Delamination detection in CFRP T-joint using laser ultrasonic technology

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Abstract
As one of the typical forms in aircraft composite structures, Carbon Fiber Reinforced Polymer (CFRP) T-joint plays an important role in the whole aeronautics structure. CFRP T-joint mainly transfers and sustains the loads from the vertical surface to achieve the continuity of force transference and integrity of structural load distribution. Therefore, it is prone to delamination under the tensile load. This paper studies the delamination detection method for CFRP T-joint using laser ultrasonic technology.

Laser ultrasonic technology employs a pulse laser to generate ultrasonic waves and a fixed sensor to collect ultrasonic signals. This technology provides several advantages, such as high spatial resolution, comprehensive information of the ultrasonic wave propagation and high scanning speed for large and curved surfaces. In this paper, the scanning area is the skin surface and sensing point is set on the web of CFRP T-joint. According to acoustic reciprocity theorem, wavefield in the skin of T-joint can be reconstructed to visualize the wave propagation. To locate the size and shape of delamination, a windowed frequency-wavenumber domain method is employed to separate the incident and reflected wave energy. A compensation method is then proposed to eliminate the influence of anisotropy in composites, making the edge of delamination clear. Comparing with the result of the immersion ultrasonic C scan, the proposed method shows the validity and accuracy in the delamination detection in CFRP T-joint.

Keywords: CFRP T-joint, Laser ultrasonic technology, Delamination

1. Introduction

From the past several decades, composite materials have been widely used in aeronautics and astronautics fields due to its high strength-to-weight ratio. For civil aircrafts, the proportion of composites in an American Boeing 787 reaches up to 50%, and as for military aircrafts, the π-joint structure has been assembled in the forward fuselage of the American F-35 Joint Strike Fighter. Furthermore a co-cured skin structure and vertical web is employed in the European EP-2000 to substantially improve validity and reliability of the structural integrity of the aircraft 1. Carbon Fiber Reinforced Polymer (CFRP) T-joint is one of the typical joints, connecting different structures like skin and web. It can transfer and sustains the loads from the vertical surface to achieve the continuity of force transference and integrity of structural load distribution.

1.1 CFRP T-joint

Researchers have presented a variety of studies on T-joint recently. Blake et al. studied the damage to the T-joint affected by viscoelastic inserts 2. Kesavan et al. 3 studied the strain distribution in glass fiber reinforced polymer (GFRP) T-joints under tensile load. Hu et al. studied the influence of initial damage location on joints with different width ratios of skin and flange under tensile load 4. Zhu et al. studied the effect of defects with different sizes and locations in the filler and filler stiffness on mechanical properties of T-joints 5. Whittingham et al. used vibration signatures to detect debond in T-joints 6. Zhu et al. studied debond of CFRP T-joints by active Lamb wave technique 7. Ramadas et al. studied the interaction of Lamb mode (A0) with structural discontinuity and the generation of modes turning to GFRP T-joints, as well as the estimation of the interface delamination using the time-of-flight of Lamb waves 8,9.
CFRP T-joint contains a bonding interface in which defects such as porosity, holes and delamination easily occur. Once the crack appears, it will soon spread through the glue layer and finally lead to structure failure, which is a hidden danger for connecting parts. Therefore, it is necessary to detect the damage in CFRP T-joint in time. In actual situations, CFRP T-joint is mainly subjected to tensile load which accounts for interface delamination. Laser ultrasonic technology provides a convenient nondestructive method to locate the size and shape of delamination areas.

1.2 Laser ultrasonic technology

Laser ultrasonic technology is one of the most popular technologies in Non Destructive Testing (NDT) field. It has many advantages 10. (1) Ultrasonic images with high space and time domain resolution can be acquired, making damage diagnosis more intuitive and easier. (2) Damage diagnosis can be performed without using baseline data obtained from the pristine condition of a target structure, enabling this baseline-free technique to be more stable under the changing environmental and operational conditions. (3) Noncontact techniques are nonintrusive, deployable, applicable to harsh environments, and require less maintenance. This paper focuses on locating the interface delamination in CFRP T-joint by laser ultrasonic technology. First, the scanning area and sensing point (AE sensor stuck point) are selected properly. Then time domain signal of each scanning point is acquired by a laser ultrasonic detection system. After getting all the wavefield data from the whole scanning points, incident wave and reflected wave can be separated by a windowed frequency-wavenumber domain method. Finally, incident wave energy and reflected wave energy are calculated to locate the size and shape of interface delamination in CFRP T-joint.

