A New Method for Detecting Internal Defects in Composite Materials Based on Time of Flight

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Abstract: Carbon-fiber reinforced polymer composites have been widely used to achieve the light-weighted design and high performance due to superior performance. Internal defects in the composite materials are the main factors that determine their performance, which makes reliable and effective detection methods of internal defects essential. Non-destructive testing (NDT) methods are the most widely-used way due to their tremendous advantages. Though the theoretical background is found, experimental results could be quite complicated and confusing, especially for composite materials with complex defects characteristics. In this paper, experimental study on internal defects in composite materials based on the time of flight (ToF) are investigated. The Gaussian echo model and the parameter estimation methods are established to build a theoretical model for measurements. Then, the distance amplitude correction (DAC) method is proposed to effectively improve the signal-to-noise ratio (SNR) and to reduce distortion of the signal during measurements. Finally, the ToF is adopted to determine depth of internal defects. Experiment study is conducted to investigate the porosity defects and the anti-impact performance of composite materials, as well as defects in objects with various thicknesses. Experimental results show that the proposed method is quite helpful for obtaining the intuition and deep understanding of internal defects, thus contributing to the determination of product performance and its improvement.

Key words: ultrasonic non-destructive testing; time of flight; porosity defects; anti-impact performance; distance amplitude correction (DAC) method

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0 Introduction

Composites have been widely used in aircraft to achieve the light-weighted design and high performance[1] due to their superior performance, such as high specific strength, good corrosion resistance and low weight[2]. One of their typical application is in aero engines of aircraft. The carbon-fiber reinforced polymer laminates are adopted in the rotor casing of aero engines to prevent malfunctions caused by the blade rupture, which could seriously threaten aircraft safety[3-5], if the rotor blade fails unexpectedly during operation at a high speed. In this regard, the compressor and turbine casing are usually made of carbon fiber reinforced resin composite materials due to their outstanding anti-impact performance. To achieve satisfactory anti-impact performance, the ply order, the ply angle and hybrid modes in the interwoven laminates need to be optimized[6], which requires the mapping relationship between internal defects and qualified anti-impact performance. Different types of internal defects may occur in composite materials. An important source of error is the forming process in manufacturing. In addition, structural damages will inevitably occur in the process of use due to the influence of environmental factors, stress concentration and fatigue load[7]. These defects in the composites will seriously deteriorate the properties of the composites, resulting in mechani-

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cal failures and even safety problems[8]. Therefore, the establishment of reliable and effective detection methods is critical to the application and development of composite structures[9].

In the testing of composite materials, non-destructive testing (NDT) methods are the most widely used due to their tremendous advantages[10]. The NDT methods involve the identification and characterization of damages on the surface and interior of materials without altering the original attributes or harming the object being tested[11]. Traditional NDT methods include ultrasonic testing, radiographic testing, magnetic particle testing, eddy current testing and penetrant testing[12]. Among them, the ultrasonic testing has the advantage of high sensitivity to defects, like cracks. Ultrasonic penetration is strong, but harmless to materials and human body. Therefore, the ultrasonic method has been widely concerned in the field of NDT.

Great efforts have been made to carry out studies on ultrasonic NDT of composite laminates by using the transmission method and the pulse-echo method[13-14]. The transmission method is based on the energy change after the pulse wave penetrates the specimen[15]. The advantage of this method is that there is no blind spot in the test and it is suitable for detecting materials with a large attenuation coefficient. The disadvantages of this method are low detection sensitivity and poor ability to extract internal defect depth information. The pulse-echo method transmits the pulse into the internal structure of the specimen, and detects the internal defects of the specimen by observing the reflected wave[16]. Representative methods based on this principle include the bottom wave method and the pulse-echo method[17]. The bottom wave method uses the variance of the bottom wave amplitude to estimate the information of internal defects. This method is usually used to detect internal defects with small volume but large density[18]. As quantitative information of internal defects cannot be obtained, it can only be used as an auxiliary means of testing. The defect echo method uses the amplitude of reflected wave to determine the size and location of internal defects, and uses the transmission time of reflected wave to deduce the depth information[19]. The pulse-echo method quantifies internal defects according to the amplitude of reflected wave. But for suspicious waves, valuable information may be missed in the experiment. In order to improve the efficiency and accuracy of the experiment, the distance amplitude correction (DAC) method[20] was introduced to improve the detection performance.

