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Non-contact detection of delamination in layered anisotropic composite materials with ultrasonic waves generated and detected by lasers

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ABSTRACT

This paper presents the non-contact detection of internal delamination in layered anisotropic composite material with ultrasonic waves generated by a pulse laser and received by a two-wave mixing laser interferometer. Three-dimensional finite element method is used to simulate the propagation of laser generated ultrasonic waves in carbon fiber reinforced plastics and the interaction with internal delamination. A composite laminate with simulated internal delamination is made as specimen, and a laser ultrasonic system for experiments is set up. The reflection and attenuation characteristics of laser ultrasonic induced by the internal delamination are analyzed theoretically and experimentally. The effects of measuring position and wave frequency on the detection of internal delamination are discussed, and suitable choices of the parameters of laser ultrasonic are suggested. The C-scan images of the composite specimen are obtained using the laser ultrasonic system. The results show that it is possible to decrease the influences of the layered anisotropic feature of composite materials on the detection of internal delamination by controlling the laser parameters.

1. Introduction

Carbon fiber reinforced plastic (CFRP) composite materials are increasingly widely used in aircraft manufacturing because of their excellent mechanical properties, such as high strength to weight ratio, anti-fatigue and so on [1–3]. In the new generation large aircrafts, such as Airbus A380 and Boeing B787, the weight percentage of composites is about 25% and 50% respectively, and quite a lot of primary structures are made of composites, e.g. center wing boxes, empennages and wing ribs, etc. Therefore, in order to ensure the aircraft safety, it is crucial to guarantee the integrity of the composite structures in the whole life cycle [1,3,4]. However, many types of defects may be introduced in the manufacturing or during the usage of these components, such as inclusions, voids, delamination, etc. The internal delamination is one of the most critical defects that seriously reduce the strength and fatigue life of composite components. Therefore, at present, the accurate detection and characterization of internal delamination in CFRP components is of great significance in the field of aircraft manufacturing [5–7].

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Various nondestructive testing methods have been used for the detection of defects in CFRP components, such as ultrasonic, radiography and infrared thermography, etc [5,8,9]. Among these methods, ultrasonic testing is one of the most efficient and widespread one. But with the fast-developing of composite technology, conventional ultrasonic methods have some limitations for the testing of composite structures, e.g. the rapid detection of the structures with complex shape, and the detection of the areas near holes or edges with high spatial resolution, etc [5,10]. Due to the above problems, the nondestructive testing of composite structures with laser ultrasonic attracts extensive attention in recent years [6,7,10]. The laser ultrasonic method uses lasers instead of transducers to generate and receive ultrasonic waves, it has some advantages such as being noncontact, having high sensitivity and resolution, being capable of rapid testing of complex-shaped structures, etc. So the laser ultrasonic method is efficient for the nondestructive testing of composite structures of the new generation aircrafts [10,11].

Many researchers have studied the propagation characteristics of laser generated ultrasonic waves, and the detection of internal delamination in composites with laser ultrasonic. In the early days, the generation mechanism and signal features of laser ultrasonic are investigated by White [12], Felix [13], Sanderson [14] and et al. Scudder et al. [15] experimentally measured the laser generated broadband ultrasonic pulses in a single plane defined by the fiber and through thickness directions, the ultrasonic modes generated by an ablative laser ultrasonic source are observed. Enguehard et al. [16] analyzed the effects of optical penetration and laser pulse duration on the features of the ultrasonic waves generated in a solid by a laser impact. Baldwin et al. [17] proposed a hybrid laser generation/air-coupled detection ultrasonic system, and proved that the system is sensitive to surface defects in composite materials. In recent years, Chia et al. [18] developed an anomalous wave propagation method with adjacent wave subtraction using laser ultrasonic scanning, and proved that it is suitable for nondestructive testing of complex composite structures. Zhenggan Z et al. realized the high precision detection of drilling-induced delamination in composites with ultrasonic waves generated and detected by lasers, and obtained the morphology features of the delamination by laser ultrasonic C scan imaging [11]. Park et al. [19] developed a noncontact laser ultrasonic wave field imaging method for delamination detection and visualization, and successfully visualized a delamination in a composite structure. In order to promote the widespread application of the laser ultrasonic technique in aeronautic industry, Dubois et al. [10] proposed a novel laser ultrasonic approach for the detection of complex composite structures, and realized typical ultrasonic C scan for composite components with a novel industrial laser ultrasonic testing system. As above, the previous works mainly focus on the generation of laser ultrasonic and the relative testing methods and systems, the special layered anisotropic property of CFRP composites and its influences on defect detection have not been well studied. Therefore, now in industrial applications for high precision detection of small delamination in key composite structures using laser detector with micron-grade laser spot, the layered anisotropic property of composites will seriously affect the correctness and accuracy of the detection of defects with laser ultrasonic. It is a pressing problem need to be solved in aircraft manufacturing industry.

Different from the previous works, this paper investigates the influences of the layered anisotropic characteristic of carbon fiber reinforced plastics on the detection of internal delamination with ultrasonic waves generated by a pulse laser and detected by a two-wave mixing laser interferometer with micro-grade laser spot, and the appropriate testing parameters are analyzed. The outline of the paper is as follows. The three-dimensional (3D) finite element (FE) method for the simulation of laser ultrasonic, and the FE models for layered anisotropic materials are described in Section 2. The experimental setup and specimen are presented in Section 3. Results and discussion and conclusions are elucidated in Section 4 and Section 5, respectively.

2. 3D FE model

2.1. FE method

The three-dimensional finite element method is used to simulate the propagation and defect interaction of laser generated ultrasonic waves in layered anisotropic composite materials [20,21]. According to the laser-induced thermoelastic mechanism, during the thermoelastic generation and propagation of elastic waves, the coupling of the thermal and elastic effect can be described by the thermal conduction and thermoelastic equation, and the relative FE equations can be expressed as:

$$[K]\left\{T\right\}+[C]\left\{\dot{T}\right\}=\left\{R_q\right\}+\left\{R_Q\right\} \tag{1}$$

$$[M]\left\{\ddot{U}\right\}+[K]\left\{U\right\}=\left\{R_{ext}\right\} \tag{2}$$

where $[K]$ is conductivity matrix, $\{T\}$ is temperature vector, $[C]$ is heat capacity matrix, $\{\dot{T}\}$ is temperature rise rate vector, $\{R_q\}$ is heat flux vector, $\{R_Q\}$ is heat source vector; $[M]$ is mass matrix, $\{U\}$ is displacement vector, $\{\ddot{U}\}$ is acceleration vector, $\{R_{ext}\}$ is external force vector. For thermoelastic analysis, the external force vector $\{R_{ext}\}$ for an element is

$$\int_{V_e}[B]^T[E]\{\varepsilon_0\}dV \tag{3}$$