2. Experimental setup

2.1 Test specimens

The quasi-isotropic CFRP T-joint specimen used in this paper is shown in Fig.1. It is composed of three parts: two L-shaped stringers and one skin laminate. The material for all laminates is T700/QY8911. The L-shaped laminate has 13 plies with layups \([45^\circ/0^\circ/0^\circ/45^\circ/90^\circ/45^\circ/0^\circ/0^\circ/-45^\circ/90^\circ/45^\circ/0^\circ/45^\circ]\), of which thickness is 2mm. The skin laminate is made up of 32 plies with layups \([-45^\circ/0^\circ/45^\circ/90^\circ/0^\circ/-45^\circ/0^\circ/45^\circ/90^\circ/0^\circ/-45^\circ/0^\circ/45^\circ/-45^\circ/45^\circ]\), and its thickness is 5.5mm. The triangle filler region is filled with foam rubber with 3.5mm radius[1]. For the convenience of comparison, one T-joint without delamination and the other with delamination are studied to make sure the feasibility of laser ultrasonic technology.
2.2 Sensor and scanning area arrangement

In this paper, laser excites specific wave modes in T-joint and AE sensor collects data. The arrangement of sensor and scanning area is shown in Fig.2. In general, the web is always hidden inside the airplane wings and the sensor arrangement would not change the shape/properties of skin surface. Scanning area is on the bottom of the skin surface, which measures 120mm×120mm and scanning interval is 1mm.

![Fig.2 sensor and scanning area arrangement](image)

2.3 Experimental scheme

Fig.3 shows the laser ultrasonic detection system of T-joint specimen, which is composed of an excitation unit (pulsed laser and laser mirror scanner), a sensing unit (AE sensor and amplifier) and a data acquisition unit (PC and data acquisition cards). Fig.4 presents the flow charts of the progress of laser ultrasonic detection system. After each point’s data combined together, a wavefiled can be reconstructed by acoustic reciprocity theorem.

![Fig.3 laser ultrasonic detection system](image)

3. Results and analysis

3.1 Wave propagation routes analysis

Before analysing the experimental results, it is necessary to study the wave propagation routes in T-joint. On non-delamination conditions, the propagation routes are shown in Fig.5 (a). It is
obvious that the wave starts from the position of sensor, and then it goes through the web to skin, next propagates in the horizontal part of L-shaped laminates, interface (glue) and skin laminates. On delamination conditions, due to the propagation characteristic of ultrasound through delamination interface, the wave can hardly propagate through delamination area. In delamination area, the wave almost exists in the horizontal part of L-shaped laminates. And then, it travels round the edges of delamination to propagate in the skin laminates. This is clearly shown in Fig.5 (b).

![Fig.5 wave propagation routes (a) non-delamination (b) delamination](image)

### 3.2 Wave separating method and wavefield estimation

Analysing the wave propagation routes in T-joint with delamination, it is found that before edge reflection appears, only incident wave exists in scanning area outside the delamination edge. Thus, it is prospective to use incident wave energy to locate the shape and size of delamination. This section proposes a frequency-wavenumber domain method that can separate incident wave from original wavefield. After the separated incident/reflected wave is obtained, several signal processing methods can be used to detect the damages.