Even though the theoretical background of ultrasonic NDT methods of composite laminates is found, experimental results could be quite complicated and confusing, especially for composite laminates with mixed layout. An advanced method[21] was proposed based on eddy current pulsed thermography (ECPT) to reconstruct the layers' orientation and to estimate the thermal and electrical conductivity of multiple CFRP samples. This is achieved by implementing an iterative inversion procedure that processed experimental measurements together with finite element simulations of the ECPT data. Experimental results show that the time of flight (ToF)[22] of thermal waves can be used to reconstruct the fibre orientations and parameter-based inverse reconstruction demonstrates better accuracy than the feather-based approach in terms of estimation of layer orientation.

Further, there is another reason to study the experimental results in depth. Ultrasonic detection signals are always contaminated by noises, which can be divided into two categories: Gaussian white noises caused by circuits and measurement systems, and structural noises caused by the scattering of sound in the crystal microstructure of the material[23]. Noise is unavoidable and difficult to quantify, which makes in-depth experimental research difficult and essential.

In this paper, the theoretical analysis and experimental study on testing of internal defects of composite materials by using NDT methods are investigated in-depth and in detail. First, the Gaussian echo model is established to represent the ultrasonic signals. Then, the time of flight (ToF) in the Gaussian echo model is estimated accurately by effective methods. Besides, approaches on how to improve signal to noise ratio (SNR) and how to reduce the distortion of the signal in the ToF measurements are investigated. Principles and drawbacks of two typical ultrasonic methods that are the most-often adopted in detecting the internal defects of composite materials are explored. To improve the detecting performance, the distance amplitude correction method is proposed. Finally, experimental study is conducted to investigate the porosity defects, the anti-impact performance of composite materials and objects with various thicknesses by using the proposed methods. Corresponding experimental results are analyzed in detail and valuable conclusions are derived in the end. This study provides useful guidance in the design and optimization of composite materials.

1 Theoretical Background

1.1 Gaussian echo model

An ultrasonic signal is commonly represented by the Gaussian echo model (GEM)[24], which is expressed as

$$G_i\left(\boldsymbol{x}^{(5)}\right)=s_i\left(\boldsymbol{x}^{(5)}\right)+w_i=$$
$$M\mathrm{e}^{-\beta(t_i-T)^2}\cos\left(2\pi f_c(t_i-T)+\varphi\right)+w_i$$
$$i=1,2,\cdots,L$$
$$\boldsymbol{x}^{(5)}=\left\{M\ \beta\ T\ f_c\ \varphi\right\} \tag{1}$$

where G_i denotes the Gaussian echo signal corrupted by noise; s_i the Gaussian echo; $\boldsymbol{x}^{(5)}$ the vector with five element parameters; w_i the white Gaussian noise with a variance of σ_2; L the signal length; T the time of flight; f_c the center frequency; β the bandwidth factor; M the magnitude; and φ the phase.

1.2 Time of flight

Once the material has been subjected to damages[25], the damage can be detected by the reflected ultrasonic wave because the distance decay of reflected wave or its frequency distribution will be changed, which will change the ToF in the GEM to a great extent. The accuracy of defect measurements is determined by the error of ToF estimation. To acquire precise model of the internal defects, accurate estimation of ToF of an ultrasonic signal is essential. In ultrasonic NDT, ToF measurements are becoming increasingly sophisticated and yield better performance. The ToF estimation is conventionally performed by gating and peak detection[26-29]. The gating and peak detection method can estimate ToF effectively when dealing with a clean and undistorted signal. When the signal is noisy or distorted[30] (Noisy means the noise level is close to or higher than the signal amplitude, and distorted means time-overlapping ultrasound signals are often encountered whenever layer thickness is small, or distance between reflectors is short), the gating and peak detection method yields poor ToF estimation results. Other conventional methods such as overlap and phase slope methods suffer from the same problem[31-32]. In this regard, experimental study on how to improve the SNR and reduce the distortion of the signal in the TOF measurements is of great importance.

1.3 Principles of typical ultrasonic methods

Typical ultrasonic NDT methods include the transmission method and the pulse-echo method. In the transmission method, double transducers are placed in both sides of the composite materials, as shown in Fig.1. One transducer is used as the transmitting transducer, and the other is used as the receiving transducer. The transmitted ultrasonic wave propagates to the receiving side via the transmitting side, while the defects are detected and evaluated by the magnitude attenuation of the transmitted ultrasonic wave.

In the pulse-echo method, a transducer is used as both the transmitting and receiving transducers, as shown in Fig.2. The transmitted ultrasonic wave propagates to the bottom of the reflected surface through composite materials, and then reflects back to the incident surface. The defects are detected and evaluated by the amplitude, phase and time transit of the reflected wave.

