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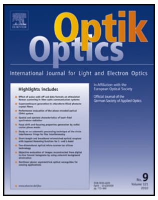

Development of an optical fiber-guided robotic laser ultrasonic system for aeronautical composite structure testing

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ABSTRACT

This paper proposes a novel all optical fiber-guided robotic laser ultrasonic system for nondestructive testing of aeronautical composite structures. A 1064 nm Nd:YAG pulse laser coupled with an optical fiber is used to generate ultrasonic signals, and a laser interferometer based on two-wave mixing in photorefractive polymers is used to measure the signals. A precise six-axis articulated robot is used as the scanning mechanism for laser ultrasonic imaging of defects in composite structures. A composite specimen with simulated internal delamination and another one with impact damage are prepared for experiments. The broadband ultrasonic signals generated by the pulse laser are measured by the laser interferometer, the signal to noise ratio is improved by a preamplifier and the narrowband signals in specific frequency ranges are extracted by a filter. The reflection and attenuation of laser ultrasonic signals induced by structure defects are monitored based on the pulse echo method. Typical C-scan imaging of the composite specimens with preset defects are realized using the fiber-guided laser ultrasonic system, and the shape, size and location of the defects are imaged clearly. The results proved that the proposed optical fiber-guided robotic laser ultrasonic system is effective for the nondestructive testing of composite structures.

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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, 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. These kinds of defects will seriously reduce the strength and fatigue life of composite structures. Therefore, at present, the accurate detection of various defects in CFRP components is of great significance in the field of aircraft manufacturing [5–7].

Various nondestructive testing methods have been used for the detection of defects in CFRP components, such as ultrasonic, radiography, 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].

However, until now, laser ultrasonic testing has failed to achieve a widespread adoption into the aviation manufacturing industry [10]. During the past 30 years, several types of laser ultrasonic system are developed for industrial application [10–13]. In 1983, general dynamics initiated a development program on laser

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ultrasonic system, and a fully functional laboratory prototype was built. Then the testing of composite structures using laser ultrasonic was demonstrated in the late 1980s [10]. In 1997, an industrial-scale laser ultrasonic system was built and then introduced into production by Lockheed Martin, and over 20,000 composite structures are inspected [13]. In parallel, Rockwell International Science Center investigated laser ultrasonic for the testing of composite structures, but stopped work in the late 1990s without any application of the technology [10]. In the mid-1990s, a laser ultrasonic inspection system (LUIS) was developed by the National Research Council of Canada and provided to Dassault-Aerospatiale for the testing of composite structures of aircrafts [10]. Between 2000 and 2005, a 4-year European project included the development of a laser ultrasonic prototype, but the prototype never resulted in any industrial deployment [10]. In 2005, a 5-year program was initiated to develop the technologies of laser ultrasonic system by Lockheed Martin, including CO_2 laser lifespan improvement, new generation laser, new detection laser, and new robotic approach [13]. The aim of this program is to have those technologies available at the beginning of 2010 [13]. Then after that, an industrial laser ultrasonic system (iPLUS) was developed in 2010 [10,13], it consists of a military level CO_2 pulse laser coupled with an articulated beam delivery system for the generation of ultrasonic signals, an improved dual-cavity CFP interferometer coupled with a fiber laser for signal measurement, a six-axis articulated robot for positioning and a precise optical scanner for imaging of composite structures, etc. [10]. The system provides high level of reliability, performance and flexibility, but it is too expansive and still trying to minimize cost. Thus laser ultrasonic testing has not been widely applied as yet. In order to promote wide-scale adoption of laser ultrasonic systems, Dubois and Drake [10] analyzed the major limiting factors and proposed that the laser ultrasonic system will achieve a widespread adoption into the aviation manufacturing industry only if the acquisition cost, reliability, performance and flexibility are simultaneously addressed.

Considering the above factors limiting the widespread adoption of laser ultrasonic testing, this paper develops a novel prototype of optical fiber-guided robotic laser ultrasonic system based on four points [10–14]: (1) Low acquisition cost. (2) Adequate performance. (3) More flexible. (4) More reliable. The outline of the paper is as follows. The optical fiber-guided laser ultrasonic generation, measurement and robotic scanning system, etc. are described in Section 2. Application tests are then followed, the ultrasonic signals generated by a 1064 nm Nd:YAG pulse laser and measured by a two-wave mixing laser interferometer are presented in Section 3. The imaging of internal delamination and impact damage in carbon fiber reinforced plastics are carried out in Section 4. Conclusions and future work are elucidated in Section 5.

