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3D Surface Profile Construction and Flaw Detection in a Composite Structure

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The nondestructive method of evaluating material properties and structural integrity is built upon ultrasonic scanning, raw data acquisition and processing, coming from an ultrasonic transducer. Commercial software LabVIEW designed by National Instruments Inc. is aimed at processing ultrasonic images. An ultrasonic C-scan image system was developed. This system is capable of constructing a 3D surface profile and detecting flaws inside the composite structure. The technique for nondestructive inspection and geometry estimation is validated experimentally on an aluminum plate with small holes and composite structure with a delamination defect.

Keywords: ultrasonic signal processing, composite structure, flaw detection.

Introduction. Ultrasonic testing has been used widely in nondestructive evaluation to characterize material properties and detect the flaws. Ultrasonic scanning in conjunction with signal processing technology can provide high resolution of the ultrasonic images, hence improve the defect characterization performance. Ultrasonic testing is based on the detection and interpretation of the ultrasonic echoes reflected by defects. Many signal processing technologies have been utilized for flaw detection, e.g., split spectrum processing (SSP) [1], expectation maximization (EM) [2] and wavelet transform (WT) [3]. Hunter et al. [4] presented a post-processing autofocus algorithm for flexible ultrasonic arrays based on image sharpness optimisation. Kim [5] employed the least mean square (LMS) method and expectation maximization (EM) algorithm to detect cracks within steam generator tubes. Benammar et al. [6] used split spectrum processing (SSP) and expectation maximization (EM) to inspect the delamination in carbon fiber reinforced composites. Ruiz-Reyes et al. [7] proposed a new high resolution pursuit (HRP) based signal processing method for detecting flaws close to the surface of strongly scattering materials. Chaki and Bourse [8] employed guided ultrasonic waves for non-destructive monitoring of the stress levels in prestressed steel strands. Karabutov et al. [9] developed a novel laser ultrasonic method for residual stress measurements in welds. Bettayeb et al. [10] improved the time resolution and signal noise ratio of ultrasonic testing of welds by the wavelet packet. De Araújo Freitas et al. [11] presented a reliable and fast nondestructive characterization of microstructural and elastic properties of plain carbon steel, based on ultrasonic measurements for ultrasonic velocity and attenuation. Hassan and Jones [12] used the ultrasonic pulse velocity and resonant frequency methods to determine the modulus of elasticity and Poisson's ratio of ultra high performance fibre reinforced concrete. Mahmoud et al. [13] utilized surface acoustic waves (SAWs) for non-destructive structural health monitoring of concrete specimens externally bonded with carbon fiber-reinforced polymer (CFRP) composites and subjected to accelerated aging conditions.

In general, there are three stages to construct ultrasonic images [14]: pre-processing (signal dynamic range and interpolation); acquisition of ultrasonic signals; post-processing (formation and display of the ultrasonic images). Custom-built ultrasonic system is directly implemented in special purpose. It is expensive in design time and has limit flexibility. The limitation of currently available commercial ultrasonic system by no means depends on the hardware, but on the lack of advanced software to process and explain the detected signals [15]. LabVIEW developed by National Instruments Inc., a well-known and user-friendly software, has been extensively used in signal processing. It provides all kinds of signal processing routines to manipulate and interpret signals, analyze its spectrum and phase spectrum. In this work, the design and development of an open and flexible ultrasonic C-scan system is presented. The system utilizes LabVIEW to conduct the post-processing and display the ultrasonic images. The proposed methodology offers better opportunity for making the system more cost-effective, flexible, fast, and accurate. The system is validated experimentally using an aluminum plate with small holes and composite materials with delamination defect.

1. **Physical Model of Ultrasonic C-Scan System**. In this work, the pulse-echo mode of the ultrasonic technique is implemented using a laboratory-made ultrasonic scan system to generate the three-dimensional surface profiles and cross-sectional profiles. The pulse-echo mode has the advantage of simplicity because it uses only one transducer and the scan is made on one side. The equipment for the C-scan system includes an ultrasonic pulse/receiver to generate ultrasonic waveform (Panametrics 5073PR), a transducer (Panametrics V311) which can emit and receive ultrasonic waves, an oscilloscope (LeCroy 9310) to transform analog signals into digital signals, a GPIB card to transmit the digital signals to computer, a personal computer equipped with LabVIEW software package, stepping motor with motion control card, an acrylic water tank. Figure 1 illustrates the schematic model of the ultrasonic C-scan system. Figure 2 shows the experimental setup of the ultrasonic C-scan system. The probe moves at a step size of 0.5 mm in both x and y directions. In every position, the probe emits an ultrasonic wave through the water into the test specimen as shown in Fig. 3. Two waves reflected from the front and back surfaces of the specimen are received by the transducer. Figure 4 shows the reflected waveforms recorded by a digital oscilloscope. The thickness of the specimen at this particular location can be calculated as follows:

