process of processing or using CFRP composites. The traditional inspection methods include ultrasonic testing [2], eddy current testing [3] and X-ray testing [4]. Although These methods can detect delamination defects accurately, there are still some problems such as high cost, low efficiency and unable to be detected online.

Infrared thermal-wave imaging detection technology [5] is a new interdisciplinary infrared detection technology. The technology uses external excitation heat source to carry out active thermal loading on the object, uses infrared thermal imager to collect the thermal radiation signal (or thermal-wave signal) on the surface of the object, and realizes the defect judgment and analysis by analyzing the characteristics of the thermal signal. At present, the infrared pulse thermal-wave imaging detection and infrared phase-locked thermal-wave imaging detection are the most mature infrared thermal-wave detection technology and widely used. Infrared pulse thermal-wave imaging testing technology is the most researched and most mature infrared detection method, and is also the most widely used infrared detection technology [6]. It has been widely used in nondestructive testing and evaluation of small thickness specimens. However, due to the limited instantaneous energy injection, this method is not suitable for the specimen with larger thickness due to its small detection depth. Infrared phase-locked thermal-wave imaging detection technology is a new infrared thermal-wave imaging detection technology based on phase-locked characteristic extraction proposed by Busse G. [7] in the 1990s. It is used for noise suppression and weak signal extraction in electronic circuits. The application of this technology in infrared thermal-wave imaging greatly improves the signal-to-noise ratio of defect detection, and overcomes the disadvantage of infrared thermal-wave detection technology which only relies on intensity characteristics (amplitude). However, in order to avoid the "blind frequency" phenomenon, the infrared phase-locked thermal wave imaging detection technology needs to select multiple modulation frequencies to test the specimen. At present, most of the detection methods based on infrared thermal-wave imaging are to obtain the integral signal within the whole thermal diffusion length range, which can only obtain the two-dimensional (2D) plane information of CFRP composites, and can not carry out the three-dimensional (3D) quantitative visual evaluation of materials. However, it is urgent to obtain the internal information of materials in the actual detection. In order to solve this problem, researchers have carried out in-depth exploration and research.

Dynamic thermal tomography (DTT) is the first tomography method using infrared thermal imaging to reconstruct 3D specimen [8-9]. It was first proposed and preliminarily analyzed by Vavilov V.P. and Maldague X.P. [10-11] in 1990. In 2009, Swiderski W. [12] of Polish military equipment Institute used dynamic thermal tomography method to conduct tomography of CFRP composites. The experimental results illustrated that this method greatly improved the signal-to-noise ratio of defect detection, and explored the efficiency of data processing. In 2012, Melnyk S.I. [13] improved the dynamic thermal tomography method, which overcame the temperature disturbance caused by the nonuniformity of the traditional thermal tomography method, and effectively improved the imaging quality by using the 3D thermal reconstruction algorithm. In 2015, Vavilov V.P. [14] proposed an improved image processing algorithm for dynamic thermal tomography. This algorithm abandons the step that the reference point must be selected in the traditional processing algorithm, and improves the extraction ability of material geometric characteristics. In 2010, Tian Yupeng [15-16] built an experimental system based on the principle of dynamic thermal tomography. The system was used to carry out imaging experimental research on different excitation conditions and defect types. Image noise filtering and image segmentation algorithm based on mathematical morphology were used to process infrared thermal-wave images, and a projection reconstruction algorithm based on isosurface was proposed. This algorithm can well reconstruct the structure information under the surface of the object.

The thermal-wave radar tomography (TWRT) studied in this paper is a kind of infrared thermal-wave imaging non-destructive testing method with frequency modulation heat flow as the main excitation which based on the traditional active infrared imaging detection technology. The TWRT uses the pulse radar with large time and wide product characteristics to excite the specimen with heat flow to improve the signal-to-noise ratio and imaging quality of defect detection. At the same time, the

10.21611/qirt.2020.054

technology can realize the 3D tomography and characteristics evaluation of the tested specimen, which provides a new method for effective and reliable detection of delamination defects in CFRP composite materials.

2. Theories of TWRT

TWRT is a nondestructive testing method which combines pulse excitation, pulse compression matching filtering and other technologies [17]. This technology is a new thermal-wave tomography method proposed in recent years which has achieved good detection depth resolution and detection effect. The excitation heat flow signal of TWRT contains multiple frequency components. According to the different types and sizes of defects detected, the heat flow loading mode in the form of pulse radar can be used.

At present, TWRT realizes tomography [18] mainly by the pulse-radar heat flow excitation method. Pulse-radar signal is a signal form obtained by convolution operation of continuous linear frequency modulation radar signal and pulse signal. The pulse-radar signal combines the both to ensure that the signal has greater compressibility and more energy injection, which ensures that the method has high signal-to-noise ratio from the excitation signal source.

The principle of TWRT is to realize the tomography by changing the pulse width and delay characteristics of the reference signal to achieve energy location at different depths when extracting the characteristics of pulse-radar thermal-wave signals. Because the diffusion length (depth) of the thermal-wave is related to the pulse width, the thermal-wave characteristics of the pulse-radar have the depth dynamic resolution, which provides an important basis for the detection of the defects in composite materials.

2.1 Time delay correlation DOD algorithm

The idea of dual orthogonal demodulation (DOD) is derived from the infrared phase-locked thermal-wave imaging detection technology. The algorithm uses the in-phase signal and orthogonal signal with the same frequency as the excitation heat flow signal to extract the amplitude and phase information of the thermal-wave signal [19-20]. The phase information obtained by the two-way orthogonal demodulation algorithm is not sensitive to the influence of uneven heating, external environment disturbance and surface emissivity, which is the main reason why the algorithm is widely used in phase-locked thermal-wave imaging detection. The application of DOD to characteristics extraction of thermal-wave radar signal can significantly improve the ability of noise suppression. In this paper, the time-domain and frequency-domain characteristics of the depth correlation of pulse-radar thermal-wave signal are extracted by using delay correlation DOD algorithm.

