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Composite repair patch evaluation using pulse-echo laser ultrasonic correlation mapping method

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ABSTRACT

Composite patch bonding repair is widely applied to metal and composite aircraft repair owing to its light weight and high resistance to fatigue and corrosion. However, composite patch repairing is done by vacuum bag processing in general, and the process itself is susceptible to manufacturing defects. In addition, the composite repair patches require more frequent inspections owing to the difficulty of the damage prediction. In this paper, we propose pulse-echo laser ultrasonic correlation mapping for a rapid quality evaluation method of composite repair patching. This method uses a pulse-echo ultrasonic propagation imaging system as a tool for in-situ and full-field inspection, and an ultrasonic correlation mapping (UCM) method was developed for fast and straightforward defect visualization. Two composite patch repair specimens were tested, and then UCM results were compared with other results using existing visualization methods. We also tested a composite laminate plate to verify the applicability of UCM to general composite parts. The UCM results showed similar or better performance than current visualization methods in all cases. Test results showed that the proposed system is suitable for both in-process quality evaluation and in-service field inspection.

1. Introduction

Composite patch bonding repair has been studied and applied as an alternative method for conventional metallic patch fastening repair owing to its light weight and high resistance to fatigue and corrosion [1–7]. Composite patch bonding repair has been regarded as an optimal way for repairing where machining of additional fastener holes is impossible or when reducing aerodynamic drag is essential, as with external skins. However, the composite patch bonding repair process is more complicated than conventional metallic fastening repair, and the repair process itself is susceptible to manufacturing defects owing to incomplete surface treatment or improper temperature and pressure control. In addition, composite repair patches are always exposed to impact damage from foreign objects during ground handling and in flight. For this reason, the composite repair patch requires stringent quality evaluation from the repair-application phase to the operational phase.

Because an accurate and effective nondestructive inspection is necessary for quality evaluation, various research studies have developed inspection methods for composite repair patches [8–13]. However, most previous studies focused on the detectability of defects in composite repair patches and did not address issues that are usually considered critical in the operational phase. From a practical point of view, the biggest concern about the inspection of a composite repair patch in the operational phase is that the entire repair patch must be inspected at a relatively short inspection interval. This is because delamination or debonding defects can occur in any area of the composite repair patch, and it is difficult to predict the initiation and growth of these defects. For example, a repair patch applied to the lower wing skin of an Australian Defense Force F-111C was inspected every 100 h [14], which was a very short inspection interval compared to those for metallic or general composite parts. These frequent inspections of the entire patch area are the main cause of increasing aircraft downtime. Therefore, the inspection method for the composite repair patch should be able to conduct a rapid inspection for an entire patch with high detectability.

To achieve the rapid inspection of an entire patch, the inspection method for the composite repair patch needs to satisfy the following conditions. First, it should be an in-situ inspection method. In many cases, in order to inspect a part of an in-service aircraft, the part must be disassembled from the aircraft and reassembled after inspection. In actual inspection, it takes a long time to disassemble and reassemble before and after inspection, and it takes more time if the inspected part is connected to many other parts. Second, full-field inspection has to be

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possible. Because delamination and debonding defects can occur in any area of the repair patch, the entire area of the patch should be inspected at one time. Finally, interpretation and evaluation of the inspection results should be done quickly. Usually, inspectors spend considerable time and effort for both the interpretation and evaluation of inspection results, and this also increases the inspection time.

In this paper, pulse-echo laser ultrasonic correlation mapping is proposed for a composite repair patch inspection method. It consists of a pulse-echo ultrasonic propagation imaging (PE-UPI) system for in-situ and full-field inspection, and an ultrasonic correlation mapping (UCM) for rapid inspection result evaluation. In Section 2, a brief introduction of the PE-UPI system and its conventional inspection result visualization methods are presented. In Section 3, the basic idea and algorithm of the UCM method are explained with an example. Section 4 presents the application results of UCM in composite specimens, and the UCM results are compared with the results of conventional methods of the PE-UPI system.

2. Pulse-echo ultrasonic propagation imaging system and its visualization methods

2.1. Pulse-echo ultrasonic propagation imaging system

Inspection methods for composite patches that require frequent inspections should be the in-situ and full-field inspections. The pulse-echo ultrasonic propagation imaging (PE-UPI) system is a laser-ultrasonic-based inspection system that is capable of in-situ and full-field inspections [15]. Laser ultrasonic is an advanced nondestructive testing method that uses a pulsed laser or Q-switched laser to generate ultrasonic waves in a remote and noncontact manner. At the same time, both excitation and sensing of the PE-UPI are performed on a single side of the structure, so in-situ inspection is possible. Fig. 1 shows the configuration and scanning mechanism of the PE-UPI system. A scanning head consists of two lasers for excitation and sensing, and it is mounted on a two-axis translation stage. This stage allows the inspector to automatically scan the entire inspection area. The inspection speed is 1600 points per second at a scan interval of 0.25 mm (2500 points per second for 0.1 mm).