Although both methods are based on the characteristics of wave energy attenuation to assess the porosity defects, the pulse-echo method has higher sensitivity to porosity defects compared with the transmission method[33].

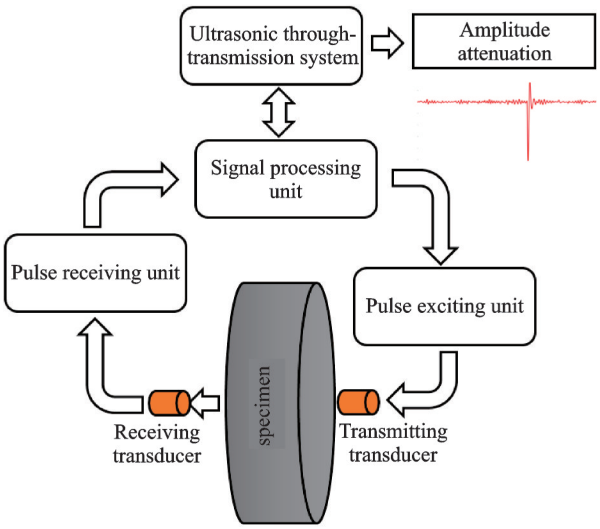


Fig.1 Schematic diagram of the ultrasonic transmission method

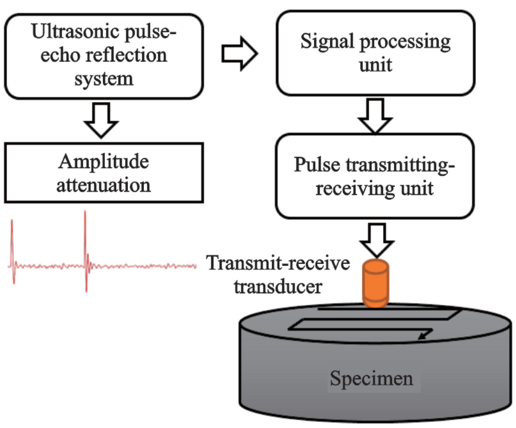


Fig.2 Schematic diagram of the ultrasonic pulse-echo method

1.4 DAC method

Ultrasonic NDT methods quantify the internal defects based on the amplitude of the reflected wave. Thus, valuable information might be missed in experimental study for suspicious waves, and internal defects located in the deeper position are hard to find. To help acquiring the comprehensive information of internal defects, the DAC method is introduced, which aims to improve the SNR in the testing and to reduce the distortion of the signal in the TOF measurements. The DAC method is to compensate for the fact that the pulse-echo response of a reflector will decrease as the distance of the reflector from the ultrasonic transducer increases. The DAC method provides a means of establishing a graphic reference level sensitivity as a function of sweep distance. In this method, the DAC curve is generated by plotting the amplitude of a known calibration reflector at different distances from the transducer, thus ultrasonic signals from the same reflected surface will have different amplitudes at different distances from the transducer. The use of DAC curve allows signals reflected from similar discontinuities to be evaluated where signal attenuation as a function of depth has been correlated.

Typical DAC curve is illustrated in Fig.3. The x-coordinate represents the ultrasonic path, and the y-coordinate represents the amplitude of the echo. The highest points of different amplitudes corresponding to different ultrasonic paths are connected to construct a smooth curve, which is called the bus line of DAC. The DAC curve is used to distinguish the amplitude change of the reflector with the same size but different distances. Normally, after the DAC curve is plotted, the echo peak generated by the reflector of the same size will be on the same curve, regardless of the reflector's position in the material. Similarly, a reflector smaller than the size indicated by the curve will fall under the curve, while a larger one will be located above the curve. Taking the bus line as the reference, dB values of the waste line, the quantitative line and the evaluation line are determined according to the corresponding flaw detection standards. Methods to construct the bus line of DAC are devided into three categories: The linear interpolation, the least square fitting and the Lagrange interpolation. These three methods are shown in Fig.3, in which the linear interpolation is the simplest, but the bus line is not smooth. The least square fitting can yield a smooth bus line but needs to be corrected a priori. The Lagrange interpolation can yield smoother curve with smaller errors, thus it is taken as a priority in constructing the bus line of DAC.