$$t = (P_2 - P_1)V/2, \tag{1}$$

where P_1 and P_2 are the arrival time of the waves reflected from the front and back surfaces, respectively, and V is the velocity of the ultrasonic wave in the test specimen.

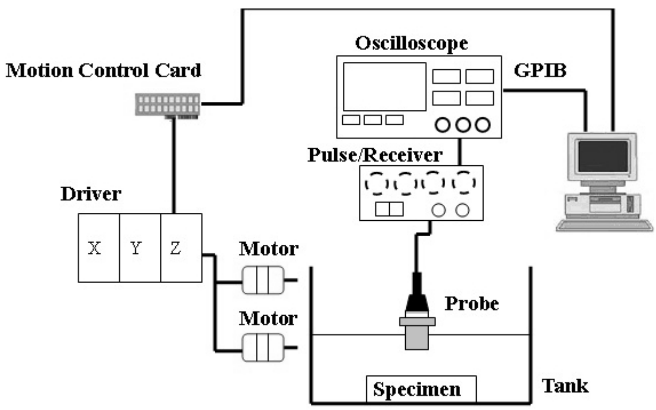

Fig. 1. Ultrasonic C-scan system.

Incorporating the position (x and y coordinates) and thickness (z coordinate), we are able to construct the three-dimensional profile of the specimen. For a specimen with internal defects, an additional waveform reflected from the defect can be found as shown in Fig. 5. The depth of the defect in the specimen is obtained using the following equation:

$$d = (P_3 - P_1)V/2, \tag{2}$$

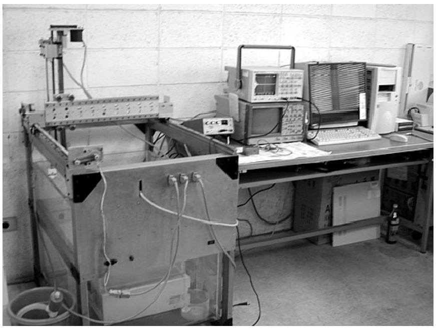

Fig. 2. Experimental setup of the ultrasonic C-scan system.

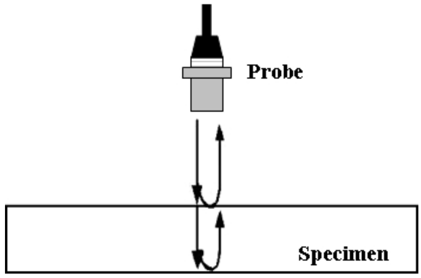

Fig. 3. Ultrasonic wave emitted from the probe.

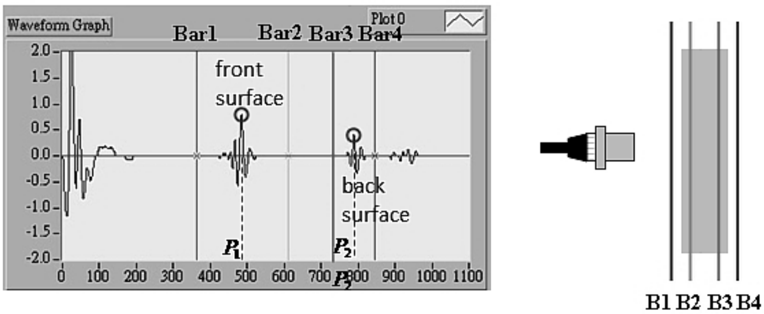

Fig. 4. Waves reflected from the front and back surfaces.