Since the actual temperature signal is discrete data, the sampling frame number of temperature signal is N and the temperature signal is $T(n)$ to obtain the characteristic amplitude and phase of DOD, the in-phase correlation function and orthogonal correlation function of thermal-wave signal should be obtained through Eq. (1).

$$R^0(\tau) = \frac{1}{N}\sum_{n=1}^{N} T(n) \cdot Q(n) \quad (1.a)$$

$$R^{90}(\tau) = \frac{1}{N}\sum_{n=1}^{N} T(n) \cdot R(n) \quad (1.b)$$

where $Q(n)$ is in-phase signal of excitation signal, $R(n)$ is orthogonal signal of excitation signal which is obtained by Hilbert transform [21-22], τ is delay time.

Thermal diffusion is a process in which heat flow is transferred gradually with time. The change of thermal characteristic parameters in material will inevitably affect the change of surface thermal wave. Since the thermal-wave diffusion length (depth) is related to the pulse width, the time-lapse reference signal can be used to extract the thermal-wave response related to the thermal diffusion length (depth). Fig. 1 shows the implementation process of the time delay correlation DOD algorithm.

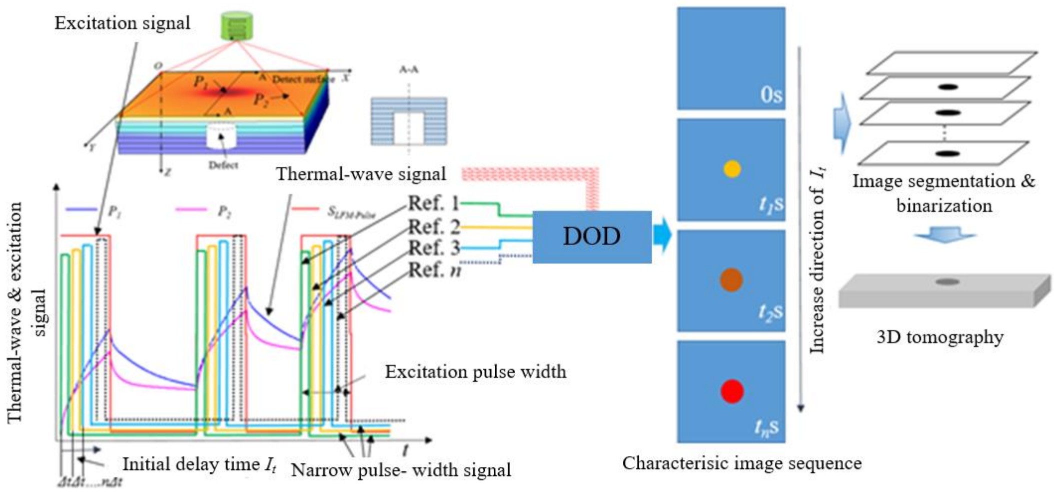


Fig. 1 Time delay correlation DOD algorithm

The time delay correlation DOD algorithm can directly extract the response characteristics of different delay pulse-radar thermal-wave, especially for the narrow pulse width reference signal, it can realize the high resolution recognition of depth direction. The characteristics image sequence in depth direction is obtained by equal interval delay pulse of initial delay time of reference signal, and 3D tomography reconstruction is realized by using the image sequence. The in-phase and orthogonal delay reference pulse sequence signals of time delay correlation DOD algorithm can be expressed as follows,

$$Q[t+I_t(t)] = H(t-t_p) \otimes \sum_{n=0}^{p} \delta\left[t - \left(\frac{-\omega_1+\sqrt{\omega_1{}^2+8kn\pi}}{2k}\right) + I_t(t)\right] \quad (2.a)$$

$$R[t+I_t(t)] = H(t-t_p) \otimes \sum_{n=0}^{p} \delta\left[t - \left(\frac{-\omega_1+\sqrt{\omega_1{}^2+8kn\pi+2k\pi}}{2k}\right) + I_t(t)\right] \quad (2.b)$$

$$I_t(t) = \lambda \Delta t \qquad \lambda = 0,1,2 \ldots M \quad (2.c)$$

where $I_t(t)$ is initial delay time, $H(t)$ is Helvetius unit function, p is the number of pulses in a cycle, t_p is reference signal pulse width, δ is Dirac function, M is the number of initial time delays, Δt is the single delay time and $k=(\omega_2-\omega_1)/T$ is scanning rate, where ω_1 is initial angular frequency and ω_2 is end angular frequency. According to the empirical formula of thermal diffusion [23], the relationship between initial delay time and detection depth is as follows,

$$\bar{z} = \frac{2\sqrt{\alpha I_t(t)}}{\sqrt{\pi}} \quad (3)$$

where α is thermal diffusion coefficient. According to the principle of the algorithm, the single delay time Δt determines the depth resolution. The smaller Δt, the higher the resolution. In other words, the maximum frame frequency of focal plane infrared thermal imager determines its maximum sampling interval, and then determines the minimum value of Δt. When the delay time $I_t(t)$ is 0, the characteristics obtained is the surface characteristics of the specimen. When the delay time increases, the deeper characteristics information can be obtained, and the relationship between delay time and depth is related to the material of the specimen. Based on the principle of DOD algorithm, the in-phase and orthogonal correlation functions corresponding to the surface temperature signal $T(t)$ when the delay time is $I_t(t)$ can be obtained,

$$R\_TD^0 = T(t) * Q[t+I_t(t)] \quad (4.a)$$

$$R\_TD^{90} = T(t) * R[t+I_t(t)] \quad (4.b)$$

where R_TD^0 is in-phase correlation function, R_TD^{90} is orthogonal correlation function. In order to ensure the operation integrity, the maximum delay time $I_t(t)$ should not exceed the interval between the last pulse of the in-phase reference signal and the cut-off time. The amplitude and phase characteristics of delay time $I_t(t)$ can be obtained by using in-phase and orthogonal correlation functions,

$$TD\_Am = \sqrt{\left[R\_TD^0\right]^2 + \left[R\_TD^{90}\right]^2} \quad (5.a)$$

$$TD\_Ph = \tan^{-1}\left(\frac{R\_TD^{90}}{R\_TD^0}\right) \quad (5.b)$$

where *TD_Am* is amplitude characteristics, *TD_Ph* is phase characteristics. Different delay time DOD amplitude or phase of pulse-radar thermal-wave related to thermal diffusion length (depth) is obtained for tomography. For TWRT, the modulation parameters corresponding to different external excitation heat flow signals affect the results of characteristic parameters. Therefore, the finite element simulation method is needed to study the influence of different heat flux excitation modulation parameters and defect size on the thermal-wave signal.