2. Optical fiber-guided laser ultrasonic generation, measurement and robotic scanning system

The schematic diagram of the proposed optical fiber-guided robotic laser ultrasonic system is shown in Fig. 1. For the generation of ultrasonics signals, a pulse laser coupled with an optical fiber and a focusing module is used. One end of the optical fiber is connected to the pulse laser, and the other end is connected to the focusing module. The exciting laser beam is transmitted through the optical fiber with little power loss, emitted at the output port of the focusing module, and focused on the target surface. The spot size of the laser beam can be adjusted by changing the focusing lens set in the focusing module. For the measurement of ultrasonic signals, a laser interferometer coupled with an optical fiber-guided laser and a focusing module, etc. are used. The transmission and focusing mode of the measurement laser beam is similar to the one used for the exciting laser beam. The measured signals are processed by a preamplifier and filter to improve the signal to noise ratio and extract narrowband signals in specific frequency range. The processed signals are collected using a DAQ card installed on an industrial control computer. For the scanning of composite structures with laser ultrasonic, a precise six-axis articulated robot system is used as scanning mechanism and the scanning process is controlled by a C-scan program. Two 3D micro-displacement platforms are fixed on a panel and the panel is mounted on the joint end of the robot. The focusing modules of the exciting and measurement laser are fixed on the micro-displacement platforms respectively, thus the focusing position of laser spots on target surface can be adjusted precisely before robotic scanning. During the scanning process, the relative position of the exciting and measurement laser spot is kept constant, and the measurement laser beam is directed essentially normal to the target surface, which are performed by robotic control of the laser spot position and beam direction. The robotic scanning trajectory can be generated from the Computer-Aided-Design (CAD) of the target, 3D laser scanning for target surface mapping, or point to point manual teaching and automatic interpolation.

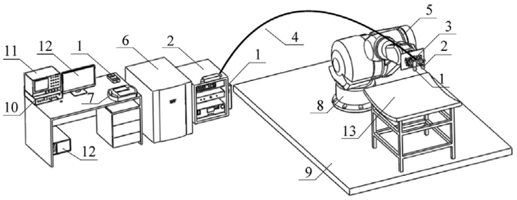

Fig. 1. Schematic diagram of optical fiber-guided robotic laser ultrasonic system.

As described above, it can be seen that the proposed system eliminates the optical scanner that typically used by previous systems for high efficient target scanning, and adopts a six-axis articulated robot as the scanning mechanism. This approach makes the laser ultrasonic system more low-cost, reliable and flexible, and the general demands for testing efficiency can be satisfied. For the specific testing demands of large scale composite structures, the high speed guide rail can be integrated into the robot system, thus improving the scanning range and efficiency. In addition to this, the type of the pulse laser for signal generation and the laser interferometer for signal measurement is different from the types generally used by previous systems. Thus, the all optical fiber transmission of the generation and measurement laser is realized, which reduces the acquisition cost and improves the reliability of the system. The specific types and parameters of the major devices integrated into the prototype of the laser ultrasonic system are described as follows.

In this study, different from the previous laser ultrasonic systems that use CO_2 pulse laser to excite thermoelastic waves in composites, a military level Nd:YAG pulse laser (Quantel, Ultra 20) is used for the generation of ultrasonic signals, which is of low cost, easy to get, and more reliable. The wavelength of the pulse laser is 1064 nm, the pulse duration is 10 ns, and the pulse energy is adjustable and in the range of 0–20 mJ. A metal-tubed step index multimode fiber with 2000 μm core diameter is used to carry the laser beam from the laser source to the focusing module. The focused diameter of the pulse laser emitted from the output port of the focusing module is 3 mm, and it can be adjusted by using different focusing lens. A new developed commercial product of laser interferometer based on two wave mixing is used as the core device of the laser ultrasonic receiver (Intelligent Optical Systems Inc., LUKS-1550-TWM). The principle of the device is it uses real-time holography in a photorefractive material to combine a distorted measurement beam with a plane-wave reference beam and match their wave fronts for homodyne detection [15]. The hologram in

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