Hindawi
Journal of Sensors
Volume 2022, Article ID 5462237, 20 pages
https://doi.org/10.1155/2022/5462237

Review Article

Ultrasonic Testing of Carbon Fiber-Reinforced Polymer Composites

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Received 18 March 2022; Revised 23 May 2022; Accepted 25 May 2022; Published 27 June 2022

Academic Editor: Carlos Marques

Composite materials have been extensively used in different fields due to their excellent properties, among which carbon fiber-reinforced polymer (CFRP) is the representative. Especially in high-precision fields, such as aerospace, CFRP has become the main structural material for some core components instead of metal. The particularity of such materials and their components in terms of structure, material properties, and required detection conditions puts forward more stringent and targeted detection requirements for detection technology. Ultrasonic testing technology as one of the important means of composite defect detection, which is derived from advanced nondestructive testing (NDT), has also been a rapid development. The propagation behavior and variation of ultrasonic waves in CFRP composites can reveal defects and damages in CFRP composites. Moreover, by constructing reasonable defect identification technology and detection technology, not only the qualitative and quantitative positioning analysis of defects and damages in CFRP composites can be realized but also the automatic, visual and intelligent NDT, and evaluation of CFRP composites can be realized. This paper mainly reviews the innovative nondestructive ultrasonic testing technology for CFRP composites and briefly introduces the research progress and application of this technology in CFRP defect detection. Finally, advanced nondestructive ultrasonic testing technology is summarized, and the problems and development direction of this kind of testing technology are put forward.

1. Introduction

With the increasing development of science and technology, more and more composite materials have been widely used due to their excellent performance [1–3]. Among them, CFRP made of carbon fiber as reinforcement and resin as matrix are shown. As high-performance structural materials, CFRP not only has the characteristics of typical carbon materials, such as high-temperature resistance, friction resistance, and corrosion resistance, but also has the characteristics of high specific strength, high specific modulus, and high fatigue resistance. Therefore, it has been well applied in different fields such as aerospace [4–6], military industry [7], automobile and sports [8, 9], and medical treatment [10].

Due to the influence of the manufacturing process, environmental factors, and some random conditions (such as impact, fatigue, and other human factors), defects and damages are inevitable in the production that is made of CFRP materials. In many cases, these defects and damages are difficult to be detected by human eyes, causing great hidden danger for subsequent use. Therefore, with the extensive application of carbon fiber composite materials in various fields, the requirements for its reliability and safety are becoming higher and higher [11]. Defects and damage have a serious impact on the quality and performance of materials and components and also greatly reduce the service life [12]. To ensure the high quality and reliability of CFRP components, defect detection and quality monitoring is necessary and important in the process of manufacturing and service via NDT technology, to find out the hidden trouble in time.

The complexity of the internal structure is therefore difficult to detect CFRP and its components. Defect signals of CFRP components with different production and processing techniques and structures have different forms of expression, and it is difficult to distinguish the coupling between characteristic signals generated by different types of defects [13]. To avoid the hidden danger caused by the defects of carbon fiber composite materials, researchers present a lot of detection technologies to detect these defects and damage. Common detection methods include X-ray detection, eddy current detection, penetration detection, ultrasonic detection, and infrared thermal wave detection. Sensors based on optical technology have also become the direction of continuous development in the detection field [14–16], such as polymer optical fiber as a sensor is used for detection [17, 18].

Currently, the commonly used detection methods of CFRP sheet defects mainly include X-ray detection method, eddy current detection method, ultrasonic detection method, and infrared thermal wave detection method, among which ultrasonic detection method is the most commonly used in the world. Ultrasonic detection technology plays an indispensable role in CFRP defect detection and has become the hot spot and focus direction of composite material detection. The detection method based on ultrasonic technology has also become one of the important research directions in NDT field.

This paper presents the research progress of ultrasonic testing technology in the field of defect detection of composite materials (especially CFRP) and summarizes the existing advanced ultrasonic NDT technology, especially in the field of defect detection of CFRP materials. It is desirable for this review can make more relevant researchers understand and invest in the research field of ultrasonic-based technologies. So that the technology can better serve the engineering application and promote the rapid development of the whole industry.

2. Basic Concepts of CFRP and Ultrasonic Technology

2.1. The Structure of the CFRP. CFRP is composed of carbon fiber and polymer resin, in which carbon fiber acts as reinforcement material to provide strength and polymer resin acts as a matrix to fix the fiber [19, 20]. The structure and performance of CFRP depend on different orientations of carbon fiber (see Figure 1(a)) [21]. The most typical CFRP structure is unidirectional laying (see Figure 1(b)), that is, all carbon fibers are laid in parallel along the same direction in the matrix. There is also the preparation of CFRP, carbon fiber mutual preparation, such a structure will increase the damage tolerance of CFRP (see Figure 1(c)).

The combination of carbon fiber and polymer resin provides the structure with many excellent properties such as lightweight, high strength, and corrosion resistance, which makes the components suitable for a variety of applications (see Figure 2).

In addition to conventional engineering fields, CFRP is also widely used in transportation, military industry, energy, and other industries. However, in the process of production, processing, and application of CFRP, it is inevitable to encounter defects and damage problems, resulting in huge hidden danger. Therefore, defect detection of CFRP is an important part that cannot be ignored.

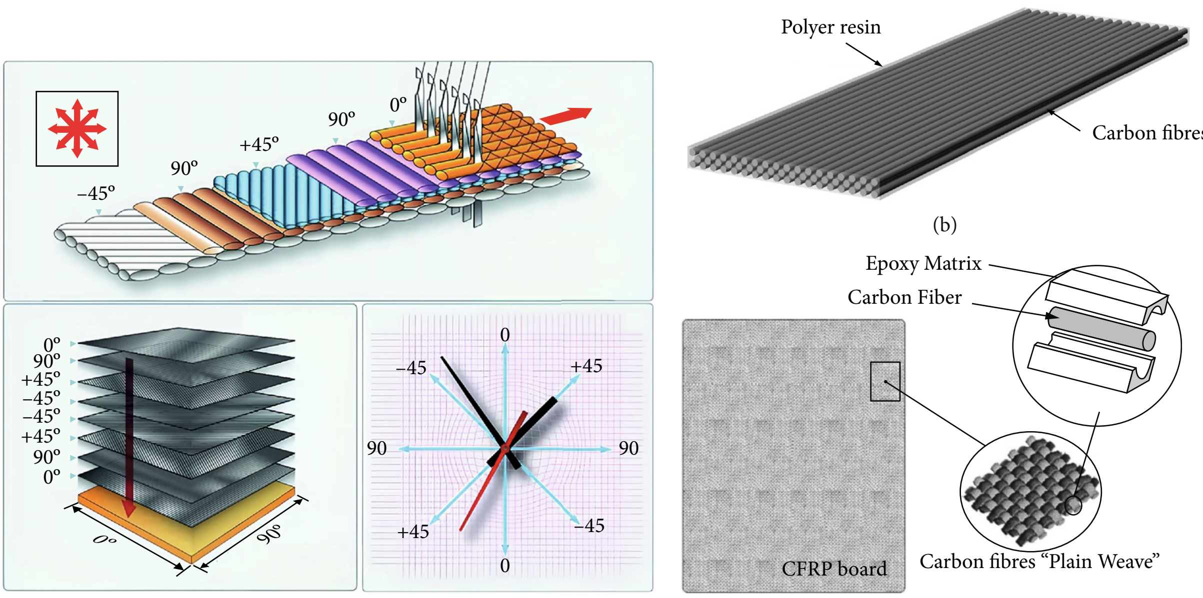
2.2. Typical Defects of CFRP. Defect damage is the main reason why the failure of CFRP. Under the influence of the manufacturing process, environmental factors, and some random conditions, defects and damage of CFRP are inevitable, and their manifestations are the same as those of other fiber composites, mainly including matrix cracking [29], fiber-matrix interface debonding [30, 31], fiber fracture [32, 33], delamination [34, 35], and pore[36, 37].

Matrix cracking is the most serious damage type in composites. Composite materials begin to fail at the onset of static live fatigue loading due to the formation of microcracks, which then rapidly spread to cause collective cracking [29] (see Figure 3(a)). Since the initial crack growth parallel to fiber direction is controlled by the toughness of the matrix, the use of tougher resins would be expected to lead improvements in the matrix-dominated properties controlled by the failure mode [38].

Fiber debonding is mainly due to friction for sliding between fiber and matrix interface. Friction between the fiber and the matrix and fiber deformation will affect the strength of the composite [39], resulting in fiber debonding. Fard et al. [31] studied the correlation between nanoscale interfacial debonding and multimode fracture in carbon fiber composites (see Figure 3(b)).

Delamination defects are very common in composite materials [40] (see Figure 3(c)). Composite laminates are degummed between layers, causing cracks and forming thin large gaps. The main reason for delamination is the mismatch of thermal expansion coefficient between the matrix and fiber or too long storage time, reinforced materials without surface treatment, external shock, etc. [41]. In addition, delamination may occur when drilling composites [42]. The delamination between carbon fiber layers is the most serious defect type in carbon fiber resin matrix composite products, which reduces the compressive strength and stiffness of the material and affects the structural integrity. Under the condition of mechanical or thermal load, the delamination in the structure will continue to increase, which may lead to material fracture when the situation is serious.

Pore refers to the formation of voids in carbon fiber products during the molding process, which is one of the principal defects of CFRP [43, 44] (see Figure 3(d)). It should be divided into fibrous pores (including pores in fiber bundles) and lamellar pores. When the porosity is less than 1.5%, the pores are spherical. When the porosity is greater than 1.5%, the pores are cylindrical parallel to the fiber axis. Pores in carbon fiber composites mainly affect the interlaminar shear strength, longitudinal and transverse bending strength and modulus, longitudinal and transverse tensile strength and modulus, and compressive strength and modulus.



(a)

(b)

(c)

Figure 1: Typical CFRP structure. (a) Format description of carbon fiber orientation angle in CFRP material [21]. (b) Typical structure of CFRP [22]. (c) A CFRP board with "plain weave" structure [23].

In order to avoid the defects of CFRP, on the one hand, it is necessary to strictly control every process from material selection to production and then to final production. From the selection of high quality raw materials for manufacturing CFRP, the supervision in the production process and the improvement of the standardization and efficiency of the whole production process, and then to the final transportation process to strictly control, all kinds of defects in CFRP can be reduced. On the other hand, the damage detection and real-time monitoring of CFRP are particularly important. In order to ensure the safe application of composite materials, detection and research of composite materials have attracted extensive attention.