3. Simulation

In this section, the finite element analysis software COMSOL will be used to simulate the TWRT of CFRP flat bottom holes. This paper studies the influence of depth correlation characteristics extraction algorithm on tomography, determines the reasonable characteristics of radar thermal-wave suitable for delamination defect tomography, and studies the influence and law of sampling frequency on tomography results, which lays the foundation for the follow-up experimental research.

3.1 Finite Element Simulation

Fig. 2 shows the geometric structure model of CFRP flat bottom hole defect sample for simulation analysis. The thermal physical properties of CFRP material are as follows: the thermal conductivity in parallel direction $\lambda_{/\!/}$ is 4.18W / (m·℃), the thermal conductivity in vertical direction $\lambda_{\perp}$ is 0.71W/(m·℃), the density ρ is 1760 Kg/m^3, and the specific heat capacity c is 795.12J/(Kg·℃). The material size is set as 100mm×100mm×2.1mm, the laying direction is [0, 45, 90, 0, 90, 45, 0], and the thickness of single layer is 0.30 mm. In the process of TWRT, it is necessary to capture the surface temperature changes as quickly as possible, so it is necessary to increase the data sampling frequency in the simulation process.

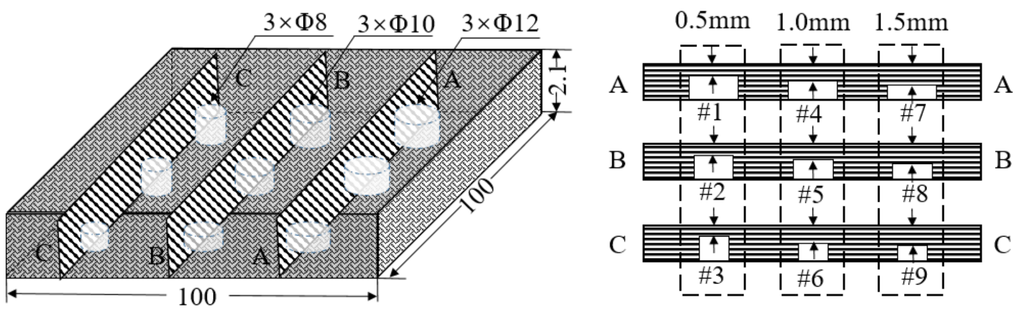
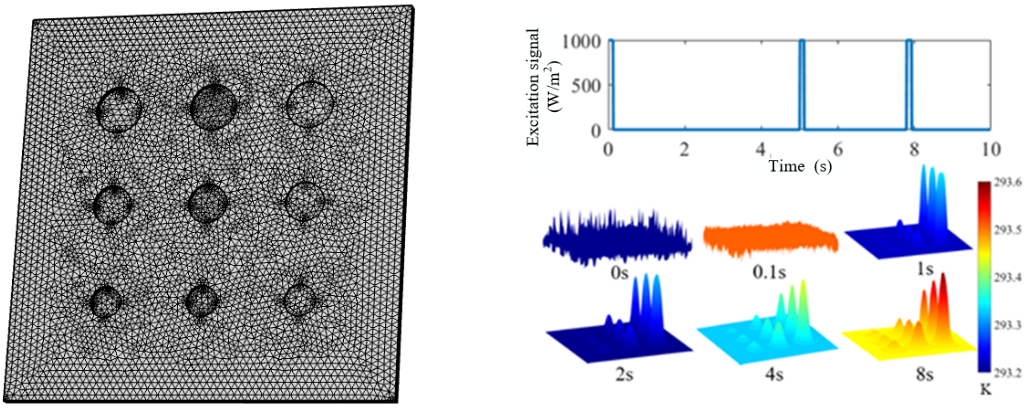


Fig. 2 CFRP simulation flat bottom hole defects structure

In order to improve the calculation efficiency, it is necessary to select the heat flow excitation parameters reasonably. The scanning period of pulse-radar signal should be at least the whole period corresponding to the lowest frequency component. If the frequency is too low, the scanning period of pulse-radar excitation signal will increase, and the longer scanning cycle time will inevitably produce large amount of data, which improves the operation efficiency of tomography. Therefore, in order to realize the TWRT, it is necessary to consider the material and internal defect characteristics, data acquisition and calculation, and pulse-radar excitation parameters. According to the thermal properties of the material, the pulse-radar excitation parameters are 0.1Hz-0.5Hz-10s-0.1s, the data sampling frequency is 100Hz, the peak power density is 1000W/m^2, and the size resolution is 100×100 pixel. Fig. 3 shows the finite element mesh model of flat bottom hole defect sample and the simulation results of surface temperature at different time points.

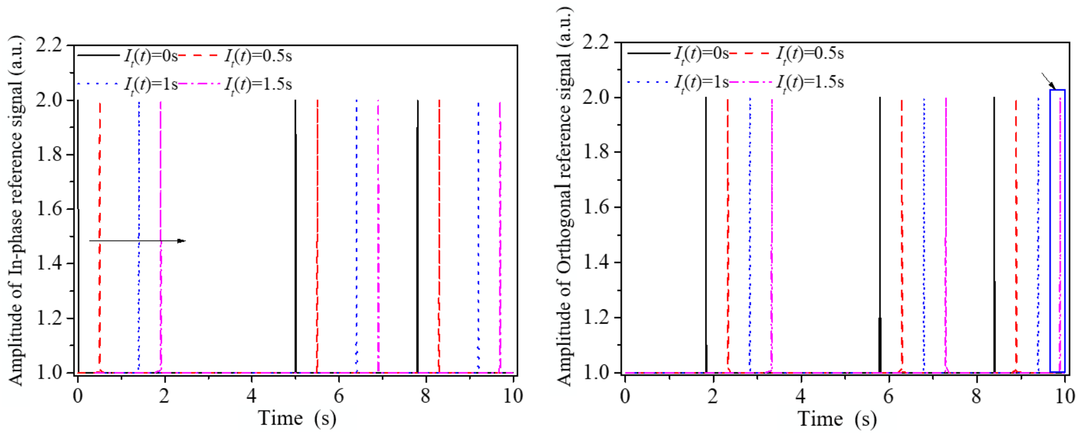


a) Finite element mesh b) Temperature field distribution at different times

Fig. 3 Finite element mesh and surface temperature simulation results

It can be seen from Fig. 3 that with the increase of time, the defects of different scales can be detected through the surface temperature sequence. During the first pulse heat source excitation time, the flat bottom hole defect can not be detected, and the temperature difference corresponding to the defect location is small. In practical detection, due to the small range of temperature variation and low signal-to-noise ratio (SNR) of defects based on thermal image sequence, it is difficult to directly use thermal image sequence for internal defect tomography detection.