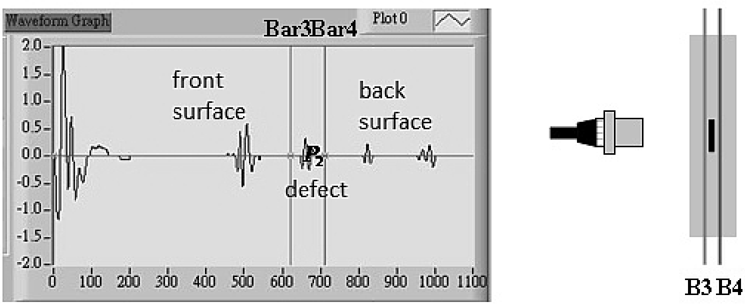

Fig. 5. Waves reflected from the front, defect and back surfaces.

where P_3 is the arrival time of the wave reflected from the defect. The image of internal defect can be displayed using the cross-sectional profile at the particular depth.

The above two equations are used to determine the thickness and depth of the defect. Based on the same process, images of sample's three-dimensional profile and internal defect can be generated by scanning the transducer and collecting data at different locations.

2. **Experimental Testing Results**. The experimental setup for the laboratory-made ultrasonic C-scan system is shown in Fig. 2. The system is operated in pulse-echo mode with one transducer served both as the transmitter and as the receiver. Ultrasonic pulses are generated and received with a Panametrics 5073PR. The received signals are digitized with a Lecroy 9310 oscilloscope and are transmitted through the GPIB interface to a personal computer. The sampling rate is 100 MHz. The C-scan system is performed under water environment with a spherically focused transducer (Panametrics V311, 10 MHz central

frequency, 12.7 mm in diameter and 101.6 mm in focal length) at a step size of 0.5 mm in both x and y directions. The obtained signals are processed and plotted using the LabVIEW software package (National Instruments Inc.). In the following, the capability of the proposed C-scan system to generate high resolution of three-dimensional profiles and cross-sectional profiles was demonstrated using three aluminum samples with surface features and internal defects.

2.1. ***Aluminum Plate with Circular Holes***. An aluminum plate is machined with the dimensions of $60\times30\times10.3$ mm. The sample contains three holes with the same diameter of 12 mm and different depths of 7.16, 5.1, and 3.44 mm, respectively, as shown in Fig. 6. The velocity of the longitudinal wave in the sample is 6358 m/s. Figure 7 illustrates the display panel from LabVIEW software for thickness measurement. The display can be divided into five regions. Region A shows scanning parameters including scan area, sampling rate, step size, and wave velocity. Region B is the start button. Region C is designed to move the cursor to a specific point in the sample. Region D displays the reflected waveforms of the specific point chosen in region C. Region E plots the three-dimensional profile of the sample. The three-dimensional and cross-sectional images of the test sample are shown in Fig. 8. It can be seen that these three holes are clearly distinguishable from one to another with different depths. The numerical values of the diameter and depth for these three holes measured by the C-scan system are listed in Table 1. It shows that the experimental results are in good agreement with the exact values with error less than 2%. The experimental test results demonstrate that the proposed C-scan system can provide high-quality images with accurate results.

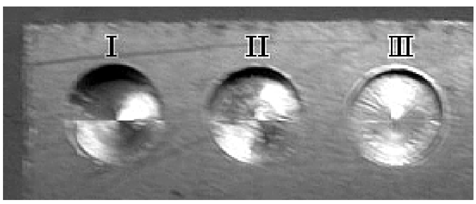

Fig. 6. Aluminum plate contains three holes with various depth.

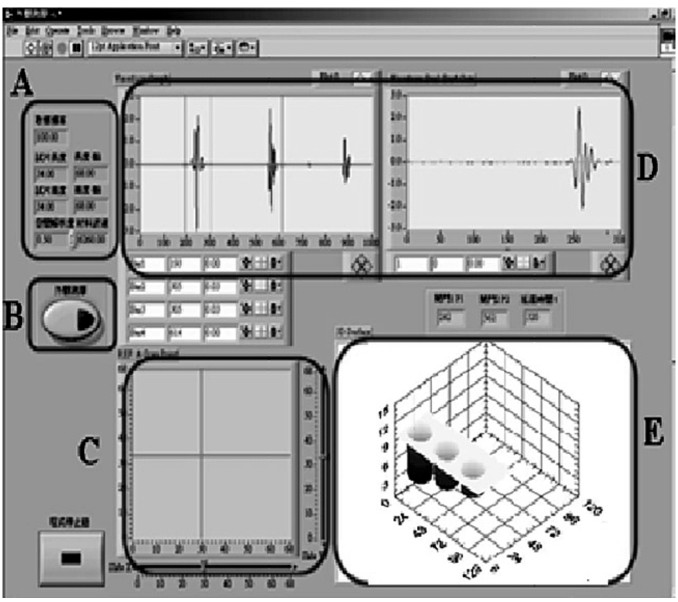

Fig. 7. Display panel for thickness measurement provided by LabVIEW.