3. Advanced Ultrasonic Testing Technology

Defect damage of carbon fiber composites can be identified by destructive methods and NDT methods. The destructive method mainly refers to the traditional metallographic method, which is to observe a certain section of the material through a metallographic microscope, and can intuitively find the internal structural characteristics of the material. Defects inside CFRP can not only be determined by metallographic methods but also can realize the understanding of the shape, size, and location distribution of defects. However, the metallographic method requires grinding and polishing of carbon fiber composite materials before metallographic observation, which is inefficient and leads to unexpected damages to the materials. In practical engineering applications, especially for the inspection of large quantity of workpieces, a metallographic method is unrealistic.

As an emerging detection method, NDT can complete the detection without destroying the performance and internal structure of the detected object. In NDT, ultrasonic testing technology has been one of the most widely used testing technologies due to its characteristics of harmlessness, high sensitivity and accuracy, easy implementation, and wide application.

The basic principle of ultrasonic defect detection is that the directionally emitted ultrasonic beam encounters a defect when it propagates in the workpiece to be tested, that is, the reflection and attenuation of the wave are generated, and the defect signal is obtained after signal processing. There are three basic defect display methods: A-scan showing defect depth and defect reflected signal amplitude, B-scan showing defect depth and its distribution in longitudinal section, and C-scan showing distribution in plane view.

Using the propagation behavior of the ultrasonic longitudinal wave in the composite, the time-domain characteristics of the acoustic wave echo signal are recorded, including the propagation time, signal amplitude, and phase information in the detected composite material, and are displayed by ultrasound A-scan. Based on the A-scan detection technique of ultrasonic echo signal technology, the accurate quantitative assessment of the thickness and defect depth of the composite parts is detected, and the qualitative-evaluation of defects can be obtained.

3.1. Ultrasonic-Based Detection Methods

3.1.1. Ultrasonic C-Scan Testing Technology. As one of the earliest methods for NDT of composite materials, ultrasonic testing technology can not only realize the qualitative and quantitative characterization and evaluation of composite material defects and damage and is easy to implement engineering testing applications; it can also be used for the internal microstructure and composition of composite materials,

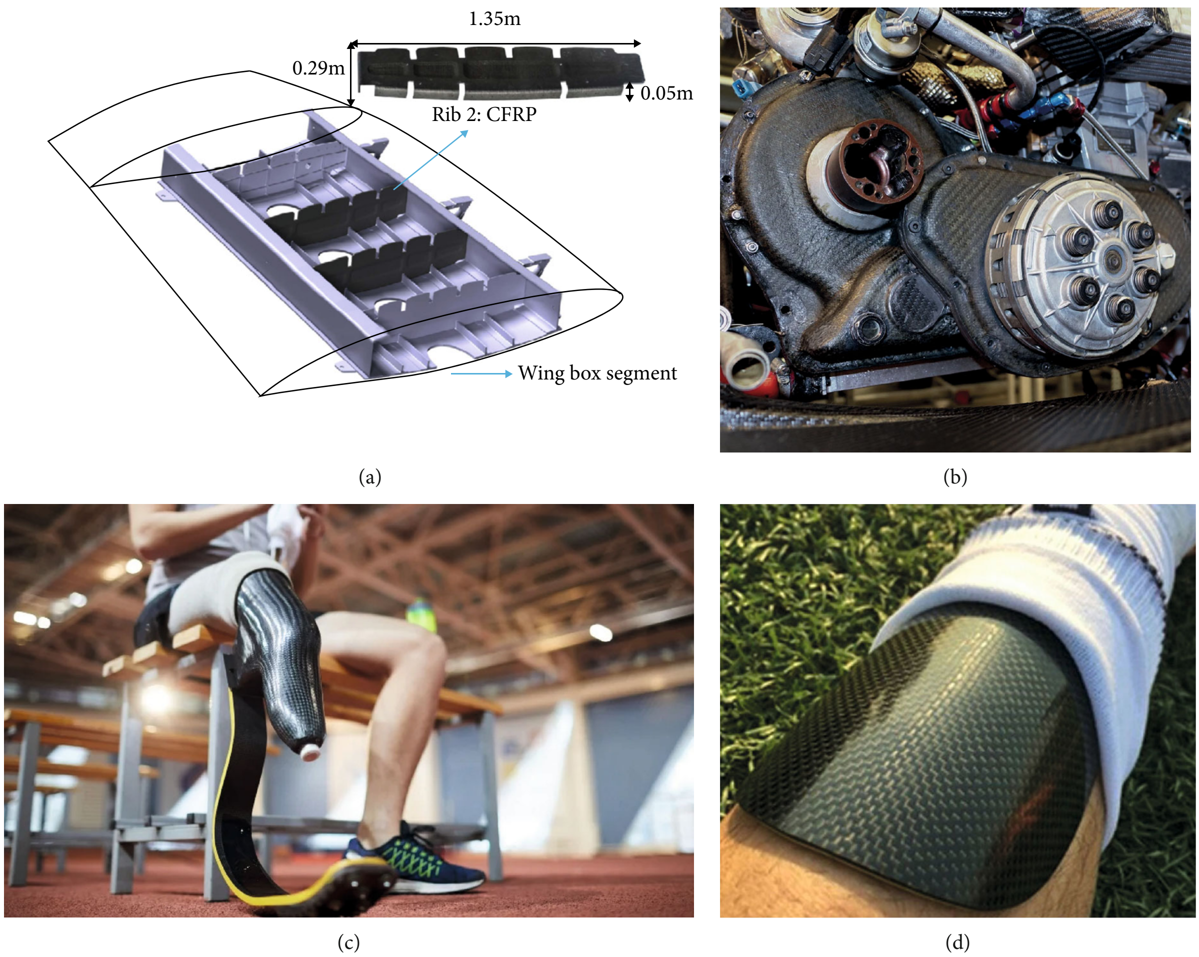
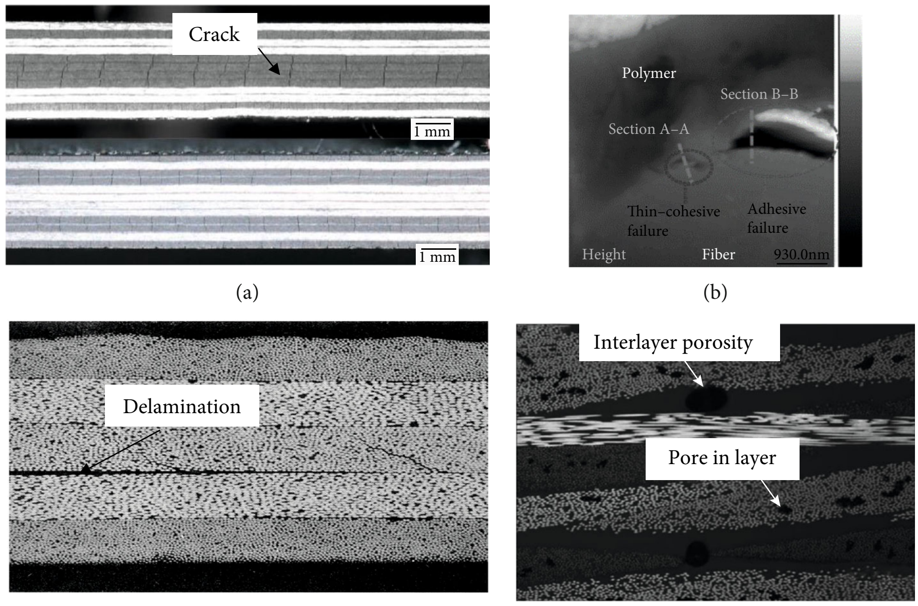


Figure 2: Application of CFRP in various fields. (a) The Airbus A350 XWB is made of 52% CFRP, including the wing SPAR and fuselage parts [24]. The rear wing SPAR of the Airbus A350 XWB demonstrator wing is covered by CFRP [25]. (b) CFRP is also widely used in high-end racing cars. It is now can be used in the engine part [26]. (c) CFRP is used in the medical field (a prosthesis made of CFRP with better strength performance [27]). (d) CFRP is used in the sports field (carbon plate running shoes and sports protectors [28]).

such as fiber content distribution, elastic properties, and other characterization.

Ultrasonic C-scan detection technology is a very extensive and important method for NDT and evaluation of composite materials. Founded on the principles of ultrasonic C-scan and B-scan imaging, it can realize ultrasonic visual NDT of composite structures. In general, the ultrasonic C-scan imaging inspection technology based on a single sound source is the most commonly used composite material inspection technology so far. Compared with the destructive method, it will not damage the measured object and achieve better detection results. Water immersion ultrasonic C-scan detection is commonly used. Water is used as the coupling agent, and ultrasonic waves enter the specimen through water for detection. However, this method may affect the specimen with the water coupling agent.

Songping et al. [45] introduced a depth-direction ultrasonic C-scan detection technology. Based on the characteristics of ultrasonic propagation in the time domain, several scanned images of the interior of carbon fiber composites can be realized, which can be used only for defect detection. Wu et al. [46] proposed a multisensor information fusion technology for defect detection of composite ultrasonic C-scan. Hasiotis et al. [47] used ultrasonic C-scanning technology to detect artificial defects added to CFRP composites, realized the determination and characterization of defects, and accurately measured the thickness of the specimen. Shiino et al. [48] used ultrasonic C-scanning to detect the damage to carbon fiber laminates caused by thermal stress caused by temperature changes. It is verified that temperature changes can cause cracks in the low porosity of the composites. Gao [49] discussed the influence of different placement methods of carbon fiber laminates on the results of water jet ultrasonic C-scan defect detection and obtained that the upper part of the part occlusion has the greatest influence on the water jet, the lower part occlusion is the second, and the left and right effects are the least. Ultrasonic C-scan has a high frequency and good penetrability. Therefore, rapid and accurate detection of delamination and debonding defects has become the primary choice for the detection of large composite components such as aircraft parts [50]. Patronen et al. [51] detected the possible debonding defects of the multilayer stepped lap structure between the carbon fiber composite wing plate and the titanium attachment in the fighter and analyzed



(a) (b) (c) (d)

Figure 3: Common defects of CFRP. (a) Matrix cracks of carbon fiber composite materials [29]. (b) The interface part of the sample is debonding [31]. (c) Section of delamination defect [40]. (d) Pore defects of fabric CFRP [43].

Table 1: Ultrasonic phased array detection of different defects.