When the time delay correlation DOD algorithm is used to extract the amplitude and phase characteristics of the pulse-radar thermal-wave signal, the pulse width, total delay time and time step of the reference signal should be determined first. Since the data sampling frequency is 100Hz, the optional time step and pulse width are both 0.01s, and the total delay time can be determined according to the characteristics of the reference signal. Fig. 4 shows the in-phase and orthogonal reference signals calculated by the time delay correlation DOD.

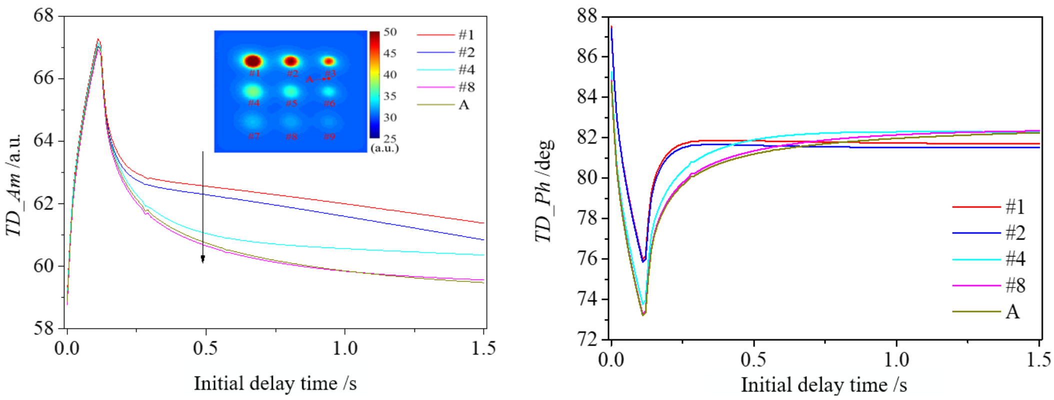


a) In-phase reference signal b) Orthogonal reference signal

Fig. 4 Dual orthogonal reference signals

It can be seen from Fig. 4 that the thermal-wave transfer of pulse-radar can be located by using the dual reference signals with different initial delay times. When the initial delay time is 1.5 s, the last pulse of in-phase and orthogonal reference signals will end. If the initial delay time is increased, the last pulse in the in-phase and orthogonal reference signals will be lost, which makes it difficult to perform the DOD cross-correlation matching filtering operation. Therefore, the total initial delay time should be strictly controlled.

Fig. 5 shows the DOD amplitude and phase characteristics of pulse-radar thermal-wave signal corresponding to the center position of defect #1, #2, #4, #8 and position a without defect under different initial delay time.



a) *TD_Am* curve b) *TD_Ph* curve

Fig. 5 DOD characteristics under different initial delay times

From Fig. 5a) it can be seen that when the initial delay time is less than 0.15s, there is almost no difference between the amplitude characteristics of DOD with and without defects; When the initial delay time is greater than 0.15s, with the increase of initial delay time, the amplitude characteristics of DOD corresponding to the position with or without defects gradually differ, which indicates that with the increase of initial delay time, the internal defects with different depths will be gradually divided from shallow to deep However, when the initial delay time reaches 1.5 s, it is difficult to distinguish and identify the amplitude characteristics of the corresponding DOD. It is difficult to distinguish and identify the #8 defect with deep defect depth. The resolution and recognition ability can be improved by further improving the pulse excitation energy (such as increasing the pulse width and peak power) and reducing the modulation frequency. It can be seen from Fig. 5b) that with the increase of initial delay time, DOD phase characteristics first decrease and then increase, and finally tend to be stable. When the initial delay time is less than 0.5 s, due to the same depth of #1 and #2 defects in the sample, the difference between the corresponding DOD phase characteristic curves is small, while the corresponding DOD phase characteristics of #4 and #8 defects are significantly different. Therefore, when the initial delay time is in the range of 0s ~ 0.5s, the phase characteristics of DOD have good resolution for different depth defects. However, in the whole initial delay time, the regularity of DOD phase characteristics for different depth defects is poor.

In conclusion, based on the amplitude characteristics of time delay correlation DOD algorithm, defects with different scales (size and depth) can be identified sensitively, and the depth location and resolution of thermal-wave energy transfer can be realized. Due to the short pulse time of pulse radar, large heat accumulation can be avoided and enough energy input can be ensured. The simulation results also show that the initial delay time DOD amplitude characteristics can be reconstructed according to the time sequence, which can realize the tomography detection of internal defects or damage of composite materials.

3.2 3D Tomography

In this paper, the pulse radar tomography method based on the finite element simulation analysis is used. The initial time delay correlation DOD algorithm is used to obtain the frequency domain and time domain characteristics of the image sequence and reconstruct to achieve tomography. In this method, ImageJ software is used to realize the visualization of 3D tomography, and the characteristics images need to be further corrected and normalized, and the transformation from eigenvalues to gray values is needed.

When the initial delay time is 0s, the amplitude characteristics of DOD should be consistent. However, due to uneven heating or uneven emissivity of the material surface, the amplitude characteristics of DOD corresponding to the initial delay time of 0s are slightly different. Therefore, the characteristic image of DOD amplitude corresponding to the initial delay time of 0s is used to analyze the whole characteristics image sequence *TD_Am*(*x*, *y*, $I_t(t)$) was corrected, and the corrected characteristic value of DOD amplitude was *Cali_TD_Am*.