2.2. Conventional inspection result visualization methods of PE-UPI

Scanned signals are visualized and interpreted to evaluate the inspection result. If the interpretation of the signal is not accurate, a defect can be missed. Therefore, the interpretation and visualization of the scanned signal is an important step in in-situ nondestructive inspection, and this process should be done by trained and qualified personnel. In addition, inspectors spend considerable time and effort during this process to make a correct decision. Therefore, we proposed ultrasonic correlation mapping (UCM) for a rapid inspection result evaluation that is appropriate for in-situ applications. This will be covered in Section 3. Then, the UCM results will be compared with conventional ultrasonic-wave-propagation images. Before that, we will briefly discuss the conventional visualization methods of PE-UPI.

The fundamental visualization method of the PE-UPI inspection is ultrasonic wave propagation imaging (UWPI). UWPI is a visualization technique that represents the state of ultrasonic wave propagation over time in the entire scan area [16]. Ultrasound signals at each point obtained through PE-UPI are composed in the form of a three-dimensional matrix. This can be expressed as

$$S(t)_{i,j} = \begin{bmatrix} s(t)_{1,1} & \cdots & s(t)_{1,j} \\ \vdots & \ddots & \vdots \\ s(t)_{i,1} & \cdots & s(t)_{i,j} \end{bmatrix} \tag{1}$$

where $s(t)_{i,j}$ is a time domain signal at i th and j th scanning points. From this matrix, scanning area size images corresponding to each time slice t can be obtained. UWPI connects these images and provides a video-type inspection result to inspectors. Using this video, the inspector can review the propagation state of the ultrasound wave according to time. Fig. 2(a) shows a schematic diagram of the UWPI algorithm.

Variable time window amplitude mapping (VTWAM) is a visualization method that complements UWPI. In fact, defects continue to appear in several frames in a UWPI video, i.e., in a specific time window. VTWAM combines signal components in this time window into a single image to make defects stand out [17]. A VTWAM image can be obtained using Eq. (2):

$$a_{i,j} = \sum_{t_s}^{t_e} |s(t)_{i,j}| \tag{2}$$

where t_s and t_e are the start and end times of the selected time window, and $a_{i,j}$ is an absolute summation value of the signal components within a selected time window at the i th and j th scanning points. Fig. 2(b) shows a schematic diagram of VTWAM.

3. Ultrasonic correlation mapping

Ultrasonic wave propagation imaging (UWPI) and variable time window amplitude mapping (VTWAM) are very intuitive compared to the typical C-scan representation, and enable the user to detect defects more easily. However, when evaluating the UWPI inspection result, it is necessary to review all of the ultrasonic propagation images over time, and the freeze frame that best represents the defect is selected after several reviews. Therefore, it takes considerable time to evaluate the inspection results. In addition, in the case of VTWAM, the inspector should make many attempts to select the best time window. Hence, the inspector should have to spend more time on the evaluation. Ultrasonic correlation mapping (UCM) uses the entire time-domain signal to distinguish defects so it can eliminate the burden of reviewing each time-

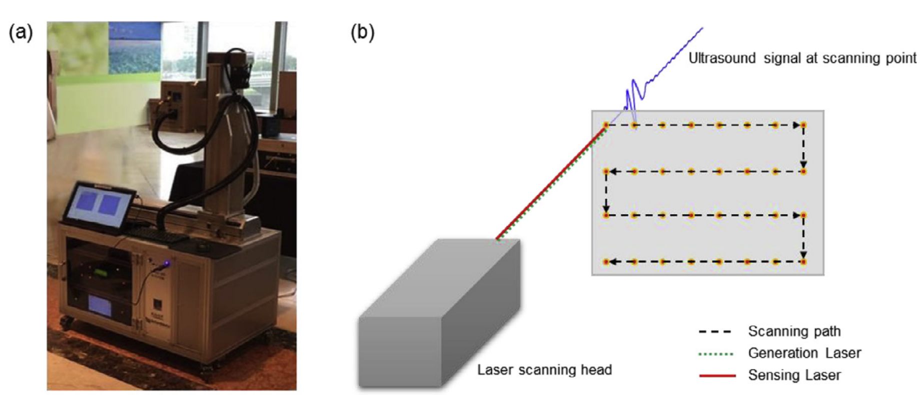

Fig. 1. (a) Pulse-echo ultrasonic propagation imager (X-NDT Inc.), (b) scanning mechanism.