Defect type	Applications
Delamination defect	Nageswaran et al. [58] accurately identified defect shape for CFRP artificial delamination defects (2006) Xu et al. [59] used linear phased array transducers to accurately detect the layer defects and depth of the R zone of L-shaped components (2013) Guang and Na [60] quantitatively measured the sample thickness and defect depth through experiments on linear array and arc array phased array probes (2013) Meola et al. [61] used ultrasonic phased array technology to measure the shape, size, and depth of a 20 mm diameter circular delamination defect embedded in CFRP (2015) Kappatos et al. [62] used modeling laminated CFRP composites with various artificial delamination defect modes and simulated detection with phased array delay timing and sampling array techniques (2017) Zhang et al. [63] focused on the feature extraction and imaging methods to characterize the size and position information of delamination defects through the ultrasonic phased array detection method (2018) Caminero et al. [64] prepared samples with preembedded layered defects of different materials, shapes, sizes, and buried depths and studied the influence of the layering method and thickness on the test results (2019) Zhang and Du [65] adopted PAU testing technology and obtained the ideal detection parameters for delamination defects of carbon fiber laminate structures through modeling of sound field and delamination defects, CIVA simulation, and detection tests (2020) Cao et al. [66] used ultrasonic phased array technology to conduct NDT and quantitative evaluation of embedded delamination defects in carbon fiber composites and analyzed the measurement error (2021)
Debonding defect	Li et al. [67] used the ultrasonic phased array system to detect three common defects in CFRP delamination, inclusion, and debonding established and trained a BP neural network to identify the three defects, and the recognition rate reached 95.7% (2015) Lamarre [68] realized the detection of small defects of 1.5 mm in carbon fiber composite materials for wind turbine blades, which can detect defects such as debonding, delamination, and wrinkles (2017) Grondin [69] proposed an array of ultrasonic inspection technology based on adaptive focusing and applied it to the accurate detection of defects in complex composite materials in aviation (2018) Grondin and Li et al. [69, 70] used all-focus 3D PAU testing to detect debonding defects of carbon fiber composite materials used in bogies (2021)
Pore defect	Zhang et al. [71] used a line array transducer to configure an angled delay block for sector scanning to detect defects such as pores and delaminations in the R zone (2013) Li et al. [72] established a CFRP microcutting simulation model with pore defects and studied the microcutting behavior of CFRP with different fiber arrangement directions under different porosity conditions (2022)

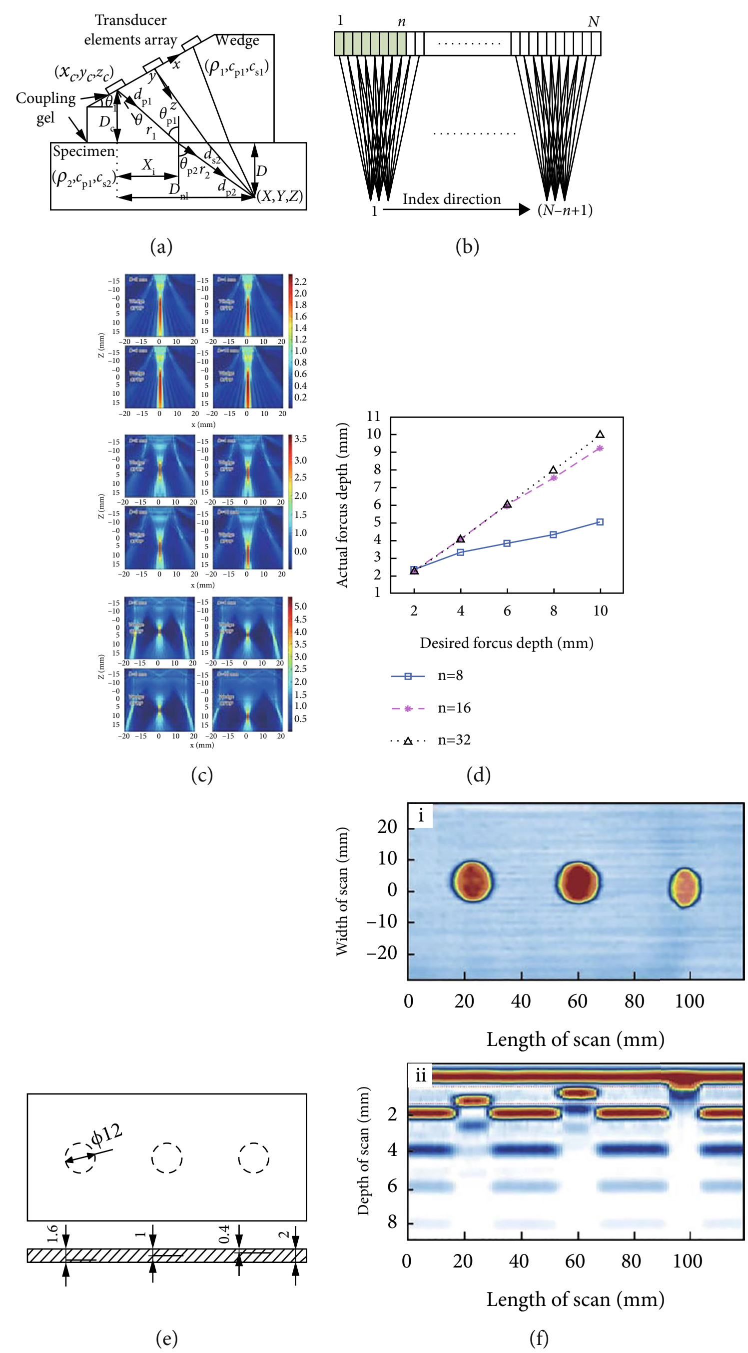


Figure 4: Phased array inspection of CFRP laminates [74]. (a) Phased array ultrasound detects the acoustic radiation schematic diagram. Phased array ultrasound realizes the deflection and focus of the acoustic beam by controlling the delay time of the excitation and receiving acoustic waves of each element in an electronic way. (b) A schematic diagram of zero-focus scanning method for testing CFRP laminates using phased array ultrasound; the focusing effect is the best when the beam is vertically incident inside the plate. (c) Simulation results of the sound field under different combinations of activation aperture and focus depth. (d) The comparison between the setting value and the simulation value of focusing depth under different activation apertures shows that the larger the activation aperture is, the smaller the error between the simulation value and the setting value of focusing depth is, and the more accurate the focusing is. (e) Schematic diagram of defect size and distribution. (f) phased array detection image of CFRP laminate (i) C-scan and (ii) B-scan.

the phase and amplitude changes of the ultrasonic waves at the interface. Defects larger than 4 mm can be detected by using the phase change, and scanning detection of the outer and inner debonding defects is realized by using different echo amplitude changes and gain adjustment.

3.1.2. Array Ultrasonic Testing Technology. Array ultrasonic testing technology has become one of the main developed detection technologies in the aerospace field in recent years due to its high detection accuracy and good flexibility. At present, different array ultrasonic testing technologies have

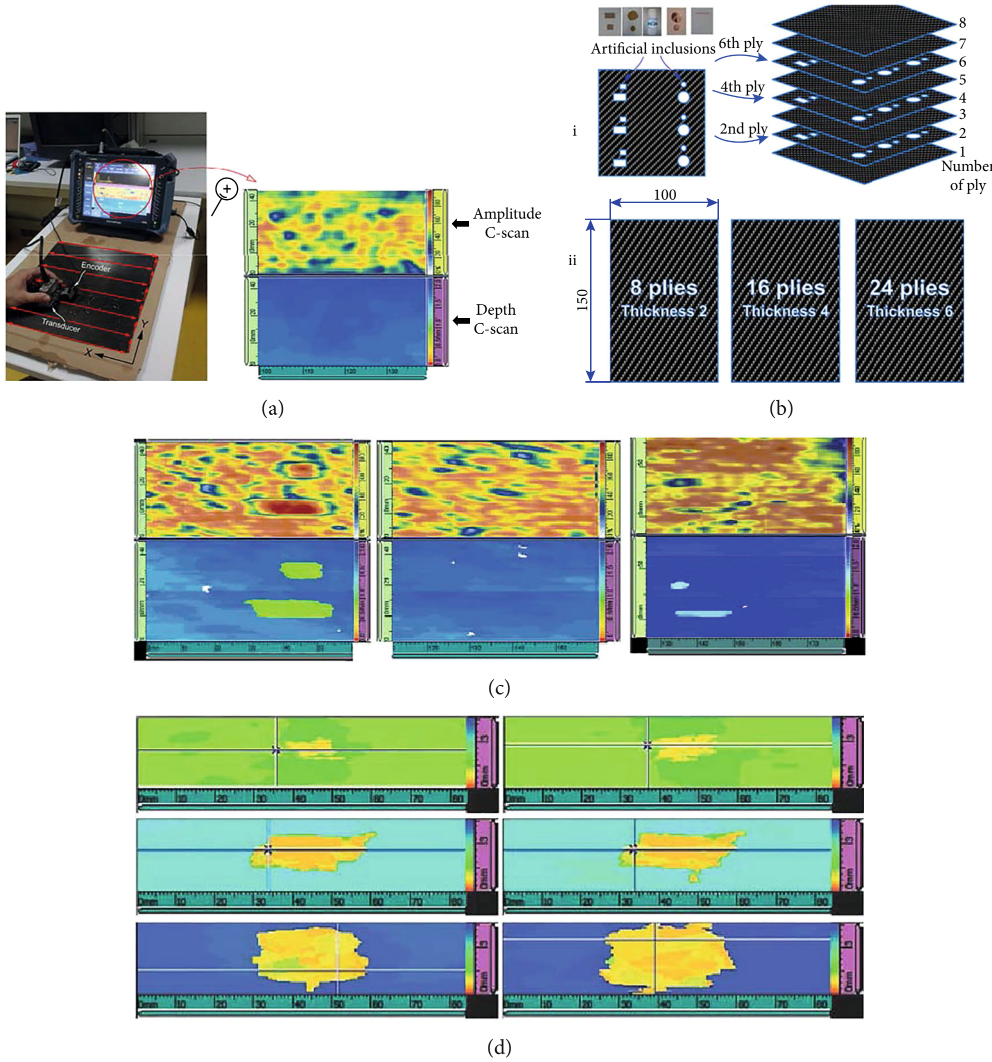
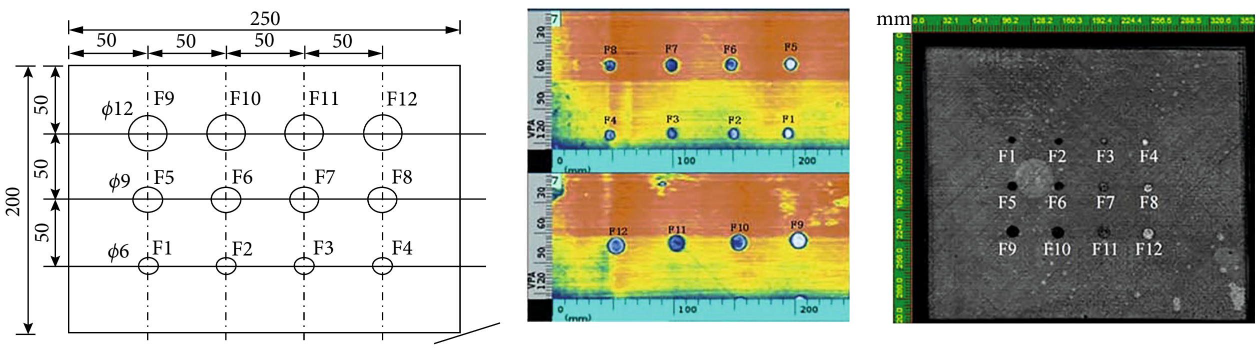


Figure 5: Ultrasonic phased array defect detection experiment [64]. (a) Experimental equipment of PAU testing and its ultrasonic C-scan image. (b) Experimental CFRP samples for inclusion defects (i) and impact defects (ii). (c) Different inclusion defect detection results. (d) Different impact energy test results.

gradually replaced conventional ultrasonic testing methods and are widely used in the NDT and evaluation of complex structures and special materials in the aerospace field, but it is difficult to identify defects and has higher requirements for the skills of operators.