In order to visualize the 3D tomography, it is necessary to transform the thermal-wave eigenvalues of pulse radar into gray scale. In order to retain the original eigenvalue information as much as possible, the *Cali_TD_Am* eigenvalue is converted to gray value by linear transformation.

Cali_TD_Am characteristics sequences with initial delay time of 0s ~ 1.5s and interval of 0.01 s are transformed into gray image sequences for tomography. Fig. 6 shows the simulation results of *Cali_TD_Am* characteristics gray image sequence tomography.

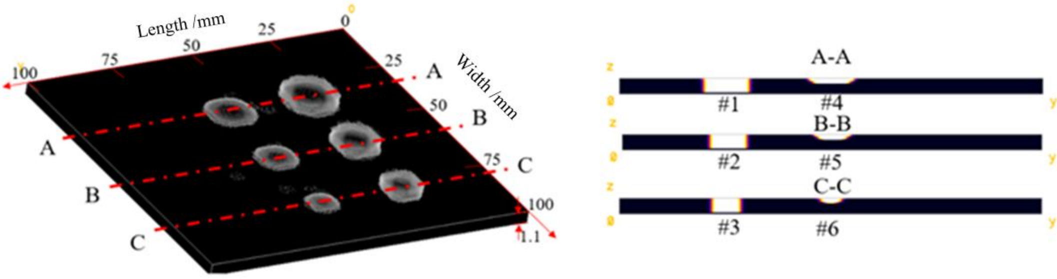


Fig. 6 3D tomography results based on *Cali_TD_Am* characteristics gray image

As can be seen from Fig. 6, it is easy to realize tomography and 3D visualization reconstruction of CFRP flat bottom hole defects based on *Cali_TD_Am* characteristics gray image sequence, but it is difficult to realize detection for given #7 ~ #9 flat bottom hole defects under the given pulse-radar excitation parameters. The reconstruction of gray image sequence based on *Cali_TD_Am* characteristics can accurately realize the tomography detection of #1 ~ #6 flat bottom hole defects, and the distortion of defect edge position is small, which indicates that *Cali_TD_Am* characteristics has good inhibition ability on transverse thermal diffusion effect. It can be seen from the slices of A-A, B-B and C-C positions that *Cali_TD_Am* characteristicss can accurately detect the shape and location of defects, and there is no intermediate fault or delamination.

The simulation results show that the method based on *Cali_TD_Am* characteristics sequence reconstruction can detect the shape and position of defects accurately, and there will be no defect characteristic fault or delamination, which can realize the tomography detection of internal defects in materials.

4. Experiment

In order to verify the correctness of the simulation analysis, this section carries out experimental research on the TWRT detection of CFRP composite materials. The specimens used is the flat bottom hole simulation delamination defect #ES1. Fig. 7 shows the optical picture of #ES1.

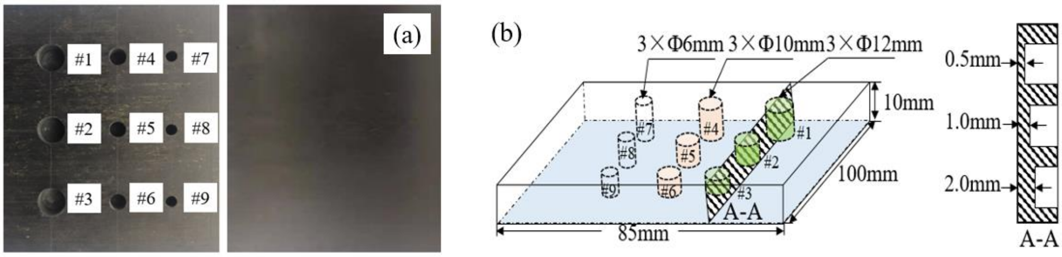


Fig. 7 a)Optical photo of the #ES1 CFRP specimens and b) its geometric dimensions

The pulse radar excitation parameters are 0.05Hz-0.10Hz-40s-2s, and the peak power density is 5000W/m^2. Due to the poor thermal conductivity of CFRP composites, in order to ensure the accuracy of defect depth resolution, the sampling frequency of infrared thermal imager is set at 50Hz. The depth dependent characteristics extraction algorithm was used to detect the simulated delamination defects in CFRP composites.

4.1 Experimental Setup for TWRT

Fig. 8 depicts the schematic diagram of TWRT. This experimental setup consists of three main parts: the active excitation part, the image sequence acquisition part, and the software control and post processing part, respectively. Two same continuous wave fiber-coupled 808-nm NIR diode lasers are the core devices of the active excitation part, and the maximum power of a single laser is 50W. An NI-6229 signal generation/ acquisition device controls the laser power source, which in turn causes the laser intensity to change at a chirp-pulsed waveform, and this active excitation heat flow induced the chirp-pulsed radar thermal -wave inside the sample. The equipment used in the image sequence acquisition part is FLIR SC7000 mid-infrared camera. The window size of this infrared camera is 320×256 pixel active elements, the spectral range is 3.6–5.1μm and the highest stable operating frequency of the whole window is 100 Hz. An appropriate laser beam homogenizer was used to maintain an average optical intensity for reducing heating unevenness. This laser beam homogenizer includes an engineered diffuser, casing, and collimator. The laser excitation signal controlling/ thermal image sequence acquisition program is designed in the LabVIEW. Post processing programs that were based on MATLAB environment are programmed for the thermal wave signal reconstruction and data processing algorithms implementation.