The amplitude of the reflected echo at different depths is compensated by the decline trend of the DAC curve along the depth direction. After depth compensation of echo amplitudes, the echo amplitude of reflector of the same size is independent of its depth in the tested materials, thus guarantee that equivalent defects have the same sensitivity at different ultrasonic path distance. When the gain condition of the detector is unchanged, it is more advantageous to find defects located in the deeper position of the material.

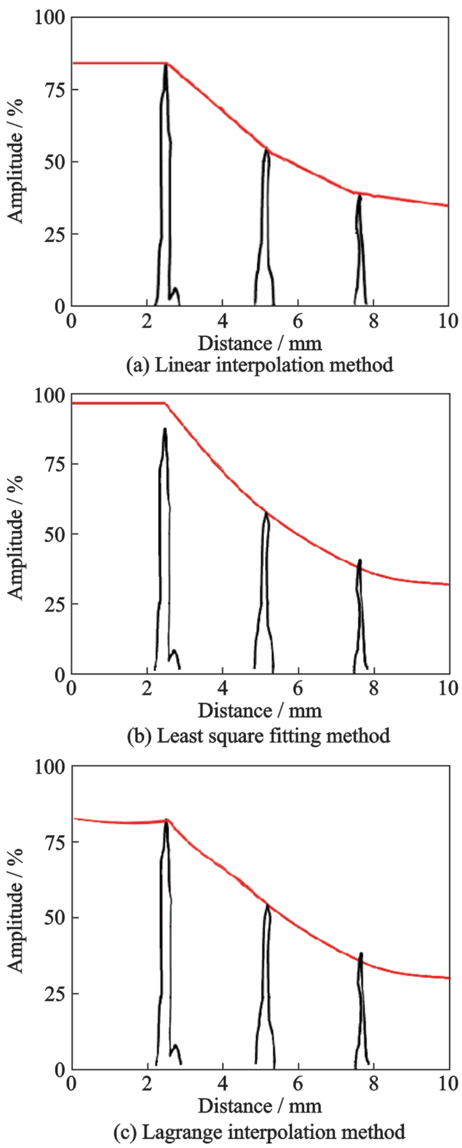


Fig.3 Bus lines of DAC constructed by using three methods

2 Experiment of Porosity Flaws in Composite Laminates

Porosity flaw is the main type of internal defects existing in the composite materials. Compared with the macro flaws such as lamination and inclusion, the porosity flaws have quite different characteristics in both size and dispersion distribution[34-36]. First, the porosity flaws have sizes of 10—100 μm, which are much smaller than the regular macro flaws. Second, the porosity flaws are scattered inside the composite materials. From these two aspects, detection methods of porosity flaws should differ from detection methods of macro defects and should be paid much more attention to.

2.1 Experiment setup

In this paper, the ring with flange composed of laminates that are made by woven fabric is studied as an example. The flange plays a critical role in the mechanism, any internal defect can cause the invalidity of the mechanism, even safety problems. From this respect, comprehensive information of the internal defects should be derived. As presented in Fig.4, the inner diameter of the flange is 1 110 mm, the outer diameter of the flange is 1 200 mm, the thickness of the flange is 10 mm and the height of the ring is 300 mm.