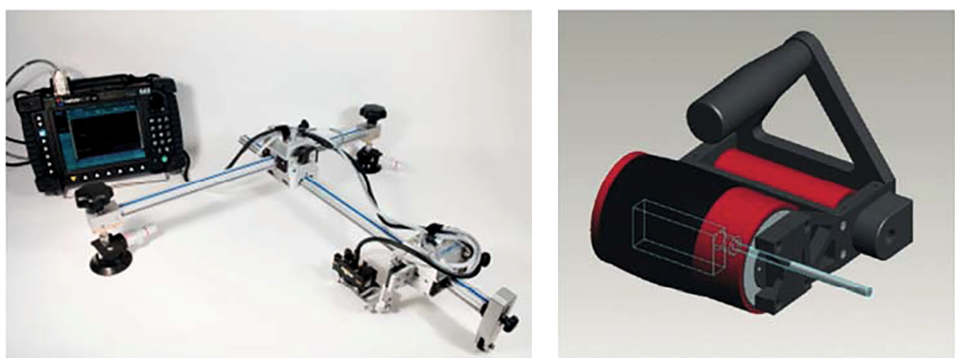
(1) Array Ultrasonic Testing. Zhou et al. [52] combined piezoelectric sensing array and ultrasonic Lamb wave detection technology to detect the debonding damage of carbon fiber composite T-joint and used the improved BP neural network system to analyze the damage state identify. The Structural Health Monitoring and Prediction Research Center of Nanjing University of Aeronautics and Astronautics [53] proposed a spatial filter damage imaging localization method independent of the signal propagation speed. Based on multidimensional piezoelectric sensor arrays and ultrasonic Lamb waves, the damage to carbon fiber laminates was realized. The positioning error is about 1 cm; the online monitoring of the damage of the composite T-joint has been realized, and it has been verified by the ultrasonic C-scan method [54]; the team also proposed a multisignal classification damage imaging method of the sensor line array. Experiments were carried out on aviation carbon fiber composite panels to achieve damage imaging and localization [55].

Wong et al. [56] used a two-dimensional ultrasonic array transducer composed of 64 piezoelectric elements to measure the full elastic constant matrix of anisotropic carbon fiber sheets, which are different from the traditional failure to determine the elastic properties of CFRP materials, a method for testing the elastic properties of composite materials in situ nondestructively. Liu et al. [57] carried out research on the detection method based on ultrasonic complex analytical signals. Using array ultrasonic detection experiments, the geometry of the fiber layup inside the microstructure of carbon fiber laminate composites can be clearly observed by the detection and imaging method of ultrasonic complex analytical signals.



(a) (b) (c)

Figure 6: Ultrasonic phased array inspection of fuselage panels [75]. (a) Defect distribution map. (b) Ultrasonic phased array inspection results. (c) High-resolution ultrasonic C-scan results.



(a) (b)

Figure 7: Improvement system of ultrasonic phased array. (a) Glide scanner combined with phased array device. The combination of glide scanner and phased array provides a completely portable inspection solution for large-area plane inspection of CFRP components [76]. (b) The ultrasonic array is placed on a rubber-coupled wheel, and the wheel can be manually applied or scanned by the structure and automatic scanning system, which can realize the inspection of a large composite structure. The glide scanner and phased array are combined [77].

(2) Phased Array Ultrasonic (PAU) Testing. PAU testing technology is a multichannel testing method based on array transducers, which can deflect and focus sound waves in a designated area inside the test piece using phase control. Compared with the conventional single-channel ultrasonic testing technology, PAU testing technology has more flexible beam control capability, higher detection sensitivity, resolution, and measurement coverage (range). A list of PAU testing for different defect types is shown in Table 1.

Kappatos et al. [62] carried out simulation detection by modeling various artificial delamination defect modes (different sizes and depths) of laminated CFRP composites, phased array delay timing, and sampling array technology, followed by Next, other types of defects will be simulated. Aschy et al. [73] compared the same ultrasonic phased array imaging methods, such as focused line scan, single plane-wave imaging, and dynamic depth focusing, and applied them to the defect detection of carbon fiber materials, identifying the performance and limitations of each method, and improved total focusing method and plane-wave imaging algorithm. Cao et al. [74] simulated the PAU sound field and studied the sound field characteristics under different activation apertures. Prepared CFRP were tested by the PAU detection system (see Figure 4), realizing the accurate identification of delamination defects of CFRP laminates and effectively improving the accuracy of defect detection.

Caminero et al. [64] conducted experiments on inclusion defects and impact damage of CFRP and 3D printing reinforced composites using ultrasonic phased array technology (see Figure 5), successfully identified artificial inclusions, and estimated their location, size, and morphology. It was also obtained that the impact damage caused more extensive delamination with increasing impact energy and composite thickness.

Li et al. [75] carried out defect detection and quantitative analysis on the carbon fiber composite fuselage panels of large aircraft using ultrasonic phased array detection (see Figure 6), providing technical support and test-ability verification for practical applications.

In addition to the continuous development of PAU testing technology, relevant testing systems have also been improved. Phased array and some special equipment are combined to achieve better testing effect or larger testing range. Habermehl et al. [76] and Freemantle et al. [77] have combined the ultrasonic phased array system to provide a new solution for defect detection of large CFRP components (see Figure 7).

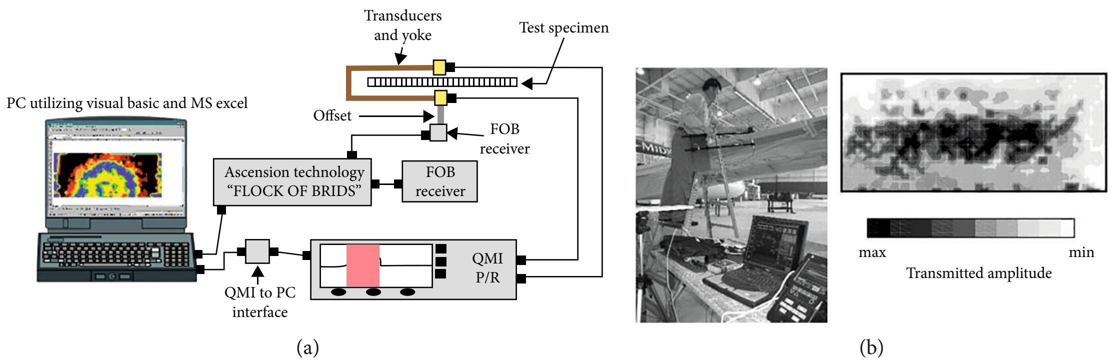


Figure 8: An on-site ACU testing system [84]. (a) ACU testing system. (b) ACU C-scan images of an airline that is manually scanned. On the left, is a photo of a scan on the right-wing of the aircraft, and on the right, is the result of the scanned image.

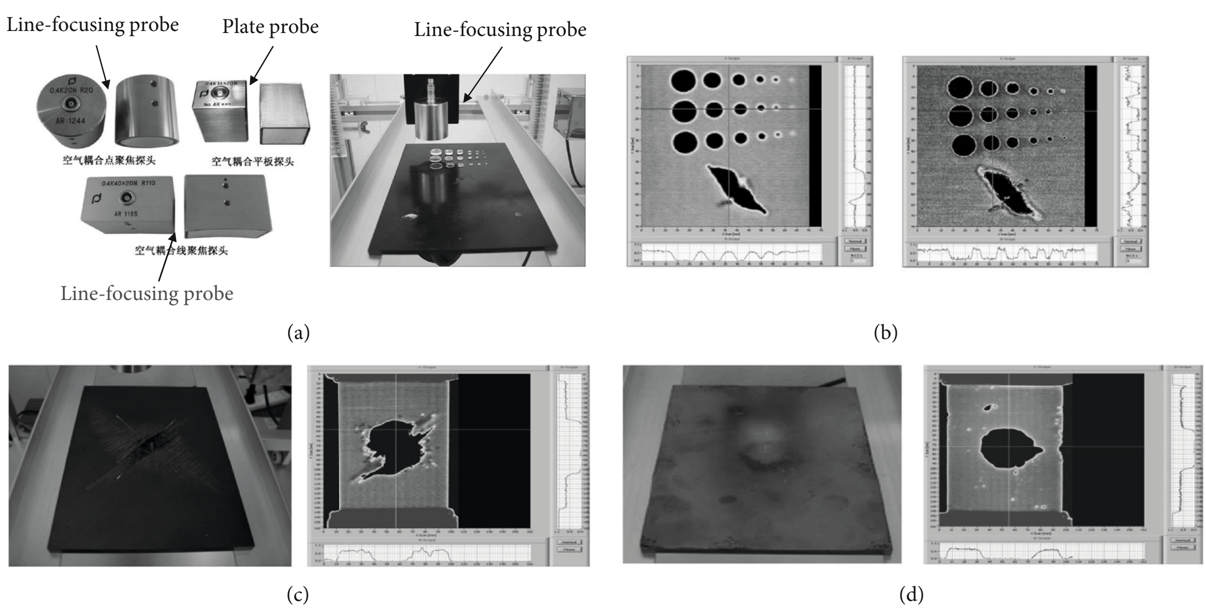


Figure 9: Noncontact ACU testing [85]. (a) Different shapes of air-coupled probes (left figure), with different frequencies of point-focused air-coupled transducers on CFRP test samples with scratches detection experiment (right figure). (b) 400 kHz point focusing probe detects that the minimum defect diameter is 2 mm, and the imaging of the simulated defect with a diameter of 1 mm is not clear (left figure); 800 kHZ point focusing probe is very clear about the imaging of 1 mm simulated defects (right figure). (c) Defect detection results of aviation CFRP plate specimens. (d) Defect detection results of CFRP plate specimens with a metal coating.