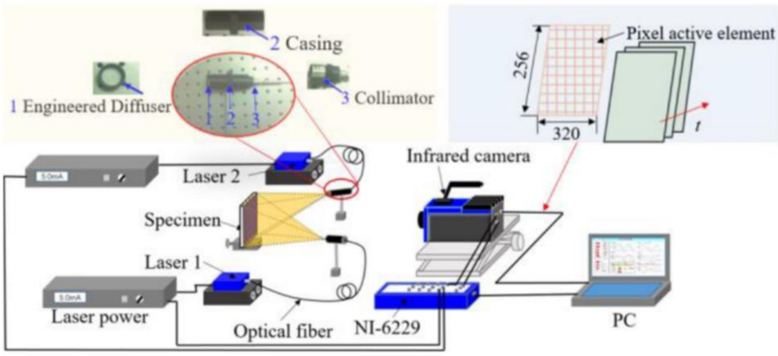
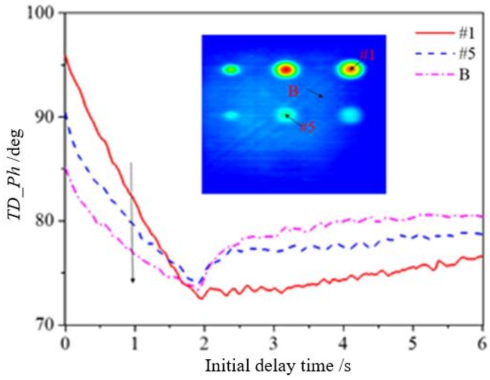


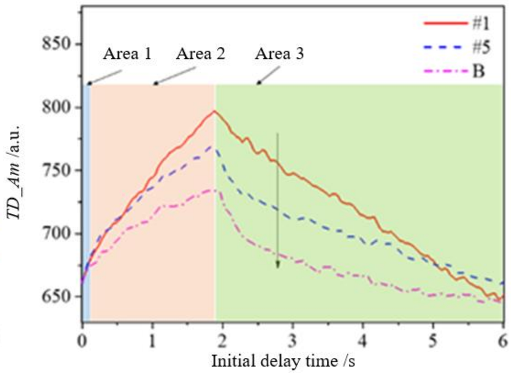
Fig. 8 Schematic diagram of TWRT

4.2 3D Visualization Tomography of Delamination Defects in CFRP

The time delay correlation DOD algorithm is used to calculate the frequency domain and delay time response of pulse-radar thermal-wave signal. Fig. 9 shows the DOD characteristic curves of pulse-radar thermal-wave signals at position #1, #5 and defect free B in #ES1 specimen under different delay times.



a) *TD_Ph* curve



b) *TD_Am* curve

Fig. 9 DOD frequency-domain characteristic under different initial delay times

It can be seen from Fig. 8b) that the amplitude characteristic *TD_Am* of DOD first increases and then decreases with the increase of initial delay time. When the initial delay time is less than 5s, *TD_Am* decreases with the increase of defect depth. When the *TD_Am* curve is located in area 1 in Fig. 9b), the *TD_Am* characteristics corresponding to the defects are almost the same, which indicates that the thermal diffusion (penetration) depth is less than 0.5mm, and the area 2 and area 3 are in the heating and cooling stages respectively. It can be seen from Fig. 8a) that with the increase of initial delay time, the phase characteristic *TD_Ph* of DOD first decreases, then increases and tends to be stable. In the initial delay time of 0 ~ 2s, *TD_Ph* decreases with the increase of defect depth. When the initial delay time exceeds 2s, *TD_Ph* increases with the increase of defect depth. The above results are consistent with the simulation analysis.

Cali_TD_Am characteristic gray image sequence with initial delay time of 0s ~ 6s is selected for tomography, and the interval between reference signal pulse width and initial delay time is 0.02s. Fig. 10 shows the 3D tomography results of #ES1 sample based on *Cali_TD_Am* characteristics gray image sequence reconstruction.

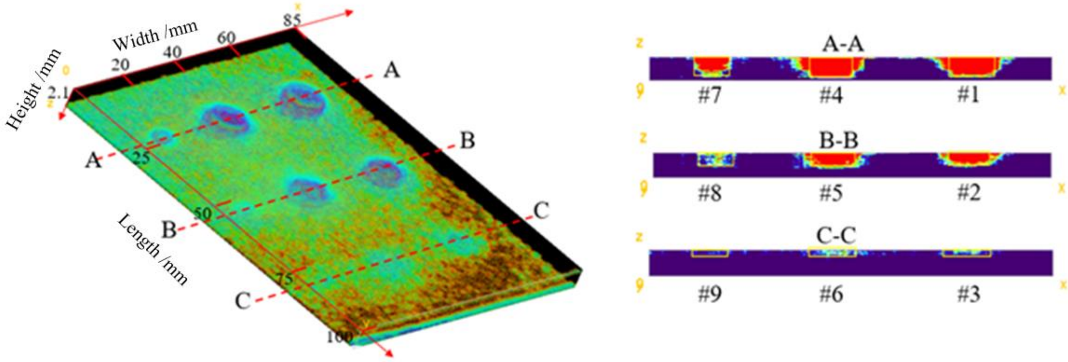


Fig. 10 3D tomography results based on *Cali_TD_Am* characteristics gray image sequence

As can be seen from Fig. 10, based on the *Cali_TD_Am* characteristics gray image sequence 3D tomography method, the defect tomography detection of CFRP composite sample except for #9 flat bottom hole defects (diameter depth ratio r = 3) is realized. With the increase of initial delay time, the detection ability of thermal-wave transfer of pulse-radar decreases, which makes the detection signal-to-noise ratio of deep defects lower. The shape and position of flat bottom hole defects can be obtained by using tomography method, as shown in Table 1.

Tab. 1 Detection results of #ES1 specimen defect size based on *Cali_TD_Am*

Number	#1	#2	#3	#4	#5	#6	#7	#8
Actual diameter	12	12	12	10	10	10	6	6
Detection Diameter	11.61	11.18	9.46	9.89	10.32	8.60	6.45	5.59
Deviation	0.39	0.82	2.54	0.11	0.32	1.40	0.45	0.41
Actual depth	0.50	1.00	2.00	0.50	1.00	2.00	0.50	1.00
$I_t(t)$/s	0.60	1.78	5.10	0.60	1.78	5.10	0.60	1.78
Detection depth	0.61	1.10	1.80	0.61	1.10	1.80	0.61	1.10
Deviation	0.11	0.10	0.20	0.11	0.10	0.20	0.11	0.10

It can be seen from table 1 that for defects with depth less than 1mm, the detection diameter deviation is less than 0.82mm, and the detection depth deviation is within 0.11mm. With the increase of defect depth, the deviation of diameter and depth increases.

