ULTRASONIC TECHNIQUES FOR INSPECTING MULTI-LAYER COMPOSITE COMPONENTS

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INTRODUCTION

The US Army is evaluating composite materials for use in armored vehicles. Such materials exhibit structural and ballistic characteristics that meet or exceed those of conventional armor at a significant savings in weight. However, to provide comparable properties multi-layer structures must be considered. Proposed armored vehicles might consist of an S-2 glass laminate to meet structural requirements, ceramic tile for ballistic protection, and additional layers for signature management. Both pre-service and in-service inspections will be required to establish the serviceability and survivability of these vehicles.

This paper discusses an ultrasonic inspection system designed to inspect thick, multi-layer composites. The system combines a flexible ultrasonic array and the synthetic pulse technique. The array can rapidly inspect large areas and produce C-scan images of inspection results. The synthetic pulse technology can achieve both improved penetration and range resolution in highly attenuative test pieces. The method synthesizes a broad-band ultrasonic pulse by transmitting a series of tone bursts at discrete frequencies and then computing the inverse Fourier transform of the received data.

The ultrasonic inspection system being developed for the Army is based on PARIS (Portable Automated Remote Inspection System), which was originally designed to inspect composite Navy aircraft components. The intent is to extend the benefits of using a flexible ultrasonic array to Army vehicles, while maintaining the capabilities for inspecting more traditional thin composite structures. Advantages of the flexible ultrasonic array system include capability to rapidly inspect a large area of a structure that may have complex geometry and obtain easily interpreted C-scan images. Because the entire digitized RF waveform is captured, additional post-processing and display of the data can be performed, if needed.

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THE PARIS FLEXIBLE ULTRASONIC ARRAY SYSTEM

The PARIS ultrasonic inspection system consists of a flexible transducer array and the associated display and control electronics. Figure 1 shows a PARIS array with 1024 transducer elements arranged in a 32 by 32 element matrix. The dimensions of the active area of this array are 8- by 8-inches providing a total inspection area of 64 square inches. Inspection time for the 64 square inch area is under one minute.

The geometry and ultrasonic characteristics of a flexible array can be designed and fabricated to meet specific inspection requirements. The array used to inspect thin composite structures operates at 2.5 MHz, while the array built to inspect thick, highly attenuative composites operates at less than 1 MHz. A flexible array can be built to conform to the complex geometry of a part. Because the flexible array is vacuum coupled to the surface, couplant may not be necessary for relatively smooth surfaces. In some cases, a light water spray is all that is needed.

The PARIS display and control unit, which is built into a portable computer, has a menu-driven operating system that controls the ultrasonic inspection. An operator can set the ultrasonic inspection parameters or load predefined inspection parameters from magnetic media. The operator can select the entire array or any subset of the array for scanning, choose from a variety of data display formats, and store data on magnetic media for subsequent recall and display. A hard copy of any of the display screens can be produced on a portable printer.

PARIS digitizes the complete RF waveform and processes the ultrasonic data in its computer. This processing includes: 1) time-averaging of the RF waveform to reduce noise, and 2) scanning of the waveform for flaw indications. The user interface provides a mechanism to define ultrasonic gates, which are typically set to monitor front surface, flaw, and back surface echoes. The width of each gate, in microseconds, and its height, in percentage of full scale, can be adjusted by the operator. During scanning, PARIS collects both amplitude and time-of-flight information for each of the three gates. The amplitude data is the peak signal amplitude occurring within the gate; the time-of-flight data is the time relative to the start of the gate that the peak occurred. After the transducer array has been scanned, the data can be viewed in a variety of display formats, including A, B, and C-scans.

Figure 2 shows a time-of-flight C-Scan and "3-D" isometric image from an inspection of a composite wing skin on a Navy AV-8B aircraft. In the time-of-flight C-Scan, depth is indicated using the gray scale shown to the right of the image. This scale depicts the depth of an indication by its shade of gray. The darker the shade, the closer the indication is to the front surface. The slight change in shading from top to bottom on the C-Scan indicates a slight change in the thickness of the component across the scan area. A delamination, caused by impact damage, is clearly visible in the center of the C-Scan in Figure 2. The "3-D" isometric display provides the same information as the C-Scan but with depth information displayed as the third dimension. The "3-D" image can be rotated and tilted to provide the operator with the best viewpoint for examining the data.

