ISSN 1027-5495. Functional Materials, 26, No.2 (2019), p. 436-440.
doi:https://doi.org/10.15407/fm26.02.436

Comparative study of different infrared thermal wave imaging techniques for defect detection of composite materials

Chunjiang Shuai

School of Physical and Telecommunication Engineering, Shaanxi University of Technology, Hanzhong, Shaanxi 723001, China

Received April 25, 2019

In this paper, the basic principles of pulse infrared thermal wave imaging technology and phase-locked infrared thermal wave imaging technology in the defect detection of composite materials were briefly introduced. Then, the defect detection of Carbon Fiber Reinforced Plastics (CFRP) laminates was carried out by using pulse infrared nondestructive testing system and phase-locked infrared nondestructive testing system. The results showed that both methods could detect the defect inside the laminates, but the phrase image of phase-locked testing technology was clearer and more detailed. Pulse infrared nondestructive testing was more suitable for rapid detection of defects in composite materials with high temperature resistant surface, while phase-locked infrared nondestructive testing technology was more suitable for the composite materials whose surface can not withstand high-power illumination.
Keywords: pulse infrared thermal imaging, phase-locked infrared thermal imaging, composite materials, defect detection.

Представлены основные принципы неразрушающего контроля композитных материалов. Анализируются импульсный метод инфракрасной тепловой визуализации и метод с фазовой синхронизацией инфракрасного теплового излучения. Выполнено обнаружение дефектов в ламинатах из углеродного волокна (CFRP) с использованием метода импульсного инфракрасного неразрушающего контроля и инфракрасной системы неразрушающего контроля с фазовой синхронизацией. Результаты показали, что оба метода позволяют обнаружить дефект внутри ламинатов, но изображение дефектов при тестировании с фазовой синхронизацией было более четким и детальным. Импульсное инфракрасное неразрушающее тестирование является более подходящим для быстрого обнаружения дефектов в композитных материалах с жаростойкой поверхностью, в то время как технология неразрушающего инфракрасного контроля с фазовой синхронизацией больше подходит для композитных материалов, поверхность которых не выдерживает мощного освещения.

Порівняльне дослідження різних методів неруйнівного контролю дефектів композиційних матеріалів. *Chunjiang Shuai*

Представлено основні принципи неруйнівного контролю композитних матеріалів. Аналізуються імпульсний метод інфрачервоної теплової візуалізації і метод з фазової синхронізацією інфрачервоного теплового випромінювання. Виконано виявлення дефектів у ламінатах з вуглецевого волокна (CFRP) з використанням методу імпульсного інфрачервоного неруйнівного контролю та інфрачервоної системи неруйнівного контролю з фазовою синхронізацією. Результати показали, що обидва методи дозволяють виявити дефект всередині ламінатів, але зображення дефектів при тестуванні з фазовою синхронізацією було більш чітким і детальним. Імпульсне інфрачервоне неруйнуюче тестування є більш відповідним для швидкого виявлення дефектів у композитних матеріалах з жаростійкою поверхнею, в той час як технологія неруйнівного інфрачервоного контролю з фазової синхронізацією більше підходить для композитних матеріалів, поверхня яких не витримує потужного освітлення.