4.3 Comparison between ultrasonic C-scan and TWRT

Ultrasonic C-scan is a mature detection technology and means for the defect

10.21611/qirt.2020.054

detection of composite materials. Ultrasonic pulse reflector C-scan imaging technology is a new C-scan method developed in recent years. It can provide multiple depth scanning images in a single scan. Ultrasonic C-scan technology monitors the multi-dimensional movement of the ultrasonic probe through the control software. The ultrasonic flaw detector sends out the signal by transmitting the probe. When the ultrasonic signal passes through the workpiece, it is received by the probe itself. The ultrasonic flaw detector processes the received signal, and the data analysis and result display are processed by the computer. Therefore, this section will carry out comparative test analysis of ultrasonic pulse reflector C-scan imaging technology and TWRT for #ES4. The ultrasonic equipment used is UT-ARS100 ultrasonic C-scan detector. The probe is BENCHMARK S/N 136007KT, the probe frequency is 5MHz, the probe diameter is 0.75 ", and the probe focal length is 4". The scanning speed was 150mm/s and the step spacing was 0.3mm. Fig. 11 shows the optical image and geometric dimension of #ES2 CFRP specimen. Fig. 12 shows the results of ultrasonic C-scan. It can be seen from Fig. 11 that ultrasonic C-scan can detect all defects of #ES4 specimen, and has good characterization of defects with different depths.

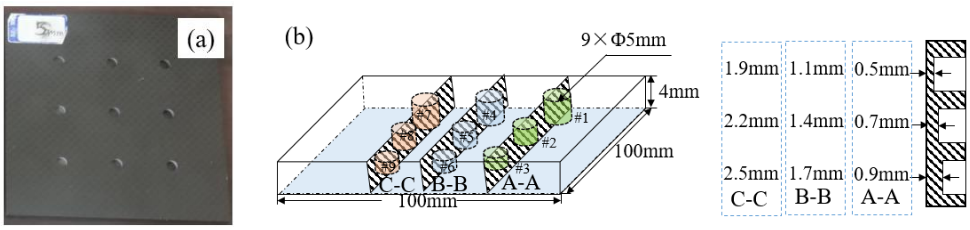


Fig. 11 a)Optical photo of the #ES2 CFRP specimens and b) its geometric dimensions

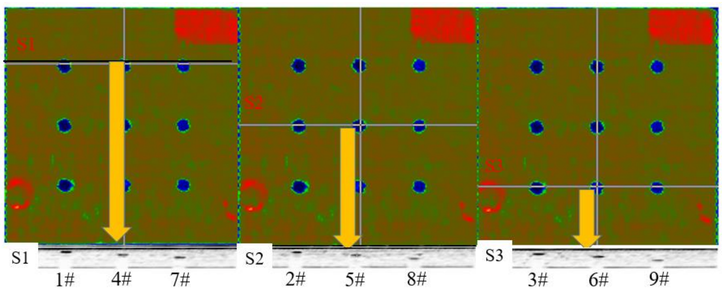


Fig. 12 Ultrasonic C-scan test results

The results show that the modulation parameters are 0.05Hz-0.10Hz-40s-3s, the peak power is 4000W/m^2, the reference signal pulse width is 0.02s, and the initial delay time is 0s ~ 6s. Fig. 13 shows the results of TWRT of #ES4. It can be seen from Fig. 13 that with the increase of initial delay time, defects are gradually detected from shallow to deep. It can be seen from the tomography results that TWRT can realize the detection of surface fiber braiding.

10.21611/qirt.2020.054

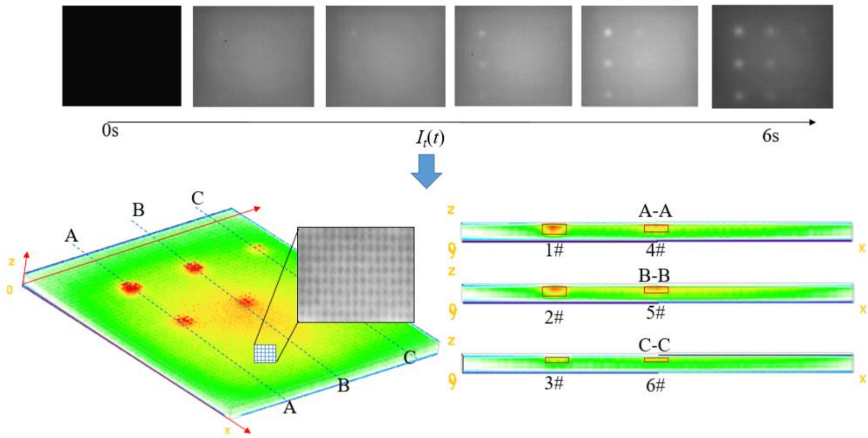


Fig. 13 The detection results of thermal-wave radar tomography

Table 2 shows the detection depth results of each defect obtained by TWRT and ultrasonic C-scan.

Tab. 2 Defects depth of #ES4 detected by chirp-pulsed tomography and ultrasonic C-scan

Number	#1	#2	#3	#4	#5	#6	#7	#8	#9
Actual depth	0.50	0.70	0.90	1.10	1.40	1.70	1.90	2.20	2.50
C-scan depth	0.47	0.60	0.94	1.06	1.28	1.76	1.76	2.12	2.23
C-scan deviation	0.03	0.10	0.04	0.04	0.12	0.06	0.14	0.08	0.27
C-scan error	6%	14.3%	4.44%	3.63%	8.6%	3.53%	7.37%	3.64%	10.8%
$I_t(t)$/s	0.60	1.00	1.36	1.64	2.72	3.40	/	/	/
Tomography depth	0.62	0.80	0.94	1.00	1.30	1.50	/	/	/
Tomography deviation	0.12	0.10	0.04	0.10	0.10	0.20	/	/	/
Tomography error	24%	14.3%	4.44%	9.09%	7.14%	11.8%	/	/	/

It can be seen from Tab. 2 that TWRT can achieve the accuracy of ultrasonic C-scan detection for #2 - #5 defect detection results. Considering that coupling agent is needed in ultrasonic C-scan detection process, non-contact TWRT has more extensive significance in practical application.

