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Application of laser ultrasonic technique for non-contact detection of drilling-induced delamination in aeronautical composite components

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ABSTRACT

The detection of drilling-induced delamination in composite components is a vital and challenging task in aviation industry. Numerous key components of aircrafts are made of composite materials, and drilling is often a final operation during assembly. Drilling-induced delamination is a very serious defect that significantly reduces the structural reliability, but it is rather difficult to be detected effectively due to its special location. A novel application of laser ultrasonic technique for the detection of drilling-induced delamination in composites is presented in this paper. A carbon fiber reinforced plastic laminate with drilling holes was made as specimen. A laser ultrasonic system was constructed and experiments were performed to detect the drilling-induced delamination, based on propagation characteristic of ultrasonic waves generated by pulse laser with a wavelength of 1064 nm and pulse duration of 10 ns. A laser interferometer based on two wave mixing is used to measure ultrasonic wave signals, and the morphology features of the delamination are imaged clearly by laser ultrasonic C-scan testing. The results proved that the laser ultrasonic technique is a feasible and effective method for the detection of drilling-induced delamination in composite components.

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1. Introduction

Fiber reinforced composites (e.g. carbon fiber reinforced plastics CFRPs) have become one of the most important structural materials in aviation industry, because of their excellent mechanical properties such as high specific stiffness and anti-fatigue [1]. Numerous key components of aircrafts are made of composite materials at present, including tail planes, center wing boxes, stringers, ribs and et al. Drilling is often a final operation during the assembly process of these components, and some kinds of defects such as delamination, fiber pullout, micro cracking are introduced after drilling [2]. Drilling-induced delamination is the most critical defect, which significantly reduces the bearing strength and fatigue life of composite components, and has the potential for long-term performance deterioration [2–4]. Although the drilling-induced delamination has serious influence on the performance of composite components, it is rather difficult to be detected effectively. With increasing application of composite components, over 50 million holes are drilled per year. The influence of drilling quality on aircraft safety is expanding, and the detection of the drilling-induced delamination is already a vital and challenging task in aviation industry [5].

Nondestructive testing of composite components to obtain the morphology features of drilling-induced delamination is highly desirable in aviation industry, and ultrasonic testing has been widely used for this purpose [5]. But due to the usage of coupling agents (e.g. water immersion ultrasonic testing), ultrasonic waves suffer from diffraction and result in blind detecting areas near the edge of drilling hole, and the on-site detection with portable ultrasonic detector is ineffective due to the low-resolution of ultrasonic transducers at the edge region of drilling hole. X-ray tomography is capable of detecting drilling-induced delamination in composite components [5,6], but it is harmful to health and inefficient for the testing of components with large dimension and complex shape. Visual inspection can only be used to measure the surface delamination in some cases [5–7]. Therefore, the effective detection of drilling-induced delamination in composite components is a burning problem needs to be solved in aviation industry.

The laser ultrasonic technique uses lasers instead of transducers to generate and receive ultrasonic waves remotely, and has opened a new area of research making possible effective detection of special structural regions that are difficult to detect. It possesses enormous advantages such as non-contact (no coupling agent is needed), high sensitivity and resolution, remote detection, on-site

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detection, the ability to detect near holes and edges, rapid testing of complex structures [8–10]. Some researchers have investigated the detection of composite components with laser ultrasonics, and recently an advanced laser ultrasonic testing system which is capable of detecting large composite components on site was developed and taken specifically to promote the wide-scale adoption of the laser ultrasonic testing technique by the aviation industry [8–12]. But the detection of drilling-induced delamination in composite components with laser ultrasonics has not been well developed.

This paper presents a novel application of the laser ultrasonic technique for the detection of drilling-induced delamination in composite components. A carbon fiber reinforced plastic laminate with drilling holes was made as specimen. A laser ultrasonic system was constructed and experiments were performed to detect the drilling-induced delamination, based on propagation characteristic of ultrasonic waves generated by pulse laser with a wavelength of 1064 nm and pulse duration of 10 ns. A laser interferometer based on two wave mixing is used to measure ultrasonic wave signals, and the morphology features of the delamination are obtained by laser ultrasonic C-scan testing. The results proved that the laser ultrasonic technique is a feasible and effective method for the detection of drilling-induced delamination in composite components, which not only provide an effective solution for evaluating the drilling quality but also promote the application of the laser ultrasonic testing technique in aviation industry.