1. Introduction

In recent years, the emergence of composite materials has been widely used in aerospace, transportation and civilian applications. Among them, composite materials with sandwich structure are the most widely used [1]. Sandwich composite [2] usually consists of two thin plates and a filling layer. The material of the thin plate can be metal, glass and carbon fiber which is commonly used at present, and the filler can have different materials according to the use of the composite material, usually including metal, foam or fiber, etc. The filling layer is for lifting strength, and is usually made into a honeycomb structure, which has the advantages of low density and high strength ratio. However, in the fabrication process of composite materials, various defects, including bubbles, impurities or cracking of the filler, may occur in the thin plate and the filling layer [3]. The above defects will greatly reduce the structural properties of the composite and even affect the service life of the composite. Therefore, it is necessary to carry out non-destructive testing of composite materials efficiently and accurately in the production process. The emergence of infrared thermal wave imaging technology [4] provides new advanced technology for non-destructive testing defects, and combined with traditional non-destructive testing technology has produced a new joint non-destructive testing technology, such as ultrasonic-infrared thermal wave detection.These infrared thermal wave imaging technologies have greatly assisted in the high quality production of composite materials. Ranjit et al. [5] studied plasma spraying technology of the surface coating in the range of 0.1-0.6 mm, using two thermal imaging techniques pulse thermal imaging and locked thermal imaging, and used infrared camera to capture the surface temperature of a heat wave propagating in the sample. The influence of the applied heat flux density of the two methods was analyzed by Fourier transform. The results showed that both methods could be used to quickly and accurately evaluate the thermal barrier coating thickness. Yang et al [6] introduced the principle of photo-thermal radar lossless imaging based on cross-correlation pulse compression and matched filtering, and applied it to carbon fiber reinforced plastics (CFRP) imaging detection and diagnosis. Shrestha et al. [7] compared the coating thickness detection accuracy of the thermal imaging camera and the locked thermal imaging camera. The results showed that both methods could be effectively used to measure the uneven top layer in the range from 0.1 mm to 0.6 mm. The accuracy of thermal imaging camera was from 0.0003 to 0.0023 mm and the accuracy of the locked camera was from 0.0003 to 0.0067 mm. This study briefly introduced the basic principle of pulsed infrared thermal wave imaging technology and phase-locked infrared thermal wave imaging technology in the detection of internal defects of composite materials. Then, the pulsed infrared non-destructive testing system and phase-locked infrared non-destructive testing system were applied to the defect detection of CFRP composite laminates.

With the development of thermal imaging technology, infrared thermal wave imaging technology has been applied to the detection of internal defects in composite materials. Among them, infrared thermal wave imaging technology is divided into several different types, such as pulsed infrared thermal wave imaging, phase-locked infrared thermal wave imaging, and ultrasonic infrared thermal wave imaging [8,9]. The methods of feature extraction for pulsed infrared images include principal component analysis, pulse phase method and information reconstruction. The information reconstruction method is used to extract the features of infrared images.The information reconstruction method is based on the one-dimensional heat conduction model of the ideal pulse excitation acting on the defect-free conductor.

In addition to pulsed infrared thermal imaging technology, phase-locked infrared thermal imaging technology [10-14] is also a kind of infrared non-destructive testing technology. Compared with pulsed infrared thermal wave imaging technology, phase-locked infrared thermal wave imaging technology uses a phase-locked system to connect a light source, a computer and a thermal imager, where the excitation light source is a periodic heat source controlled by a phase-locked system. When the intensity of the light source is continuously excited by the sinusoidal variation, the surface temperature of the sample also changes in sine rule. When there is a defect inside the sample, the amplitude and phase of the surface change will produce differences which are used to estimate the type of defect.

The imager records the surface temperature change of the sample, and transmits the collected image data to a computer. After processing, the resulting image will be output.

The purpose of this work is to compare these two methods of non-destructive testing of defects in laminates and to determine a more suitable method.

2. Experimental

Pulse infrared non-destructive testing system and its hardware related specifications include 10.4 inch touch screen, lithium battery power; 6000 J flash limit luminous energy, thermal imager with maximum resolution 388x278, collection frame number with maximum 110 Hz, camera acquisition range of 350x250 mm^2. The system software could normally realize the adjustment of the flash excitation energy, the synchronization time, the collection time and the number of collected frames, and could analyze and process the collected infrared images.

Phase-locked infrared non-destructive testing system and its hardware related parameters include periodic heat source as modulated laser with maximum power 350 W, 388 x 278 thermal imager maximum resolution, collected frames with maximum number 110 Hz, camera acquisition range of 350x250 mm2. The system software could normally adjust the modulation laser power, synchronization time, collection time and collection frame number, and analyze and process the collected infrared images.