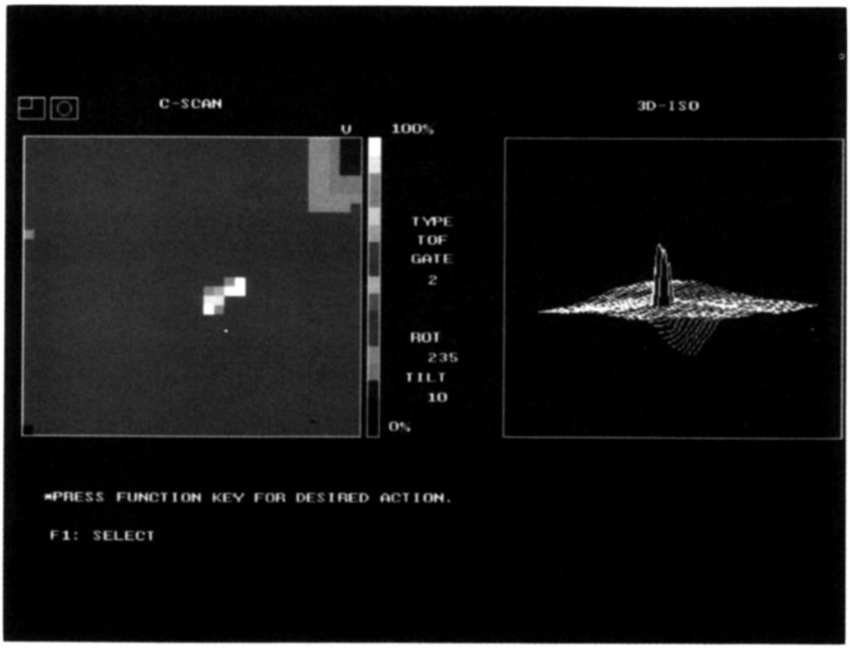

Figure 1. PARIS flexible ultrasonic transducer array

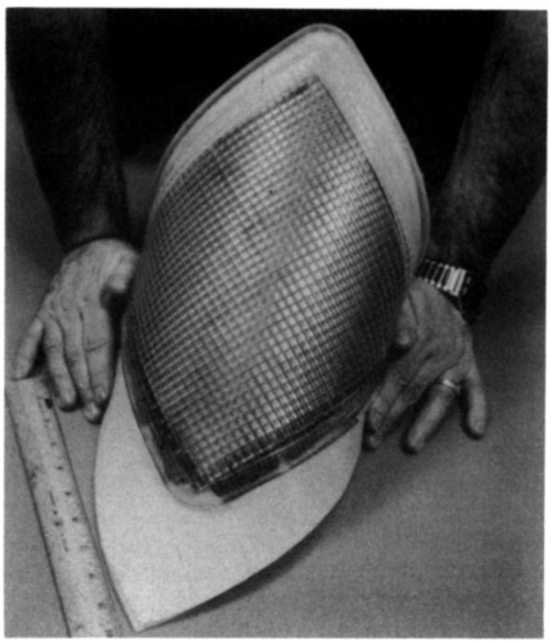

Figure 2. PARIS inspection of AV-8B wing skin impact damage

As previously mentioned, PARIS was originally designed to inspect relatively thin fiber reinforced plastic composites. The goal of current research for the Army Tank Automotive Command (TACOM) is to adapt the technology to inspect thick composites, such as the multi-layer composite structure currently being evaluated for the Army's Composite Armored Vehicle (CAV). The CAV design may include bonded fiberglass, ceramic, and signal management layers. The multiple bondlines increase the challenge of inspecting large areas of highly attenuative material. Capabilities are needed to inspect for manufacturing defects in the factory and to inspect for service damage in the field.

The technical approach for this specific adaptation is to increase ultrasonic penetration by 1) fabricating an array that operates at a lower frequency and at a higher voltage than is typically used for thin composites; and 2) employing a synthetic pulse technique. Figure 3 shows a plot of frequency versus attenuation for glass fiber reinforced plastic composite material. As may be seen, attenuation increases rapidly as the frequency is increased beyond about 700 KHz. Accordingly, a key design goal for the transducer array is an operating frequency range from 400 KHz to 900 KHz.

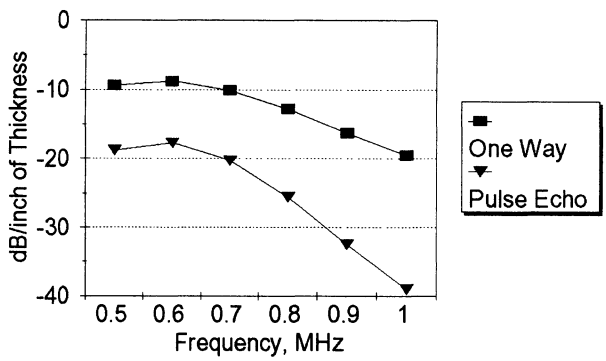

Figure 3. Frequency versus attenuation for a fiberglass composite material

A prototype flexible array was fabricated and successfully used to inspect thick fiberglass panels representative of composite armor material. Figure 4 shows the actual frequency response for the prototype array using a 1 inch thick piece of Lucite as a target. The frequency range, as defined by the 3 dB points, is approximately 350 KHz to 900 KHz. The actual frequency response of the prototype array meets the design specification at both the lower and upper frequency limits. The frequency response is very flat over the bandwidth of interest resulting in good performance for synthetic pulse applications.