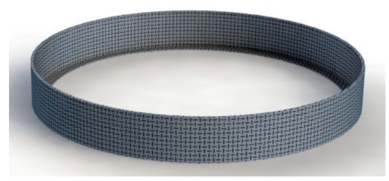


Fig.4 Sketch of the ring with flange

2.2 Detection of internal defects

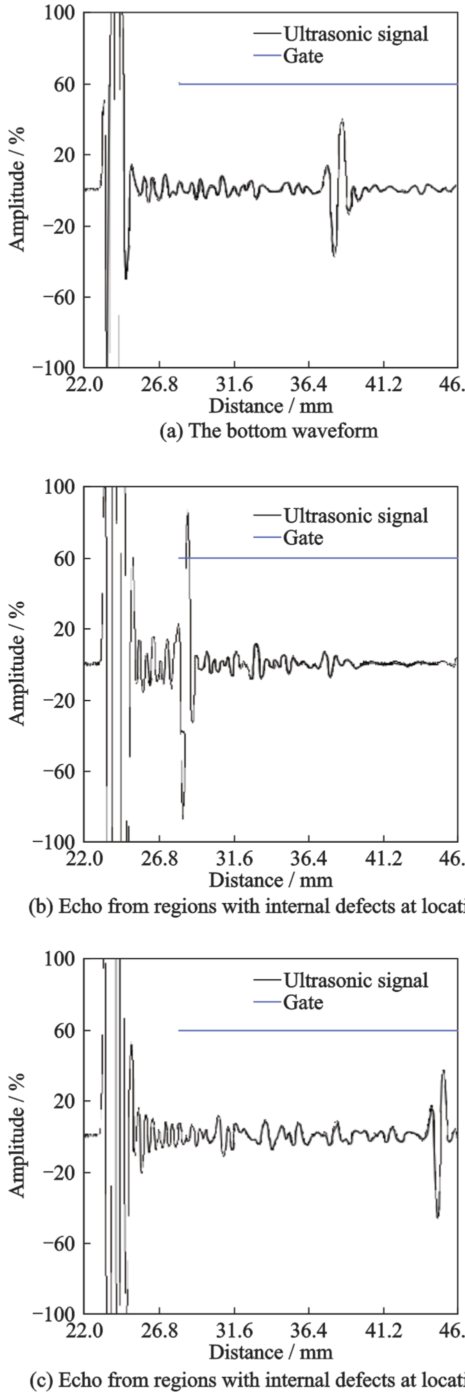
To detect the flaw existed in the flange, the transmission method is adopted due to its high efficiency. Two transducers are used in this experiment. One transducer is placed on one side of the flange to transmit the ultrasonic wave, while the other transducer is placed on the other side of the flange to receive the ultrasonic wave that penetrates the flange, as illustrated in Fig. 1. The internal defects are studied by analyzing the energy change between the transmitted ultrasonic wave and the penetrated ultrasonic wave. The experimental results which adopt amplitudes to determine in-plane locations of internal defects are displayed in Fig.5. Dark-colored areas represent internal defects where pene-

Fig.5 Testing result in the experiment using the transmission method

trating signals have low energy and light-colored areas represent intact regions where penetrating signals have high energy.

Type A pulse testing is conducted to explore the characteristics of internal defects. The results are given in Fig.6. It can be inferred through experiences that the internal defects are disperse porosity.

Therefore, the ToF of the flaw echo is measured by using the pulse-echo method and the results are shown in Fig.7. Dark-colored areas represent internal defects with short transmission time of the flaw echo, which means the internal defects are close to the detection surface. And light-colored areas represent internal defects with long transmission time of the flaw echo, which means the internal defects are far from the detection surface. The blank indicates no internal defects. The three-dimensional model of internal defects are constructed and shown in Fig.8.



(a) The bottom waveform

(b) Echo from regions with internal defects at location A

(c) Echo from regions with internal defects at location B

Fig.6 Experimental results of Type A pulse reflection ultrasonic testing

Fig.7 ToF of the flaw echo in the sample of the flange

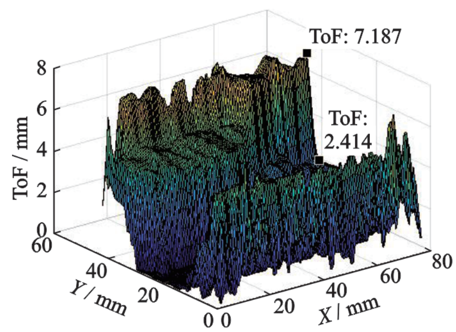


Fig.8 Three-dimensional model of internal defects

2. 3 Analysis and discussion

To verify the three-dimensional model of internal defects, the flange is dissected to find out its metallographic phase, and the result is given in Fig.9. As can be seen, the section has two porosity defects, and the distance from the bottom is 2.4 mm and 7.4 mm, respectively, which match the detection result in Fig.8 to a good extent.

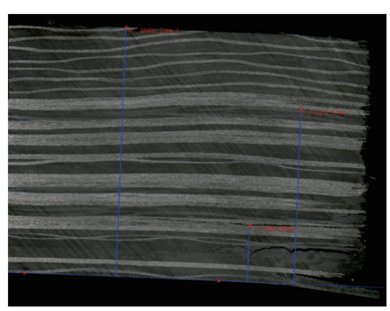


Fig.9 Metallographic phase of the flange after dissection

3 Experiment on Anti-impact Performance of Composite Materials

The compressor and turbine casing are usually made of carbon fiber reinforced resin composite materials for their advantages in anti-impact performance[37-39]. GEnx engine first adopted two-dimensional three-axis braided carbon fiber reinforced resin matrix composite fan casing[40], as shown in Fig.10 (a). Then, this technology was applied to LEAP engine and improved into three-dimensional weaving process[41], as shown in Fig.10(b). Due to the existence of fiber reinforcement in the direction of thickness, 3D braided/woven structure composite materials can effectively resist impact layering and can directly shape parts with complex structure, which is an important application direction of the new generation of aero engines. From this respect, it is of significance to study the anti-impact performance of composite materials.