To simplify wave propagation in T-joint, one dimensional propagation model is carried out as an example to study the characteristics of incident/reflected wave. When original wavefield contains only incident wave and reflected wave, the general form of wave equations are described as follows:

\[
\begin{align*}
\Psi_i(x,t) &= A_i \cos(\omega t - kx) \\
\Psi_r(x,t) &= A_r \cos(\omega t + kx + \phi) \\
\Psi(x,t) &= \Psi_i(x,t) + \Psi_r(x,t)
\end{align*}
\]

Where \( \Psi(x,t) \) is original wavefiled expression, \( \Psi_i(x,t) \) is incident wave expression, \( \Psi_r(x,t) \) is reflected wave expression. \( A_i \) and \( A_r \) represent the amplitudes of incident wave and reflected wave respectively. \( \omega \) is angular frequency and \( k \) represents the wavenumber. \( \phi \) is the phase difference between reflected wave and incident wave.

By comparing (1) with (2), we find that the difference between \( \Psi_i(x,t) \) and \( \Psi_r(x,t) \) is the sign of \( \omega k \). If the direction of positive axis \( x \) is defined as the incident wave propagation direction, the negative sign of \( \omega k \) represents the incident wave and the positive sign represents the reflected wave. Based on the above conclusion, the window functions \( \Psi'_i(x,t) \) and \( \Psi'_r(x,t) \) are proposed to separate the incident and reflected wave, which can be expressed as
\[ \Psi_i(k_x, \omega) = \begin{cases} 1 & \omega k < 0 \\ 0 & \text{others} \end{cases} \]  
\[ (4) \]

\[ \Psi_r(k_x, \omega) = \begin{cases} 1 & \omega k \geq 0 \\ 0 & \text{others} \end{cases} \]  
\[ (5) \]

Then the proposed incident/reflected wave separating method can be divided into three steps.

**Step 1.** Transform \( w(x,t) \) from time domain to frequency domain by Fourier Transform:

\[ W(\omega, k_x) = \int w(x,t) e^{-i(\omega t + k_x x)} dx \]  
\[ (6) \]

**Step 2.** Calculate the product of \( W(\omega, k_x) \) and \( \Psi_i(k_x, \omega) \) (or \( \Psi_r(k_x, \omega) \)):

\[ W_i(k_x, \omega) = W(k_x, \omega) \Psi_i(k_x, \omega) \]  
\[ (7) \]

\[ W_r(k_x, \omega) = W(k_x, \omega) \Psi_r(k_x, \omega) \]  
\[ (8) \]

**Step 3.** Transform \( W(\omega, k_x) \) from frequency domain to time domain by Inverse Fourier Transform:

\[ w_i(x,t) = \int W_i(k_x, \omega) e^{i(\omega t + k_x x)} dk_x d\omega \]  
\[ (9) \]

\[ w_r(x,t) = \int W_r(k_x, \omega) e^{i(\omega t + k_x x)} dk_x d\omega \]  
\[ (10) \]

After employing the above steps, the incident and reflected wavefield can be separated respectively. Thus, wavefield energy evaluation methods are used based on incident/reflected wavefield to study the characteristics of complex structures like CFRP T-joint.

Usually total wave energy method is employed as the most common evaluation method to analyze the conditions of structure. The total wave energy can be described as:

\[ E(x, y) = \int w^2(x, y, t) dt \]  
\[ (11) \]

It should be noticed that the interval of integration should be adjusted to the time intervals according to the arrival time of wave from each coordinate \((x, y)\), thus the disturbing factor (different distances from specific points to wave source corresponding to arrival time of wave) can be filtered and a better result will be achieved. Moreover, incident or reflected wave energy can be figured out respectively to make the damage (delamination in this paper) visualized by the above mentioned method.

Since it is not easy to visualize the damages obviously in composites due to its anisotropy, a compensation method based on experimental configuration is proposed to make the detection results visual. Details are discussed in section 3.3.

In addition, SNR (Signal-to-Noise Ratio) estimation is proposed to evaluate the wavefield which is defined as:

\[ \text{SNR} = \frac{E_{\text{signal}}}{E_{\text{noise}}} \]  
\[ (12) \]

Where \( E_{\text{signal}} \) stands for the energy of effective signal and \( E_{\text{noise}} \) represents the energy of background noise signal. SNR value judges the quality and intensity of a signal. In section 3.3, SNR value is calculated to characterize the directivity of composites.