SYNTHETIC PULSE TECHNIQUE

Ultrasonic attenuation decreases with frequency, as shown in Figure 3. Unfortunately, at low frequency, range (depth) resolution also suffers. The energy in the ultrasonic inspection beam can be increased but there is a physical limit to the amount of sound power that can be generated with typical ultrasonic equipment. The phase velocity is also a function of frequency. The synthetic pulse technology attempts to compensate for this problem by altering the transmitted spectrum as necessary to generate the desired receiving spectrum. The desired response, namely a broadband pulse corrected for dispersion, is obtained by this process.

A synthetic pulse test begins by generating a tone burst at the desired frequency. This is accomplished using a programmable function generator. The function generator also provides a reference source for the coherent detectors in the Holomodule, which is an analog signal processor. The tone burst is amplified

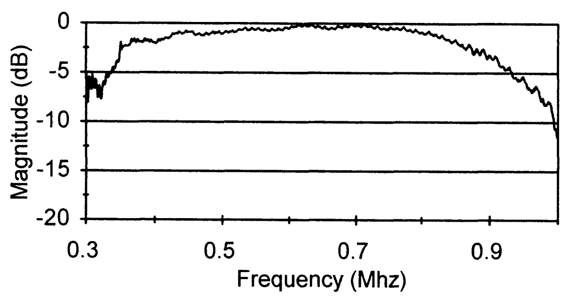

Figure 4. Frequency response of the prototype transducer array

by an RF power amplifier and routed to the transducer array multiplexer. The multiplexer is controlled by the computer to direct the signal to a particular array element. The returned echo is detected by the selected array element and amplified. From the receiver, the signal is routed to the coherent detectors in the Holomodule. The coherent detectors implement a complex demodulation scheme to extract the Fourier amplitude coefficients. Figure 5 shows a block diagram of the detection scheme.

The in phase and quadrature components are digitized using a 12 bit analog to digital converter. As the frequency is swept, the Fourier coefficients are digitized and stored. At the completion of the sweep, the synthetic pulse algorithm is applied to generate the equivalent broad band pulse. This signal is then processed using the existing PARIS software as if it were digitized directly by the high speed analog-to-digital converter (ADC).

ULTRASONIC INSPECTION SYSTEM

A block diagram of the ultrasonic array system being developed for the Army is presented in Figure 6, showing the signal flow for the major system components. Several interface cards are installed in the system computer to control the transducer array, function generator, and power amplifier. These cards include two data acquisition cards, one low speed card to acquire synthetic pulse parameters from the Holomodule and a high speed card to digitize RF data from the transducer array.

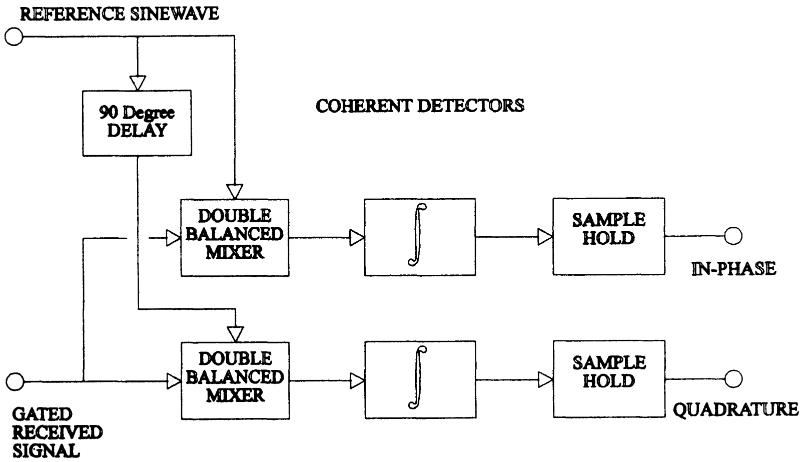

Figure 5. Coherent signal detection scheme

The transducer array is controlled by the system computer using a 24 bit parallel input/output (PIO) interface. The software selects a transducer element number which is converted to a row and column address in the array multiplexer. The multiplexer software/hardware is designed to allow random access to the transducer elements. The PIO interface also controls a programmable attenuator that provides a mechanism for adjusting the analog gain of the system. The attenuator is required to compensate for variations in element sensitivity, acoustic coupling, and variation in amplifier components.