3.1.3. Air-Coupled Ultrasonic (ACU) Testing. Typically, the ultrasonic inspection of composite aerospace composite parts employs the ejector technique [78]. However, water coupling brings disadvantages such as pressure changes, air bubbles, limescale, algae, and mechanical corrosion. ACU testing technology uses air as the coupling medium and uses the ACU transducer to excite and receive ultrasonic waves to detect defects in materials and structures.

The difference between ACU testing technology and traditional ultrasonic testing technology is mainly in the presence of a coupling medium, which is intuitive and easy to implement for defect detection of composite materials. With the continuous development of key technologies, such as transducers, signal processing, detection methods, and detection systems, ACU detection technology has been gradually applied in aerospace and other fields to solve structural parts for which liquid couplants are prohibited (such as honeycomb sandwich materials) and inspection challenges for in-service components such as helicopter tail booms [79]. Due to the large sound attenuation coefficient and the low acoustic impedance of air, the center frequency of the transducer is generally lower than 1 MHz, and a multiperiod modulation pulse train needs to be used as the excitation signal to increase the energy, resulting in a large wavelength and focus of the excitation ultrasonic sound field. Spots have a faint lateral and vertical resolution and mainly use the penetration method to detect thin-walled, low-impedance materials (CUCUEVAS nonmetals such as composite materials).

Salazar et al. [80] designed and developed a high-power and high-resolution pulse generator ACUNDT system, which solved the problems caused by liquid couplants and contact systems in composite material testing. The Kaunas

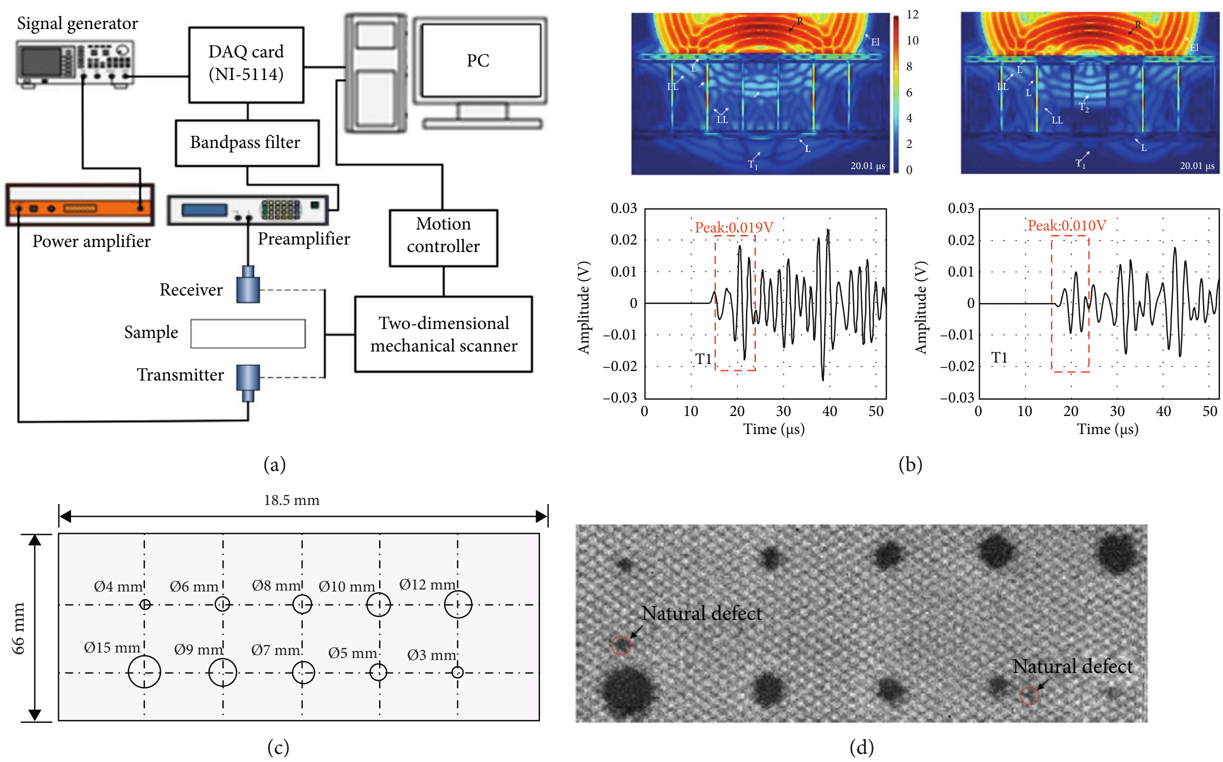


Figure 10: Noncontact ACU testing technology [866]. (a) Schematic diagram of the experimental device (DAQ: data acquisition). (b) Composite material samples and defect layout. (c) The top figure is the sound field distribution of the complete honeycomb sandwich composite model at 20.01 μs and the A-wave signal obtained by calculation and simulation, and the bottom figure is the sound field distribution of the honeycomb sandwich composite model with embedded peeling defects and the A-wave signal obtained by calculation and simulation. (d) C-scan result.

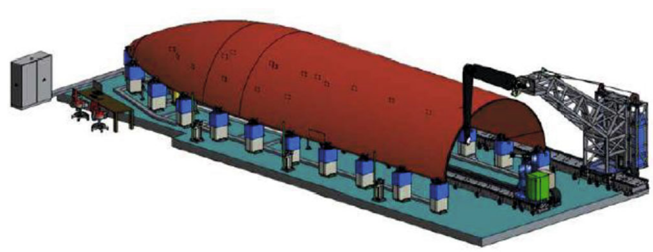


Figure 11: One of the largest air-coupled ultrasound C-scan systems in the world [78].

University of Technology Ultrasound Team [81] studied the accuracy of air-coupled ultrasound technology to detect delamination defects in composite materials such as carbon fibers at low frequencies, using a 4700 kHz transducer to measure the 25 mm diameter in GLARE3-3/2 composites. The delamination defect was detected, and the defect diameter was 22 mm obtained by the -6 dB method from the C-scan results. Steinhausen et al. [82] proposed a detection method based on multiarray air-coupled transducers in order to use different frequency transducers to detect various types of defects (inclusion, delamination, debonding, etc.) in the CFRP board, in which each array is excited at different frequencies, and all the arrays are simultaneously excited during detection to increase bandwidth, thereby improving the detection efficiency. Imielińska et al. [83] studied the ACU detection method for impact damage defects of carbon fiber, glass fiber, and polyamide fiber reinforced resin matrix composites. Peters et al. [84] developed an on-site inspection system applied to aircraft components based on ACU inspection technology (see Figure 8), which can realize image inspection of defects and damages of various aircraft composite materials. Chang and Lu [85] developed a set of the high-sensitivity noncontact ACU detection system to achieve accurate detection and evaluation of carbon fiber composites (see Figure 9). Li and Zhou [86] used noncontact ACU testing technology to detect and characterize debonding defects in aviation carbon fiber honeycomb sandwich composites (see Figure 10).

Hillger et al. [78] in Germany made progress in the detection and imaging difficulties of ACU testing technology in aerospace sandwich components, composite materials, and other components and carried out ultrasonic testing of

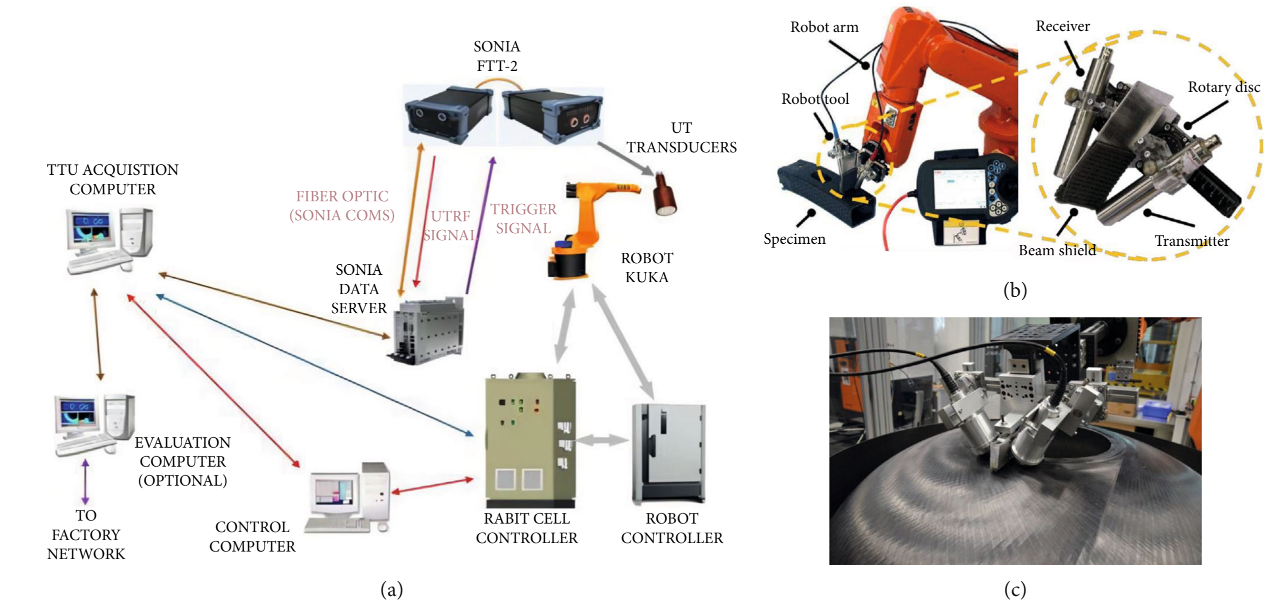


Figure 12: Joint robot combined with ACU C-scan. (a) New ACU C-scan system based on a joint robot [87]. (b) Joint robot to adjust the detection angle, the probe is installed on the rotating disc [88]. (c) A joint robot is being tested on a sample [89].

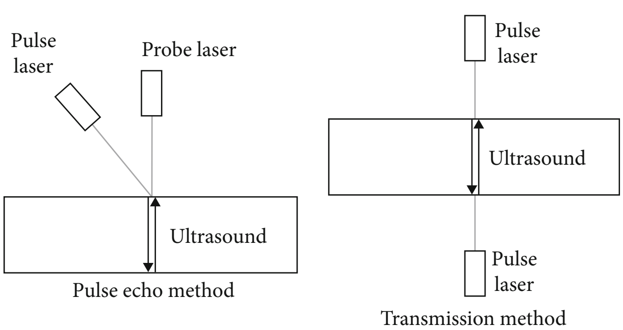


Figure 13: Laser is used to exciting and receives ultrasonic waves to detect defects in materials and structures. The commonly used detection methods include penetration method, pulse reflection method, surface wave method, and Lamb wave method. Among them, the pulse reflection method and penetration method are the most widely used [93].

metal sandwiches with CFRP and can automatically calculate the area of the defect; the team also introduced the technical framework and performance parameters of the world's largest ACU C-scan system (see Figure 11), with an accuracy of less than 2.5 mm.