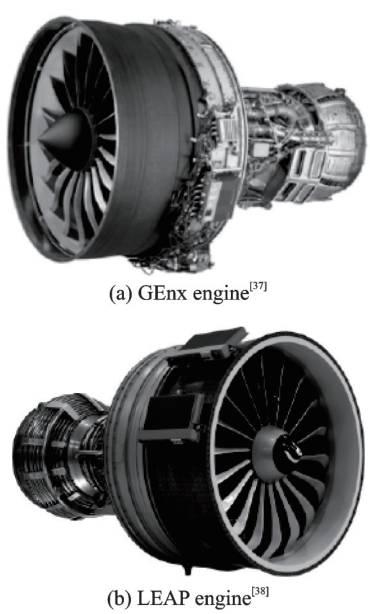


Fig.10 Aero engines adopting carbon fiber reinforced resin composite materials

3.1 Experiment setup

Ultrasonic NDT method is utilized to analyze the anti-impact performance of the rotor casing of aero engines. Typical layout of composite materials used in the casing is given in Fig.11. For fully comparison and in detail data analysis, 12 types of resin-based composite laminates are treated as specimens, which has different anti-impact performance due to their different ways of ply angles and ply orders. The experimental scheme is illustrated in Fig.12. The adopted specimen is of 250 mm×250 mm×8 mm, and hit by blocks made of Titanium alloy. The clamping width of each specimen is 25 mm, and the preload of bolts during each experiment is guaranteed to be uniform by the torque spanner.

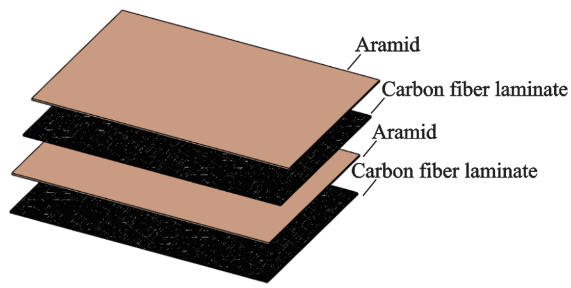


Fig.11 Typical layout of the rotor casing of aero engines

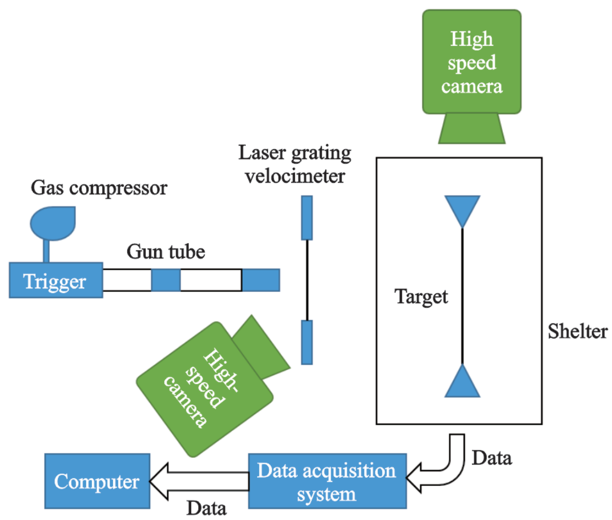


Fig.12 Schematic diagram of experiment setup

3.2 Detection of internal defects

The transmission method is firstly adopted due to its high efficiency. The results of batch #4 are given as an example in Fig.13. It can be seen that internal defects exhibit all dark colors. It is hard to distinguish the dissipation of these internal defects.

To derive the comprehensive information of this problem, the ToF of the flaw echo is measured by using the pulse-echo method. Since there are multiple layers of composite laminates in the specimen, echoes are generated between two layers. Due

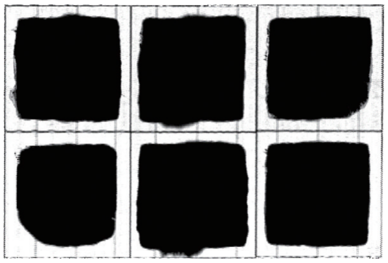


Fig.13 Results detected by the transmission method

to the expansion of the ultrasonic beam and the attenuation of materials, equivalent defects at different ultrasonic path distance may cause echo with different magnitudes; and echos from interfaces between layers may have overwhelming magnitudes than echos from internal defects, which greatly reduces the SNR in detecting, as shown in Fig.14.