### 3.3 Wavefield reconstruction results

Fig.6 and Fig.7 show skin surface wavefield snapshots in T-joint without delamination and with delamination at different times. It is found that the wave propagates from web to skin and it starts to spread from \( y=60\text{mm} \) (skin surface position where web is mapped to) in Fig.5 (a). The wave propagates from two oblique lines, which are confirmed to be the delamination edges between L-shaped laminate and skin laminate. It is clearly shown in Fig.5 (b).
Also, the wavefield snapshots present antisymmetry in wave propagation. It is evident that the intensity of wave varies in different directions, which is caused by anisotropy in composites. Therefore, it is difficult to detect damages in areas where intensity of wave is relatively low. 

Aimed at the particular structure like CFRP T-joint, a compensation method is presented to eliminate the influence of anisotropy in composites.

Fig. 6 wavefield snapshots in T-joint without delamination at different moments. 
(a) 55μs, (b) 75μs, (c) 80μs.

Fig. 7 wavefield snapshots in T-joint with delamination at different moments. 
(a) 55μs, (b) 75μs, (c) 80μs.

Fig. 8 total energy (non-delamination) Fig. 9 total energy (delamination)

Fig. 10 normalized SNR value Fig. 11 incident wave energy (delamination)
By Eq.11, Fig.8 and Fig.9 show the wave energy graph of T-joint without delamination and with delamination respectively. The graphs confirm the directivity of wave energy in composites. It is found that most energy is distributed from 90° to 180° and less energy is distributed from 0° to 90°. After calculating SNR values of each scanning point by Eq.12 and convert each point’s Cartesian coordinates (take the center scanning point as origin of coordinates) to polar coordinates, the distribution of each point’s SNR value in the whole scanning area has been shown in Fig.10. From Fig.10, it is found that most points’ SNR value is distributed around 135°/-45° and less is around 45°/-135°, so SNR value is able to describe several characteristics of the directions of layups.

It is hard to distinguish the delamination edge obviously from Fig.9. Therefore, incident wave energy is applied to determine the delamination edge as shown in Fig.11. Area inside the two lines is the delamination area, and this method presents a relatively good result.

Theoretical derivation and numerical simulation are not suitable to analyze wave propagation conditions in composite laminates because of composites’ anisotropy, properties and various directions of layups. An improvement based on sensor arrangement is proposed to combine sensors as line arrays to eliminate the changing wave intensity in different direction. The concrete configuration is shown in Fig.12. In actual experiment, four independent sensors of which distance between the adjacent sensors is 20mm are placed in a line to construct the sensor arrays.

Similarly, incident wave energy graphs of four different sensors are visualized in Fig.13. It is observed that the energy graphs shift from left to right as sensors’ position shifts. four energy graphs are averaged to get an energy graph as shown in Fig.14, which almost eliminates the directivity in composites and detects the delamination clearer than each single energy graph.
To prove the validity and accuracy of this method in delamination detection, the immersion ultrasonic C scan result is presented as a comparison, which is shown in Fig.15. Comparing with Fig.14 and Fig.15, we can find that delamination area detected by laser ultrasonic technology is a little bit smaller than immersion ultrasonic C scan, while the shape of delamination is similar to C scan graph. Therefore, laser ultrasonic technology performs well in locating the size and shape of delamination in CFRP T-joint.

![Fig.14 averaged energy graph](image1.png) ![Fig.15 C scan TOF graph](image2.png)

**4. Conclusions**

This paper studied the application of laser ultrasonic technology in delamination detection in CFRP T-joint. Laser was used to excite ultrasonic waves in the skin surface of T-joint and an AE sensor was used to acquire wavefield data from skin surface. Then wavefield images could be reconstructed by acoustic reciprocity theorem and wave propagation routes can be visualized. After comprehending the propagation form of wave in T-joint, the incident wave energy estimation was proposed to visualize the delamination area. Furthermore, a compensation method is proposed to eliminate the influence of anisotropy in composites, making the edge of delamination clearer. Finally, immersion ultrasonic C scan result was compared to confirm the validity and accuracy of the proposed method in detecting the delamination in CFRP T-joint.

**References**

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