With the continuous development of modern science and technology, robots are also constantly combined with the ACU testing technology, so that the detection technology has been previously improved (see Figure 12). Cuevas et al. [87] proposed a new ACU C-scan system based on joint robots and applied it to the nondestructive testing of large composite components such as aircraft. Huber [88] combined the ACU Lamb wave detection technology with the joint robot technology to realize the ACU inside profiling scanning imaging detection of the aerospace composite cylindrical structure. Adebahr et al. [89] designed an ACU detection system based on a joint robot. Two ACU transducers arranged on the same side were used as excitation and receiving ultrasonic Lamb wave detection defects, and a six-axis joint robot was used as a scanning actuator. The system can realize three-dimensional profiling scanning imaging detection of large and complex structures.

3.1.4. Laser Ultrasonic Testing. The laser ultrasonic testing technology uses the thermal stress generated by the instantaneous thermal interaction between the laser pulse that can propagate in the air and the composite material to be tested to excite ultrasonic waves inside the material and then uses optical instruments to measure the sound waves noncontact (see Figure 13). Laser ultrasonic testing does not use ultrasonic couplants in the application and also has the characteristics of high resolution. The pulsed laser can also realize long-distance excitation and reception of ultrasonic waves under the condition that it is not perpendicular to the structure. Therefore, laser ultrasonic testing is also used in aviation. The detection of composite materials in high-precision fields such as aerospace has been applied, and this technology is especially suitable for rapid automatic detection of large and complex structures [90–92].

Chia et al. [94] used the Lamb wave excited by the laser to scan the CFRP material of the wing and initially realized the location of the impact damage. Zhou et al. [95] designed a set of laser ultrasonic testing systems based on all-optical excitation and reception, which can clearly distinguish the characteristics of delamination defects above 2 mm in carbon fiber composites, and verified that the application of laser ultrasonic testing technology to the feasibility of delamination detection of carbon fiber composites has realized the detection of impact damage of carbon fiber composites. Sun et al. [93] independently developed a noncontact laser ultrasonic NDT system (see Figure 14), which can effectively detect layered defects with an internal diameter of more than

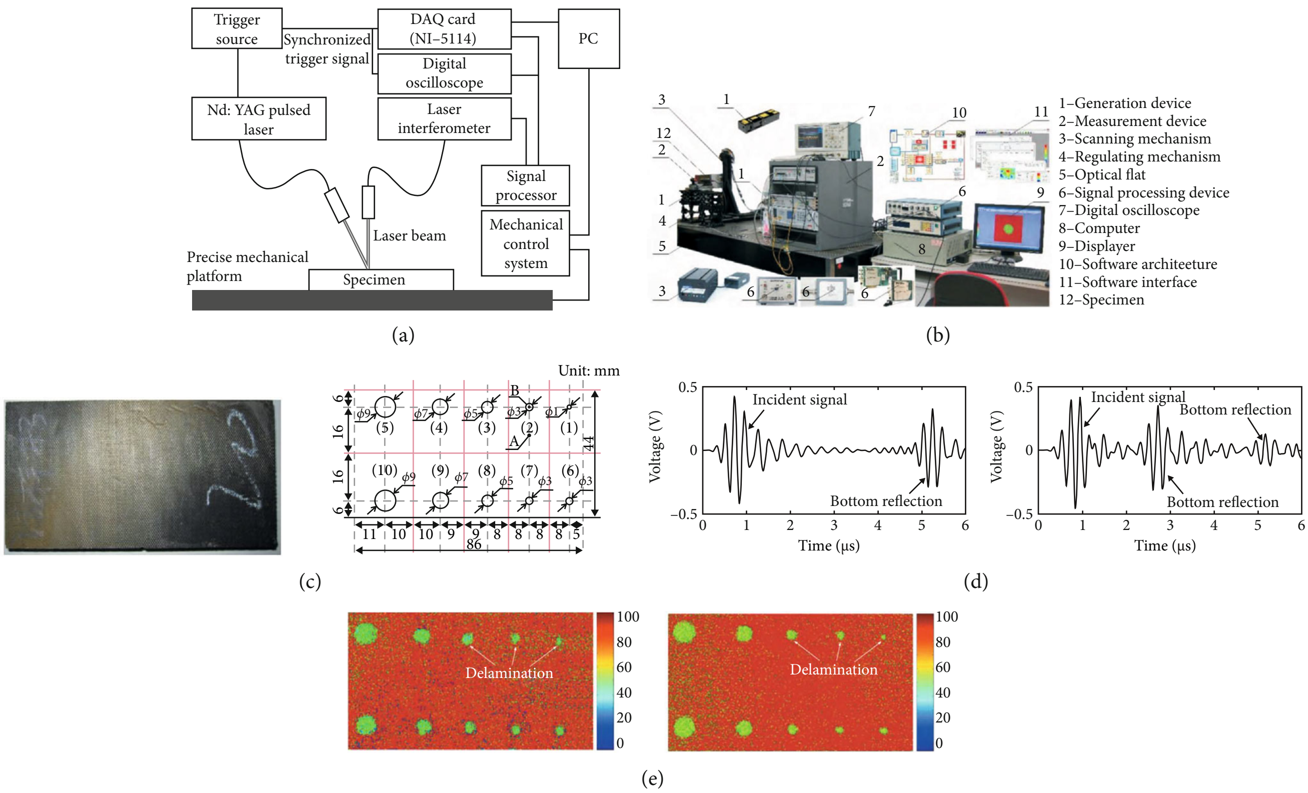


Figure 14: Laser ultrasonic testing of advanced composites [84]. (a) Basic theory of laser ultrasonic testing system. (b) Picture of the laser ultrasonic testing system. (c) Photo and layout of the CFRP specimen with internal delamination. (d) Narrow band signals extracted from the broadband laser ultrasonic signals measured at the intact (A) and defect (B) region of the CFRP specimen [96]. (e) Laser ultrasonic C-scan test of CFRP composite with delamination.

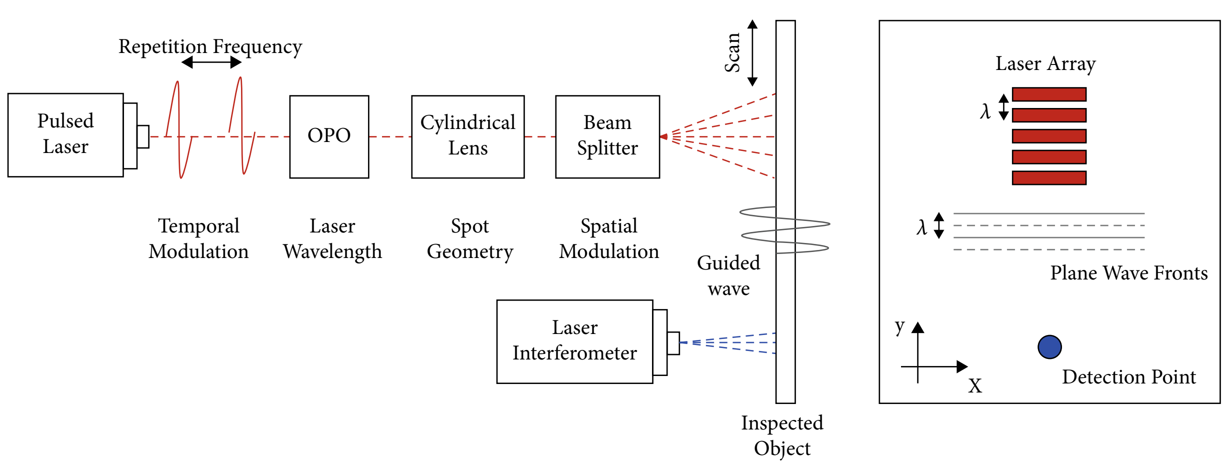


Figure 15: Ultrasonic guided wave inspection of composite materials based on laser excitation and detection methods [98].

2 mm in carbon fiber resin matrix composites and can also detect carbon fiber composite materials. Small size is layering at the edge of the fastening hole.

Nakahata et al. [97] used the thermal stress generated by the short-pulse laser and the instantaneous thermal interaction of the material to excite ultrasonic waves inside the material and used a photoacoustic microscope to scan the defects in the CFRP sample at a distance of 50 μm in the X and Y directions. The three-dimensional reconstruction of the delamination defect is carried out, the position and size of the defect can be accurately analyzed from the results, and the orientation of each fiber layer of the carbon fiber composite material is also reflected. Germany's Kelkel et al. [98] provided great potential for noncontact detection of fiber composites through the combination of laser excitation and detection of ultrasonic guided waves. As showed in Figure 15, the effects of laser wavelength, beam geometry, and spatiotemporal modulation of laser pulses on the