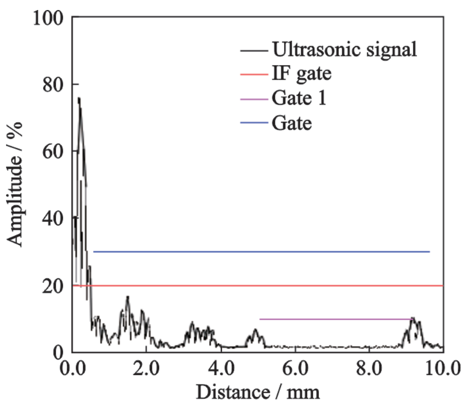


Fig.14 Comparison of echos between layers from interfaces and from internal defects

To solve this problem, the DAC curve is introduced to calibrate each batch so that echos from internal defects at different depths have the same magnitudes. In this paper, the amplitude of the flaw echo is set to be 80%, as shown in Fig.15. It can be seen that flaw echoes have much higher magnitudes even when they are located at long distances, which greatly improve the SNR and make the detection more precise. DAC curves of all batches are shown in Fig.16.

After calibration, it can be seen that echos from internal defects have overwhelming magnitudes than echos from interfaces between layers, as illustrated in Fig.17.

The impact tests are conducted at different batches, and different batches exhibit different anti-

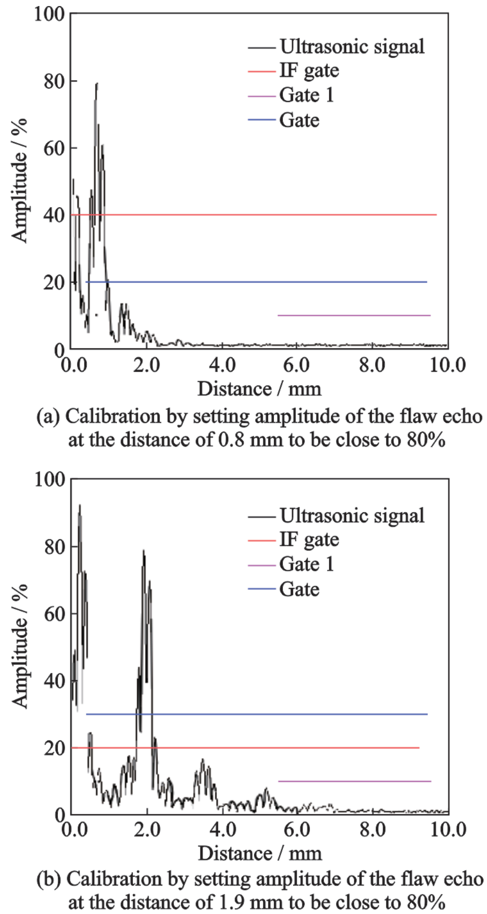


Fig.15 Calibration by setting amplitude of the flaw echo at different distances to be close to 80%

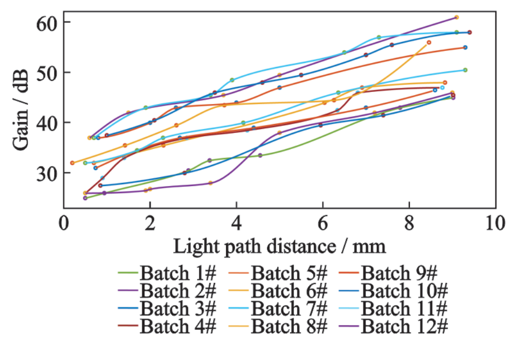


Fig.16 DAC curves of all batches

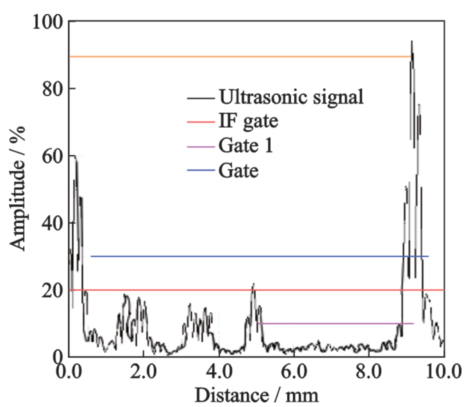


Fig.17 Comparison of echos between layers from internal defects and from interfaces

impact performance. This can be attributed to the difference in ply orders and ply angles of each batch.