Table 1

Experimental Results of the Diameter and Depth of the Holes (unit: mm)

Characteristic	Hole I		Hole II		Hole III	
	diameter	depth	diameter	depth	diameter	depth
Measurement result	12.12	7.24	12.21	5.00	12.21	3.38
Error (%)	1.00	1.11	1.75	1.96	1.75	1.74

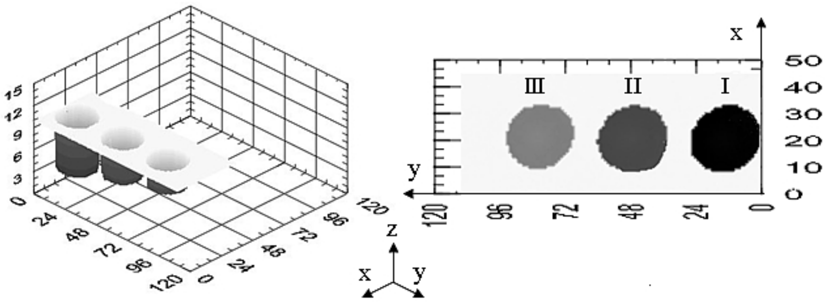

Fig. 8. 3D and cross-sectional profiles of an aluminum plate with three holes.

2.2. ***Aluminum Plate with Circular and Polygon Holes***. An aluminum plate with dimensions of 56×40×5 mm is used in the experimental test. The sample has a circular hole with diameter of 7 mm in the up right corner, and a polygon hole in the middle as shown in Fig. 9. The sample is inspected using the ultrasonic C-scan system. Figure 10 shows the three-dimensional profile and cross-sectional image of the test sample. The resulting surface contour image indicates that the sample has a small circular hole and a large polygon hole in the middle area. The location and size of the holes match well with the sample geometry.

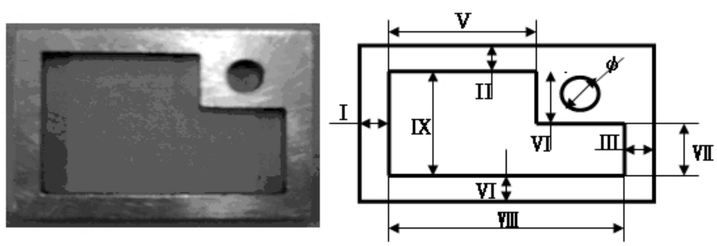

Fig. 9. Aluminum plate with circular and polygon holes.

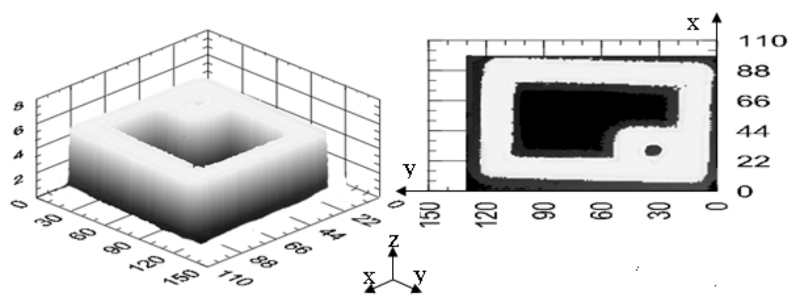

Fig. 10. 3D and cross-sectional profiles of an aluminum plate with circular and polygon holes.

2.3. ***Composite Structure with Delamination Defect***. A composite structure containing a hidden artificial defect is fabricated and scanned by ultrasonic waves to demonstrate the capability of the delamination defect detection. The specimen is prepared by gluing an aluminum plate to a copper plate with epoxy adhesive. The dimensions of the composite structure are: 50 mm in length, 45 mm in width, and 5 mm in thickness. During the specimen preparation, an approximately circular delaminated area of about 20 mm diameter was fabricated near the center of the aluminum/copper interface. This was accomplished by applying no epoxy to this region. Figure 11 shows the test specimen. After the specimen is fabricated, no defects could be visually detected. The delamination in such specimens was performed via the ultrasonic nondestructive evaluation technique. Figure 12 illustrates the display panel provided by the LabVIEW software for the defect detection. The software computes the maximum amplitude of the signal in the gate and then plots it in a grey scale with respect to the position (x, y) of the transducer. Figure 13 shows the cross-sectional image. The cross-sectional image obtained by the C-scan system presented in Fig. 13 matches well with the delamination defect shown in Fig. 14.