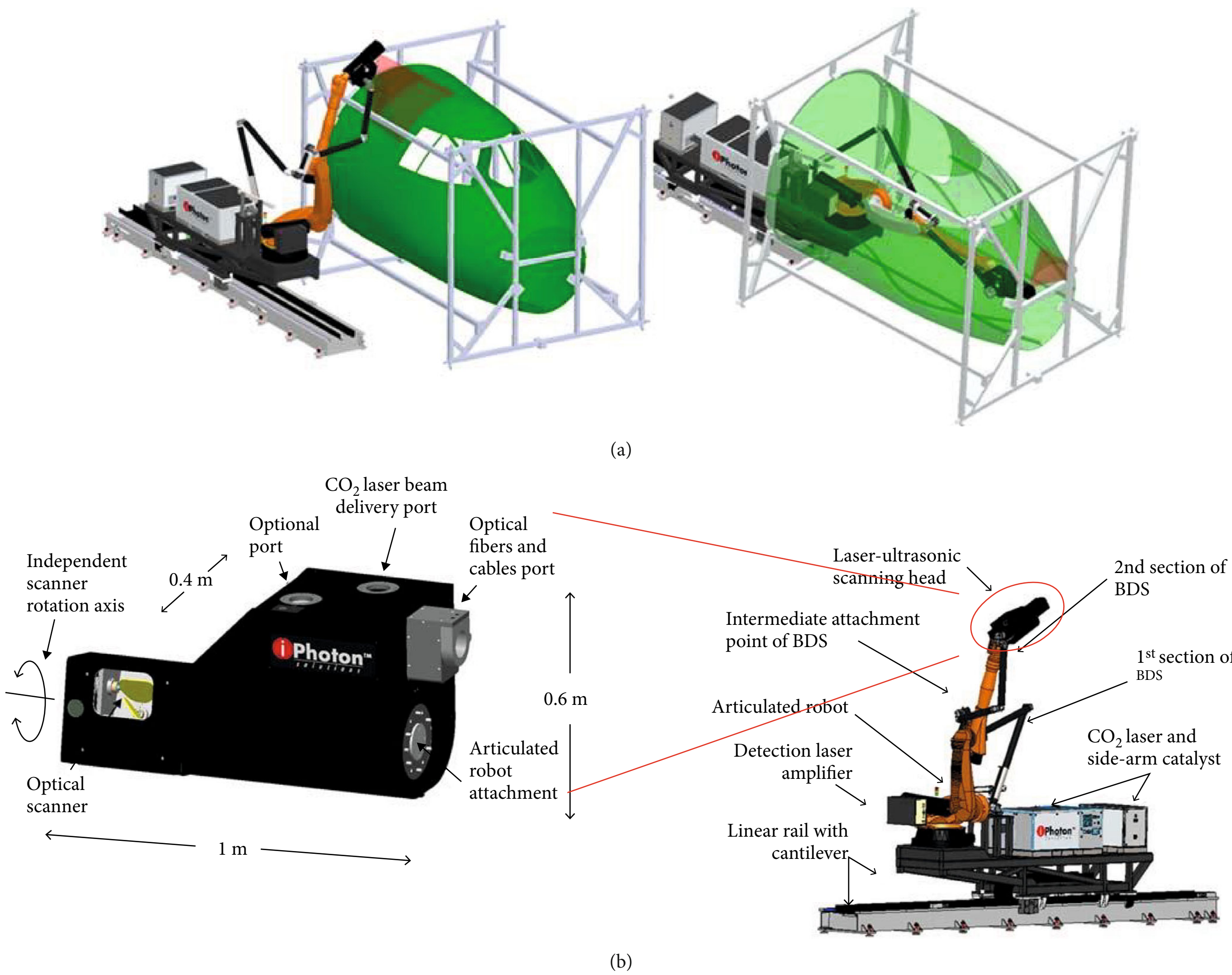


Figure 16: Laser ultrasonic detection system based on a joint robot [104]. (a) Illustrations of the inspection of the exterior (left figure) and interior (right figure) of large composite fuselage sections. (b) Schematic diagram of the laser detection system and laser-ultrasonic scanning head.

bandwidth, directivity, and amplitude of the generated acoustic wave are discussed. This method significantly improves the amplitude and signal-to-noise ratio of the ultrasonic guided wave signal.

Wang et al. [99] developed a multiscale ultrahigh-resolution laser ultrasonic inspection system for carbon fiber composites, which can identify microscale damage in CFRP and use a 2D laser with a high spatial resolution of 60 μm and a 3D image representation. Fischer et al. [100] designed a new noncontact laser ultrasonic inspection system based on optical microphones and used the transmission method to detect the internal defects of composite materials with quasistatic mechanical properties and low-speed shock response characteristics, which proves that the detection system has a high detection resolution. The Spanish Advanced Aviation Technology Center [101] realized the porosity detection of carbon fiber composites by laser longitudinal wave. Li et al. [102] verified the feasibility of laser ultrasonic detection for damage identification of complex-shaped aerospace composites with curvature. Qiu et al. [103] used noncontact laser ultrasonic technology to detect aviation composite materials and imaged defect damage by extracting the energy and wavenumber information of ultrasonic signals. Dubois and Drake [104] combined laser ultrasonic inspection technology with robotics and developed a laser ultrasonic inspection system based on joint robots (see Figure 16). The system can detect the damage and defects of large-scale CFRP components in real-time. By installing a seven-axis robot with high flexibility on the guide rail for the positioning of the detector, and the system is equipped with a high-performance computer to process the collected data, automatic detection is realized.

3.1.5. Laser Air-Coupled Ultrasonic Testing. Bustamante et al. [105] used a hybrid laser air-coupled ultrasonic system CFRP for defect detection (see Figure 17); the system detects defects through the ultrasonic B-scan mode and determines the existence of internal defects in the material by the change

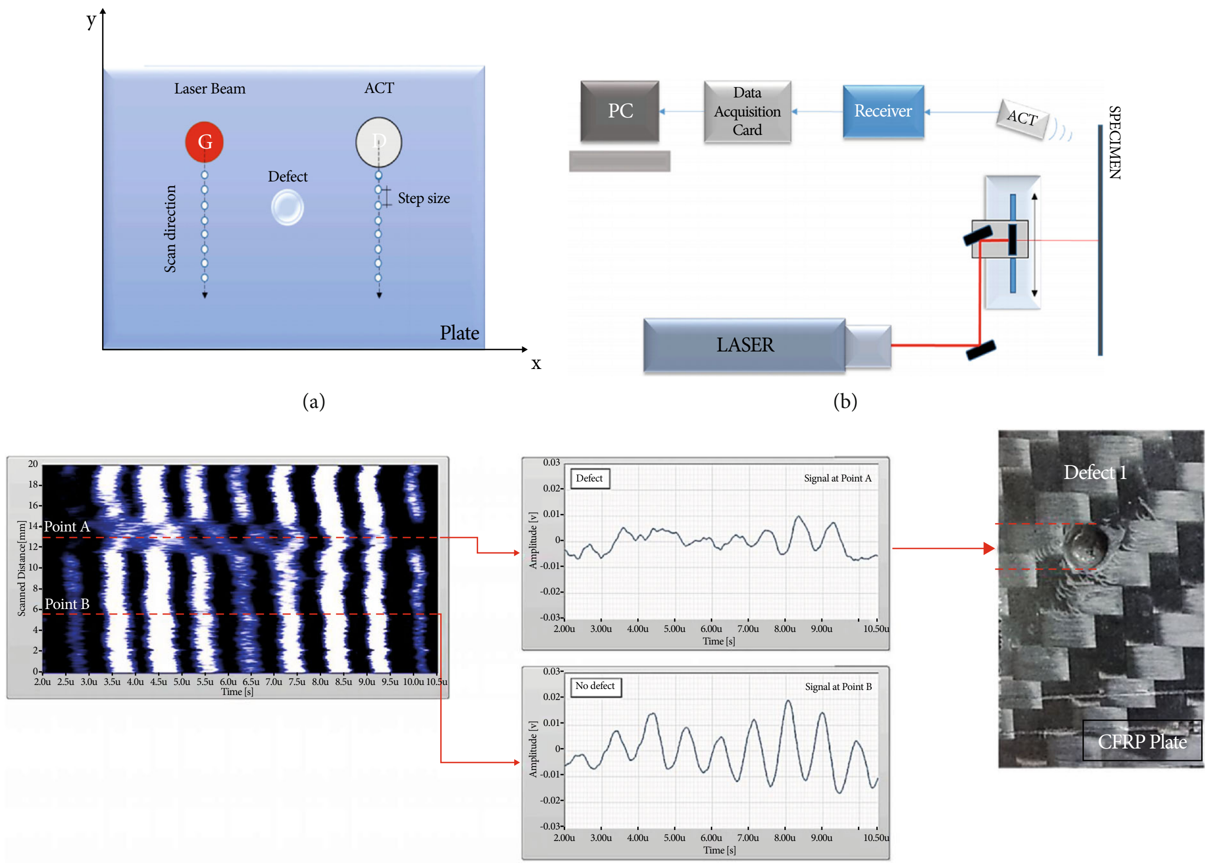


Figure 17: Scanning results of laser air-coupled ultrasonic system [105]. (a) Scanning direction and defects. (b) Scanning system. (c) Scanning results of CFRP defects.

of the acoustic wave amplitude. The defect detection of CFRP is shown in Figure 17(c).

Zeng et al. [106] proposed an air-coupled laser-ultrasonic system for detecting the microstructure and defects of woven carbon fiber cloth. Compared with PAU testing, it has higher resolution and defect detection and can detect the microstructure characterization of CFRP, as well as shallow and deep defects (see Figure 18).

3.2. Ultrasonic-Assisted Detection Methods

3.2.1. Ultrasonic Infrared Thermal Imaging Detection. Ultrasonic infrared thermal imaging detection technology is to apply a short-pulse, low-frequency ultrasonic waves on the surface of the object, and the ultrasonic waves are coupled to the interior of the object through the contact surface for transmission. If there are defects, such as cracks and delaminations in the composite material, under the excitation of ultrasonic waves, the two interfaces of the medium damage will contact and collide, and the mechanical energy of ultrasonic waves will be converted into heat energy under the action of friction, and then, the temperature clothing of the defect and its adjacent areas will increase. The change of the corresponding surface temperature field can be observed and recorded using an infrared thermal imager [107].

Yang et al. [108] carried out ultrasonic infrared thermal imaging NDT on the impact damage of CFRP specimens for UAVs (see Figure 19). The imaging defects are segmented, and the geometric distortion of the defects during the camera imaging process is also compensated (see Figure 19(d)). Umar et al. [109] studied the defect detection of composite materials by ultrasonic infrared imaging technology and successfully detected the damage defects of carbon fiber composite materials. This technology not only improves the efficiency of defect detection but also reduces the detection cost.

Chulkov et al. [110] added two infrared image sequences obtained under optical and ultrasonic excitation (see Figure 20) and then detected the defects of CFRP, realizing the detection of small opening cracks with low thermal resistance.