2.1. Experimental sample

CFRP plate was used as an experimental sample. The size of the CFRP plate was 250x170x30 mm^3, and there were two flat bottom holes on one side. The diameter of the flat bottom holes was 30 mm, and the depths were respectively 3.5 and 4.1 mm. The sample was then skinned with a skin thickness of 0.3 mm and the skin was blackened to enhance the absorption and emission of infrared light, simulating the surface lossless model.

2.2. Experimental methods

Pulsed infrared non-destructive testing was that the experimental sample in the darkroom of the system was placed, the relevant software in the computer was operated, the flash energy was set as 5000 J, the experimental detection duration was 15 s, and the imager collected the image frame frequency of 25 Hz. After clicking the start button, pulse infrared non-destructive testing was used in the sample, and information reconstruction was used when processing images.

Fig. 1 Results of pulse infrared non-destructive testing.

Phase-locked infrared non-destructive testing was that the experimental sample was place in the darkroom of the system, the corresponding software was operated in the computer, the modulation laser frequency was set to 0.2 Hz, the experimental detection duration was 30 s, and the image frame frequency of imager collection was set as 25 Hz. After clicking the start button, pulse infrared non-destructive testing was used in the sample, and 1024-point FFT was used when processing images.

3. Results and discussion

As shown in Fig.1, two bright spots could clearly be seen in the detection image of CFRP laminates with the pulse infrared nondestructive testing system, and the shape of flat bottom holes in CFRP could also be clearly seen in the image. The bright spot was very different from the surrounding color, and its position basically coincided with the position of the flat bottom hole of the template, which indicated that the bright spot was the flat bottom hole of the template tested. After comparison, it was found that

Table. Comparison of two infrared thermal wave imaging techniques

Comparison item	Pulsed infrared heat wave detection	Phase-locked infrared heat wave detection
Time required for detection/s	15	30
Data processing time/s	30	70
Maximum temperature of sample surface/°C	35	27

Fig. 2 Phase-locked infrared detection amplitude diagram

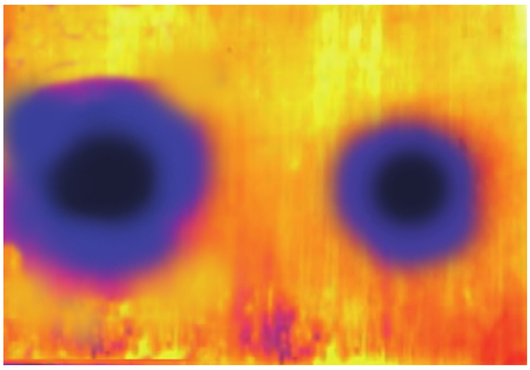

Fig. 3 Phase-locked infrared detection phase diagram

brighter spots corresponded to deeper flat bottom holes. It was concluded that pulse infrared thermal wave imaging could effectively test the invisible damage in the non-destructive sample on the back surface of the skin.

There were two kinds of images collected by the template through the phase-locked infrared detection system, one was the amplitude image, as shown in Fig. 2, the other was the phase image, as shown in Fig. 3. From the phase diagram of the sample, we could see its surface information that the temperature in the middle of the sample was higher than that in the corner. Although some flat bottom holes in the sample could be observed, they were very blurred. Only one defect could be counted and could be found by careful observation. The phase diagram of the sample was clearer than the amplitude diagram and pulse diagram, from which the flat bottom hole of the sample could be clearly seen, and unlike Figs.1 and 2, the defect shown in the phase diagram was no longer a bright spot but a dark spot compared with the color of the whole image, and the shape of the defect was clearer, and the range of the dark spot corresponding to the flat bottom hole with larger depth was larger.