3.3 Analysis and discussion

After the impact, type C testing is used to obtain a more intuitive display of the internal defects distribution. ToF in all specimens are derived. From the results, it can be found that different batches exhibit different anti-impact performances due to their different ply orders and ply angles. The ToF in different specimens in #4 batch is demonstrated in Fig.18 as an example. It shows that even within one batch, different specimens exhibit different anti-impact performances under different impact speeds, which proves the complexity of the anti-impact mechanism and the necessity for in detail experiments studies.

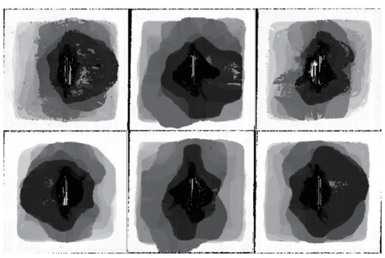


Fig.18 ToF of the six specimens under different impact speeds in batch #4

4 Experiment on Internal Defects in Composite Laminates with Various Thicknesses

When detecting the internal defects in composite laminates, it is quite common to deal with composite laminates with various thicknesses. An example is an object with three different thicknesses. Since the thickness varies along the direction of ultrasonic waves, different detection sensitivities are necessary in detecting the object with such characteristics, which brings great difficulties and time cost into test. An alternative way is to use constant sensitivity during the test, while post-process the measured data to adapt to different thicknesses, which is also inconvenient and error prone.

In this paper, the proposed testing method is also adopted to deal with this problem, which eliminates difficulties caused by different sensitivities or post-processing. The results are demonstrated in Fig.19. The darker color than the surrounding area indicates internal defects that has been detected and has been illustrated by red and yellow circles for clear demonstration.

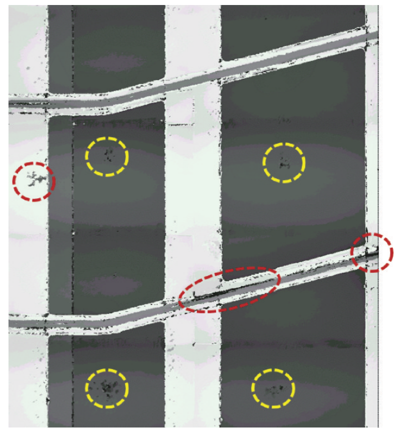


Fig.19 Results of object with three different thicknesses by using the proposed method

5 Conclusions

Theoretical analysis on basis of Gaussian echo model and the parameter estimation methods is firstly proposed to explore the information of internal defects in composite materials. To improve the detection precision and efficiency, the DAC method in combination with the ToF measuring method are introduced to derive a comprehensive and deep insight of the internal defects in composite materials. Considering the difference between theoretical analysis and practical detection, in-detail experimental studies based on the proposed method are carried out to detect the common porosity defects in composite materials and to measure the anti-impact performance of the layered composite materials. Meanwhile, the proposed method is used to detect objects with various thicknesses along the direction of the ultrasonic waves. Experimental results show that the proposed method is quite helpful to obtain the intuition and deep understanding of internal defects, thus contributing to the determination of product performance and its improvement. Future research will focus on improving the detection precision and efficiency while retaining its feasibility and value in practice, and further quantitative analysis and comparison will be provided in the future study.

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基于飞行时间的复合材料内部缺陷检测新方法

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摘要: 碳纤维增强聚合物复合材料因其优越的性能而被广泛应用于轻量化和高性能设计。复合材料的内部缺陷是决定其性能的主要因素,可靠有效的内部缺陷检测方法对复合材料的应用至关重要。无损检测(Non-destructive testing, NDT)方法由于其巨大的优点而得到了广泛的应用。虽然理论方法较为成熟,但针对具有复杂缺陷特征的复合材料而言,详尽和深入的试验研究尚为数不多。本文基于飞行时间(Time of flight, ToF)对复合材料内部缺陷的进行了试验研究。首先建立了高斯回波模型和参数估计方法,基于此建立了测量的理论模型。然后,引入距离幅度校正(Distance amplitude correction, DAC)方法,有效地提高了信噪比(Signal-to-noise ratio, SNR),降低了测量过程中的信号失真。再次,采用ToF有效确定内部缺陷的深度。最后,将所提方法应用于复合材料的气孔缺陷和抗冲击性能的试验研究,以及不同厚度物体的气孔缺陷检测。相应的实验结果证明了所提方法的有效性。

关键词: 超声无损检测;飞行时间;气孔缺陷;抗冲击性能;距离幅度校正方法