3.2.2. Fiber Ultrasonic Testing. Hudson et al. [111] designed a real-time online monitoring system based on PSFBG, and the results show that the system can detect the ultrasonic signal propagating in CFRP and then can realize the detection of defects. Wang et al. [112] studied a fiber grating ultrasonic testing system to solve the problem of ultrasonic nonlinearity caused by cracks in the composite matrix (see Figure 21), by introducing a phase-shifted fiber Bragg grating (PSFBG)

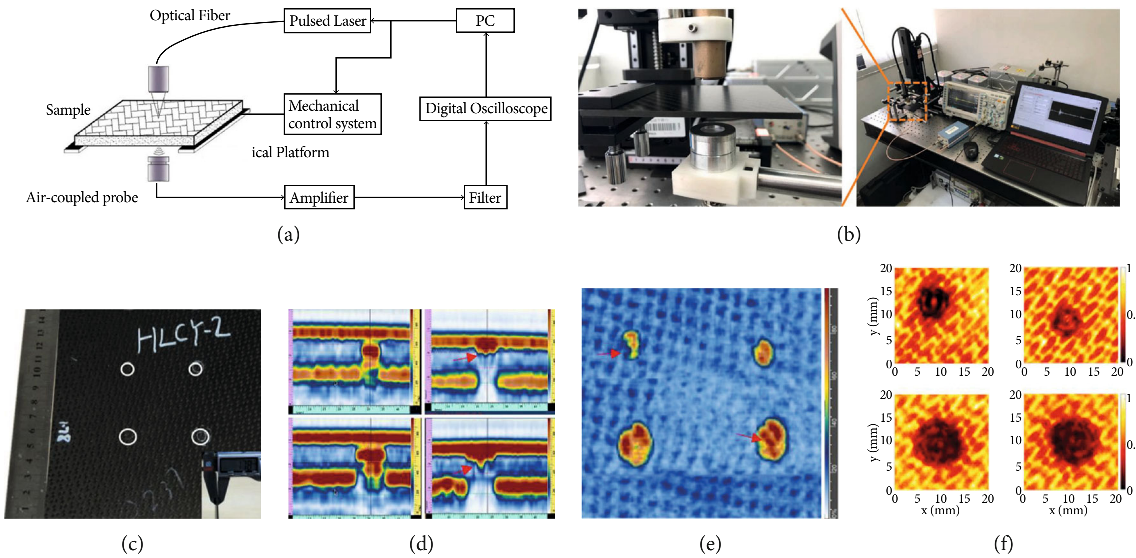


Figure 18: Air-coupled laser hybrid system [106]. (a) Schematic diagram of the system. (b) Photo of the experimental setup. (c) Air-coupled laser ultrasound imaging of CFRP samples. (d) 5 MHz phased array B-scan image. (e) 20 MHz phased-array C-scan image. (f) Air-coupled laser scan image.

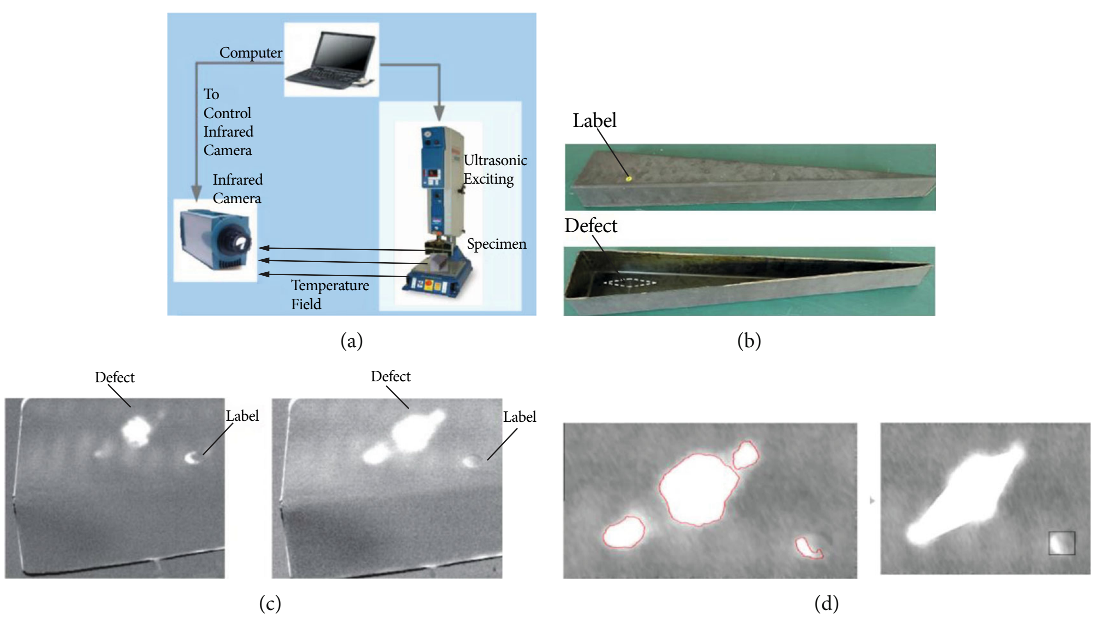


Figure 19: Ultrasonic infrared thermal imaging CFRP inspection [108]. (a) Experimental setup. (b) Before and after photos of CFRP specimens. (c) Before and after thermal imaging inspection results. (d) Defect segmentation results (left figure) and defect compensation results (right figure).

to improve the sensitivity and bandwidth of ultrasonic detection and realize the damage assessment of CFRP matrix cracks.

4. Problems and Development Trends

(1) The components of CFRP in different fields often have the characteristics of complex structure, special material, and rapid upgrading, which put forward higher requirements for the corresponding advanced ultrasonic NDT technologies and equipment such as array ultrasound, air-coupled ultrasound, and laser ultrasound. High precision, automation, intelligence, and engineering have gradually become the development trend of advanced ultrasonic testing technology in the future

(2) The difficulties and key points in the detection of CFRP composites, especially in the field of aerospace. The detection of various defects of CFRP needs to be combined with various advanced ultrasonic testing and imaging technologies to cross and integrate to improve the detection efficiency. At the

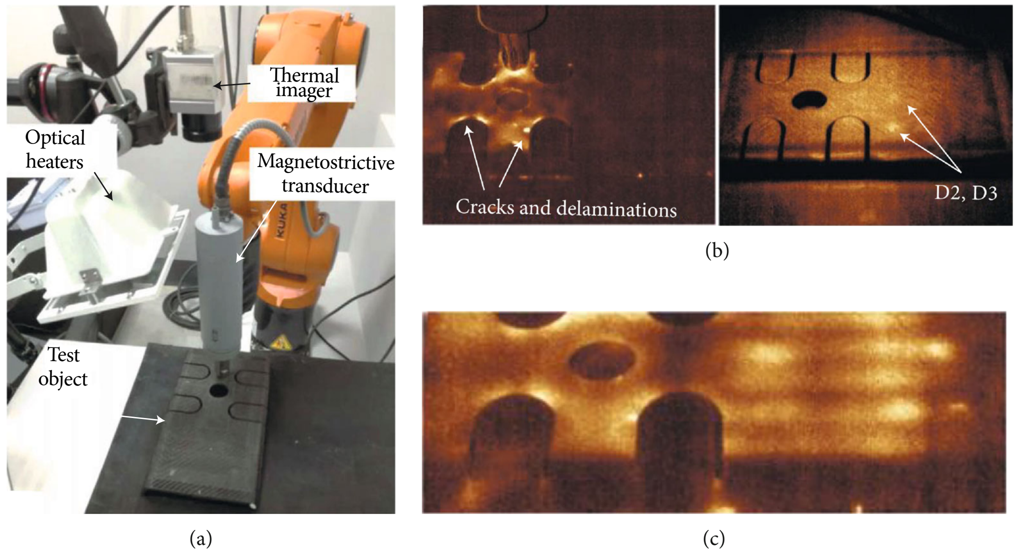


Figure 20: Optical and ultrasonic excitation infrared imaging detection [110]. (a) Experimental setup and experimental samples. (b) Ultrasonic excitation (left figure) and optical excitation (right figure) infrared imaging. (c) Infrared synthesis detection diagram.

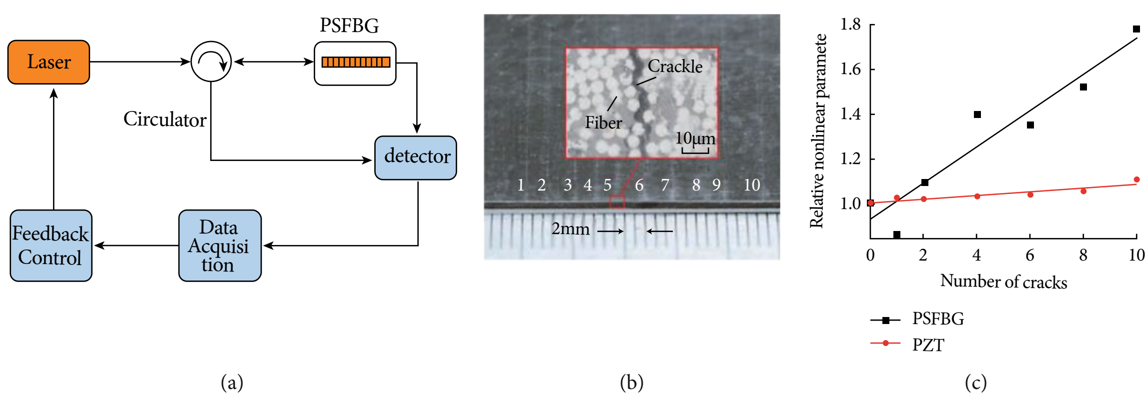


Figure 21: Fiber Bragg Bragg Grating Ultrasonic Testing System [112]. (a) System schematic diagram. (b) Experimental sample. (c) Relationship between the number of cracks and nonlinear parameters (different sensors).

same time, basic research on the acoustic characteristics and detection model of CFRP composites is carried out to improve the detection accuracy and reliability of CFRP

(3) In view of the advanced ultrasonic testing technology, such as array ultrasonic, ACU, and laser ultrasonic automatic testing technology, it is necessary to determine the relevant defect detection methods, position calibration, type determination, and parallel control technology according to the research of complex CFRP components tested and further improve the accuracy and efficiency of automatic testing combined with other advanced NDT technologies

(4) With the rapid development of artificial intelligence, the defects of CFRP can be detected by combining various ultrasonic technologies, and the relevant parameters can be optimized by using deep learning and other methods. The robot technology can help the detection technology to realize real-time detection, automation, intelligence, and other operations and can be used for NDT of large and complex CFRP components and high precision areas to achieve better detection results

5. Conclusion

Recent research shows that ultrasonic is still the most active hot spot in the field of composite materials. Using the appropriate ultrasonic method and ultrasonic technology, not only the defects can be characterized, evaluated, and qualitatively and quantitatively detected but also the automation and visualization of carbon fiber composite structure can be easily realized, and intelligent NDT and evaluation. In the actual test, appropriate test methods should be selected according to the characteristics of various carbon fiber composites, or multiple methods should be used to complement each other to complete different test tasks. The outstanding advantages of ultrasonic NDT are that it is harmless to human body, low cost, and easy to operate. It will certainly play a greater role in the field of NDT of composite materials. However, in the face of the continuous introduction of new composite materials, new processes, new structures, and new testing requirements, there are still many technical problems and difficulties in ultrasonic NDT and electronic testing.

Abbreviations

CFRP: Carbon fiber-reinforced polymer
NDT: Nondestructive testing
PAU: Phased array ultrasonic
ACU: Air-coupled ultrasonic.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grant 51875477 and Grant 51475013 and in part by the Fundamental Research Funds for the Central Universities under Grant 3102020ZDHKY01.

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