As shown in Table, the time required for phase-locked infrared heat wave detection was 30 s, and the pulsed infrared heat wave detection was 15 s, which was significantly less than the time required for phase-locked infrared detection. The reason was that the thermal excitation of pulsed infrared detection was instantaneous and the actual time required for detection once was less than 1 s. In the experiment, 15 s was set to improve the detection accuracy, and multiple detections were performed. The phase-locked infrared detection was because the thermal excitation of the emission was continuous and periodic and accuracy required enough time to ensure the integrity of the cycle. The data processing time of pulse infrared detection was 30 s, and the data processing time of phase-locked infrared detection was 70 s. The reason was that the data collected by pulse infrared detection was transient, while the phase-locked infrared detection collected continuous data, and the data volume was much larger than that of pulse infrared detection. Also, FFT which consumed both time and computing resources was used in the process and analysis of data, and finally the pulse infrared detection took larger advantage in the time of data processing. The maximum temperature of the surface of the sample during pulse infrared detection was 35 °C. The maximum temperature of the surface of the sample during phase-locked infrared heat wave detection was 27 °C. The reason was that the pulse excitation used in pulse infrared detection had a short power and high energy. The thermal excitation of the phase-locked infrared detection was continuous transmission, and did not require excessive power. It is only necessary to increase the duration of the detection accuracy. Thus, the phase-locked infrared detection was more suitable for the sample specimens whose surface could not withstand high-power illumination.

4. Conclusions

This study briefly introduced the basic principle of pulsed infrared thermal wave imaging technology and phase-locked infrared thermal wave imaging technology in the detection of internal defects of composite materials. Then, the pulsed infrared non-destructive testing system and phase-locked infrared non-destructive testing system were applied on the defect testing of CFRP composite laminates. The results were that both methods could detect the defect of flat-bottom hole inside the sample, but the amplitude map of the phase-locked detection could only detect the surface information, and the detection of the defect was fuzzy. The phase map of the phase-locked detection was clearer than the amplitude diagram and the pulse detection diagram, and the defect details were more clear. Pulse non-destructive detecting took 15 s, data processing took 30 s, and the highest temperature of the sample surface is 35°C during the detection process, 30 s for phase-locked non-destructive testing, 70 s for data processing. 27°C was the maximum surface temperature of the sample during the test, indicating that infrared non-destructive testing was more suitable for quickly testing defects of composite materials with high temperature resistance on the surface, while composite materials whose surface could not withstand high-power illumination were more suitable for testing defects by phase-locked infrared non-destructive testing.

Acknowledgement

This study was supported by the Project of Scientific Research of Ministry of Education (2016) "Biological effects of electromagnetic targeting technology for diseases and insect pests in tea gardens in southern Shaanxi" (16JK1158).

References

1. M. Pawlak, M. Streza, C. Morari et al., *Meas. Sci. Technol.*, **28**, 025008 (2017).
2. H. Cai, X. Dong, M. Zhu, Z. Huang, Int. Conf. Opt. Instrum. Tech.: Optoelectr. Imaging/spectrosc. Signal Proc. Tech. (2018).
3. B. Feng, Z. L. Shi, Z. Chang et al., *Infrared Phys. Techn.*, **85**, S1350449516306533 (2017).
4. V. Arora, R. Mulaveesala, P. Bison, *J. Nondestruct. Eval.*, **35**, 1, (2016).
5. S. Ranjit, W. Kim, *Infrared Phys. Techn.*, **92** (2018).
6. R. Yang, Y. He, A. Mandelis et al., *IEEE T. Ind. Inform.*, 1(2018).
7. R. Shrestha, W. Kim, *Infrared Phys. Techn.*, **83**, 124 (2017).
8. K. Murali, D. V. R. K. Reddy, R. Mulaveesala, *Mater. Today Proc.*, **5**, 544, (2018).
9. R. Mulaveesala, V. Arora, *Quant. Infr. Therm. J.*, **14**, 1 (2016).
10. C. Li, H. Jiang, *Int. Conf. Electr. Packaging Tech.* (2016).
11. V. Arora, R. Mulaveesala, P. Bison, *J. Nondestruct. Eval.*, **35**, 1 (2016).
12. H. N. Zhang, Z. W. Zhang, Y. Lei, et al., Selected Papers of the Photoelectronic Technology Committee Conferences Held November (2016).
13. K. Murali, D. V. R. K. Reddy, R. Mulaveesala, *Mater. Today Proc.*, **5**, 544, (2018).
14. D. Roy, S. Tuli, *IEEE T. Instrum. Meas.*, **26**, 2688 (2017).