2. Theory

Thermal elastic effect is the dominant mechanism used for the generation of laser ultrasonic waves in NDT. The thermal elastic mechanism is formed as the composite material is illuminated by a pulse laser with power density lower than the ablation threshold of the material. During the illumination process, part of the laser energy is absorbed by the material and result in local thermal expansion, which is the source of elastic waves. The thermo elastic mechanism can be described by the thermal conduction and thermal-elastic equation:

$$K\nabla^2 T - \frac{\rho C \partial T}{\partial t} = -q \quad (1)$$

$$(\lambda + 2\mu)\nabla(\nabla \cdot U) - \mu\nabla \times \nabla \times U - \frac{\rho \partial^2 U}{\partial t^2} = \alpha(3\lambda + 2\mu)\nabla T \quad (2)$$

where K is the thermal conductive coefficient, T is the temperature distribution, ρ is the density, C is the thermal capacity, and q is heat source; λ and μ are the Lame constants, U is the displacement, and α is the thermal expansion.

3. Specimen and experimental setup

3.1. Specimen

A CFRP composite laminate (HT3/NY9200G) was made by autoclave molding. The dimension of the composite laminate is 100 mm × 50 mm × 7.5 mm, and the stack sequence was $[\pm 45]_{25}$. Drilling processes were conducted on the laminate, and the drilling holes are numbered form 1 to 5. Visible internal delamination (more than 1 mm in length and about 0.5 mm thickness) is artificially made around hole 3, and it can be regarded as drilling-induced delamination. Fig. 1 shows the schematic of the specimen.

3.2. Experimental setup

A laboratory prototype of laser ultrasonic testing system was developed. A Nd:YAG pulsed laser (the wavelength is 1064 nm, the pulse duration is 10 ns, and the energy range is 0–20 mJ) was used

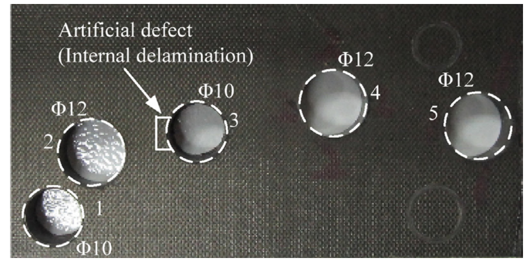

Fig. 1. Schematic diagram of the CFRP composite laminate with drilling holes and artificial defect.

to generate ultrasonic waves with characteristics of broadband and multi-mode. A laser interferometer which is sensitive to the out-of-plane displacement was used to receive the ultrasonic waves, and the instrument is equipped with a continuous laser (the wavelength is 1550 nm, and the power range is 0–0.5 mW) for the measurement. The received voltage signals from the laser interferometer were amplified by a preamplifier, processed by a band pass digital filter, and then recorded by a 10GS/s digital oscilloscope (Tektronix DPO7254C) and a 250MS/s DAQ card (NI-5114). A trigger signal synchronized with the laser source was used to trigger the digital oscilloscope and the DAQ card. The specimen was rested on a precise mechanical platform to accurately control the scanning point in the C-scan process. A control program for automatic detection was developed. The schematic of the laser ultrasonic system is shown in Fig. 2.

4. Results and discussion

4.1. Laser generated broadband ultrasonic waves in CFRP laminate

A pulse laser was shot on the surface of the CFRP specimen to excite ultrasonic waves. The laser energy was 1 mJ, the pulse width was 1×10^{-8} s, the radius of the laser spot was about 1.5 mm, and the spot was located at the edge of the hole. The surface of the specimen was not ablated and the waves were generated by the thermo elastic effect of the material. The laser interferometer (uses a continuous laser for measurement) was used to measure ultrasonic waves. The power of the continuous laser was adjusted to 0.1 mW to prevent ablation during the measurement, the spot diameter was about 100 μm, and the distance of the spot to the edge of the drilling hole was about 0.5 mm. The spots of the two lasers were overlapped on the surface of the specimen (for the measurement of longitudinal wave). Fig. 3 shows a typical measured time trace of the laser generated longitudinal wave and its frequency spectrum. It can be seen from the figure that the wave signal possesses the feature of broadband, and the signal to noise ratio is high enough. Although the low

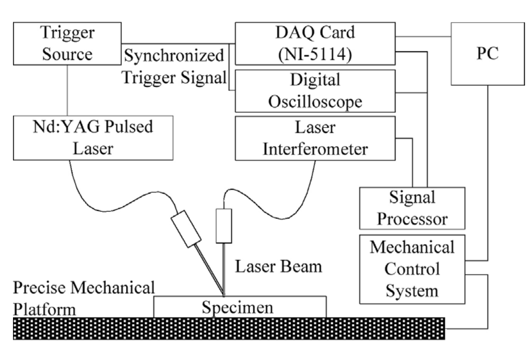

Fig. 2. Schematic diagram of the experimental setup used for detection of drilling-induced delamination.

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