5. Conclusion

In this paper, TWRT based on time delay correlation DOD amplitude characteristic sequence reconstruction is proposed to detect delamination defects in CFRP composites. The composite tomography method based on time delay correlation DOD algorithm is determined. Through the finite element simulation, it is confirmed that the initial delay time DOD amplitude characteristics which are reconstructed according to the time sequence can realize the tomography detection of delamination defect. 3D tomographic test was carried out to simulate delamination defects of CFRP composites, which show that under the condition of given CFRP composite parameters, the DOD phase characteristics can accurately detect the defects with diameter less than 12mm and depth less than 2mm, and the deviation rate is low. It is proved that the 3D imaging detection of carbon fiber composite defects using TWRT is feasible. Through the comparative experimental study of ultrasonic pulse reflector C-scan imaging method and TWRT, it is proved that the defect detection results of TWRT can achieve the accuracy of ultrasonic C-scan detection, and the cost is lower than that of ultrasonic C-scan. In conclusion, TWRT can realize the 3D tomography detection of delamination defects in CFRP composites, which provides a new method for effective and reliable detection of delamination defects in CFRP composites.

Acknowledgments

Foundation for Innovative Research Groups of the National Nature Science Foundation of China under Grant No.51521003; the National Natural Science Foundation of China under Contract No.61571153, No.51173034; Self-planned Task of State Key Laboratory of Robotics and System (HIT) and the Programme of Introducing Talents of Discipline of Universities (grant No.B07108).

References

[1] Zhang Ligong, Zhang Zuoguang. Analysis of main defects in advanced composites [J]. FRP / Composites, 2001 (2): 42-45

[2] Luo Zhongbing, Cao Huanqing, Lin Li. Research progress of phased array ultrasonic testing in R-zone of aviation composite components [J]. Aviation Manufacturing Technology, 2019, 62 (14): 67-75.

[3] Wang Han Dong. Eddy current testing of delamination defects in carbon fiber reinforced resin matrix composites [D]. Xiamen: Dissertation of Xiamen University, 2017.

[4] Stamopoulos A G, Tserpes K I, Dentsoras A J. Quality assessment of porous CFRP specimens using X-ray computed tomography data and artificial neural networks[J]. Composite Structures, 2018(192): 327-335.

[5] Zhang Jian, Qi Shuhua. Application status of infrared thermal imaging technology in nondestructive testing of composite materials [J]. Engineering Plastics Application, 2015, 43 (11): 122-126.

[6] Tang Q, Liu J, Wang Y, et al. Experimental study of inspection on SiC coated high-temperature alloy plates with defects using pulsed thermographic technique[J].

Infrared Physics & Technology, 2013(57): 21-27.

[7] Ekanayake S, Baldo C, Fernandes T, et al. CT applied as a reference technique for evaluating active lock-in thermography in characterizing CFRP impact damage test samples[C]. 7th Conference on Industrial Computed Tomograpy, 2017: 1-6.

[8] Peng W, Wang F, Liu J, et al. Pulse phase dynamic thermal tomography investigation on the defects of the solid-propellant missile engine cladding layer[J]. International Journal of Thermophysics, 2018, 39(4): 48.

[9] Ji Jiaqi. Experimental study on dynamic thermal tomography detection of grain coating defects [D]. Harbin: Harbin Institute of Technology Dissertation, 2017: 43-62.

[10] Vavilov V P. Dynamic thermal tomography: perspective field of thermal NDT[C]. Proceedings of SPIE, 1990(1313): 178-182.

[11] Vavilov V P, Maldague X P. Dynamic thermal tomography: new promise in the IR thermography of solids[C]. Proceedings of SPIE, 1992(1682): 194-206.

[12] Swiderski W. The characterization of defects in multi-delamination composite materials by thermal tomography methods[J]. Acta Physica Polonica A, 2009, 115(4): 800-804.

[13] Melnyk S I, Melnyk S S, Tuluzov I G. Method of projection dynamic thermal tomography (PDTT)[C]. 11th International Conference on Quantitative Infrared Thermography, 2012: 1-6.

[14] Vavilov V P. Dynamic thermal tomography: Recent improvements and applications[J]. NDT&E International, 2015(71): 23-32.

[15] Lin Cui, Tian Yupeng. Study on morphological processing method of infrared thermal imaging defect detection [J]. Laser And Infrared, 2009, 39 (7): 784-787.

[16] Lin Cui. Thermal wave imaging detection and tomography reconstruction [D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2010: 39-49.

[17] Liu J Y, Gong J L, Qin L, et al. Study of inspection on metal sheet with subsurface defects using linear frequency modualted ultrasound excitation thermal-wave imaging (LFM-UTWI)[J]. Infrared Physics & Technology, 2014(62): 136-142.

[18] Kaiplavil S, Mandelis A, Wang X D, et al. Photothermal tomography for the functional and structural evaluation, and early mineral loss monitoring in bones[J]. Biomedical Optics Express, 2014, 5(8): 2488-2502.

[19] Wang F, Wang Y, Liu J, et al. The characteristics recognition of CFRP subsurface defects using low energy chirp-pulsed radar thermography[J]. IEEE Transactions on Industrial Informatics, 2019, 16(8): 5160-5168.

[20] Yu Shuang, Jiang Honghui. Design and Simulation of quadrature demodulation for digital radar [J]. Journal of Sichuan Military Engineering, 2010, 31 (8): 88-96.

10.21611/qirt.2020.054

[21] Zhang Min, Cheng Jiaxing, fan Fuhua, et al. Study on extracting instantaneous characteristic parameters of signals by Hilbert transform [J]. Telecommunication Technology, 2003 (4): 44-48.

[22] Siddiqui J, Arora V, Mulaveesala R, et al. Hilbert transform-based pulse compression approach to infrared thermal wave imaging for subsurface defect detection in steel material[J]. Insight, 2014, 56(10): 550-552.

[23] Tavakolian P, Sivagurunathan K, Mandelis A. Enhanced truncated-correlation photothermal coherence tomography with application to deep subsurface defect imaging and 3-dimensional reconstructions[J]. Journal of Applied Physics, 2017(122): 023103.