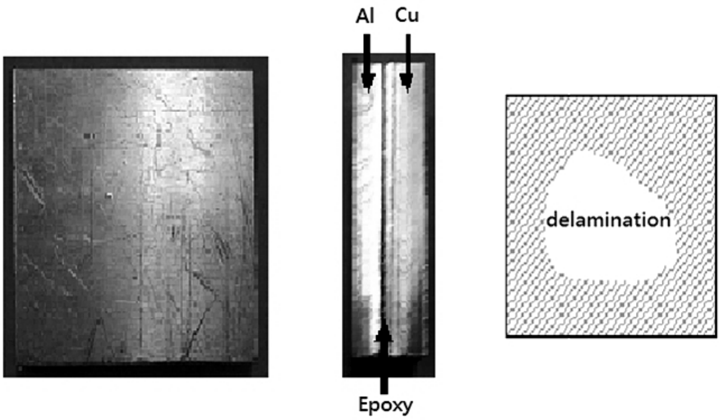

Fig. 11. Aluminum plate adheres to copper plate with delamination defect.

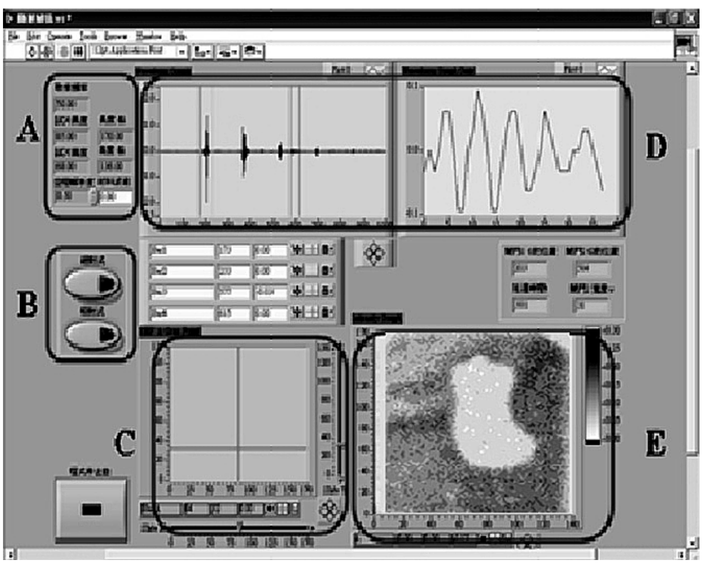

Fig. 12. Display panel for defect detection provided by LabVIEW.

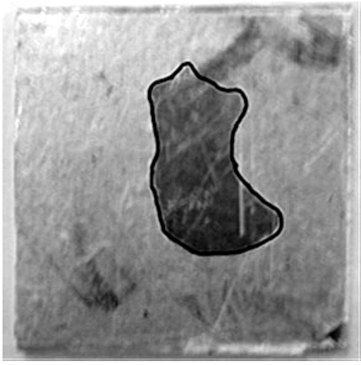

Fig. 13. Cross-sectional image.

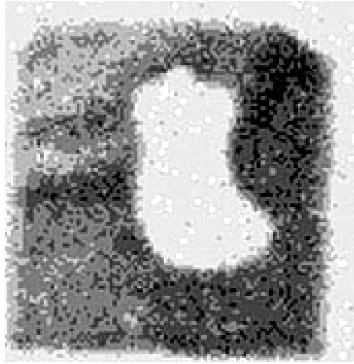

Fig. 14. Delamination defect.

Conclusions. A physical model of ultrasonic C-scan system based on the pulse-echo mode was established in this study. The system incorporates a general commercial ultrasonic transducer with an analog/digital converter unit and computer equipped with the LabVIEW signal-processing software, for which a user-friendly interface for digit signal processing was developed. The system can be used to generate accurate and reliable images not only of three-dimensional profiles but also of cross-sectional ones. Three specimens were tested and proved that such a C-scan system is a valuable tool for nondestructive evaluation as well as geometry characterization of both metals and composites. The experimental results have shown a very good performance of the system, being capable of producing three-dimensional profile and detecting the delamination of composite structure. The advantage of the proposed method is that it is simple, efficient and easily implemented, which is especially suitable for industrial applications.

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