The synthesizer/function generator is controlled using the IEEE-488 interface protocol. Under computer control, the synthesizer generates a continuous wave (CW) signal at a specified frequency. This signal is provided to the Holomodule, which includes an analog signal processor that generates a tone burst signal from the CW signal and then processes the received signals. The tone burst is amplified by the Matec RF amplifier and routed to the selected transducer element. The received signal is amplified on the transducer array and then routed to an ultrasonic receiver for additional amplification.

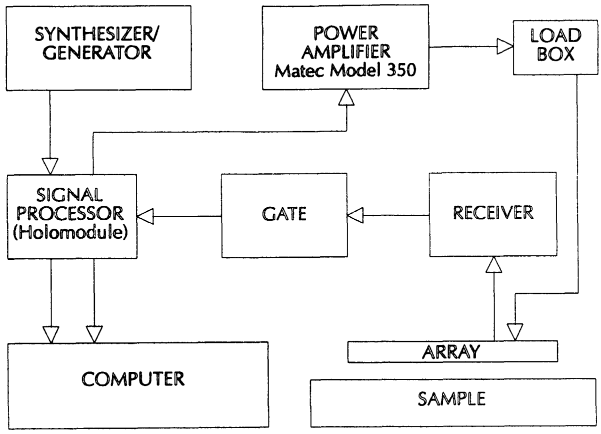

Figure 6. Signal flow block diagram

From the receiver, the signal is sent to the time gate. The time gate extracts just the portion of the received signal that is of interest and passes it to the Holomodule. Coherent detectors in the Holomodule implement an analog phase sensitive demodulation scheme to extract the complex Fourier amplitude coefficients of the gated signal. These are also referred to as the in-phase and quadrature components of the signal. The two signal components are provided as DC voltage levels that are digitized using a 12 bit ADC card. The digitized in-phase and quadrature components at each frequency are stored in computer memory until a complete data set has been acquired. After all of the data have been acquired, the reconstruction technique is used to synthesize a broad band pulse.

The ultrasonic inspection system being developed for the Army will retain the capability to inspect thin composite components using standard pulse-echo techniques. The conversion to conventional pulse echo mode is accomplished by switching the Holomodule to generate a one cycle tone burst and switching the load box from bipolar to unipolar mode. The operation of the software is essentially the same in both modes.

INSPECTION OF THICK FIBERGLASS PANELS

The prototype array and synthetic pulse technique were used to inspect fiberglass panels, ranging from 0.5 to 1.5 inches thick and containing urethane inserts at different depths. For the 1 inch panel, the reconstructed waveform (Figure 7) shows both the front and rear surface echoes. Figure 8 shows the waveform from a 0.5 inch diameter insert located 0.5 inch deep in the 1.0 inch thick panel. These figures illustrate the capability of the prototype array to detect defects in the thick composite armor material. Current work involves incorporating these same capabilities into a full-sized array.

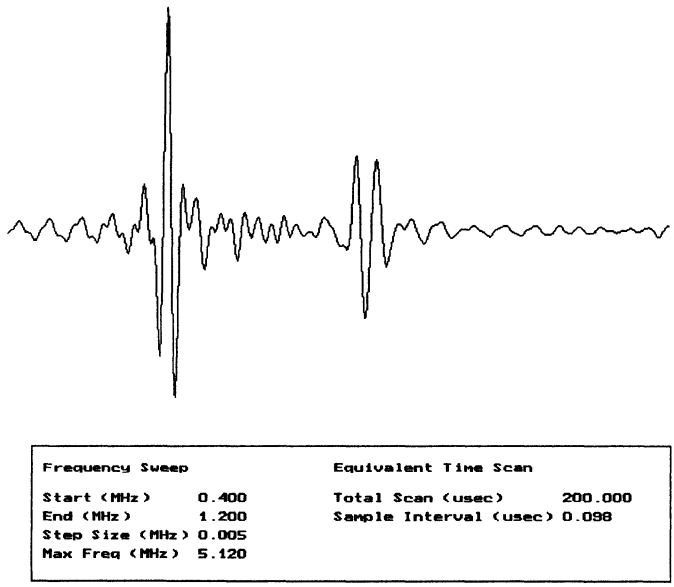

Figure 7. Waveform from 1" thick fiberglass panel

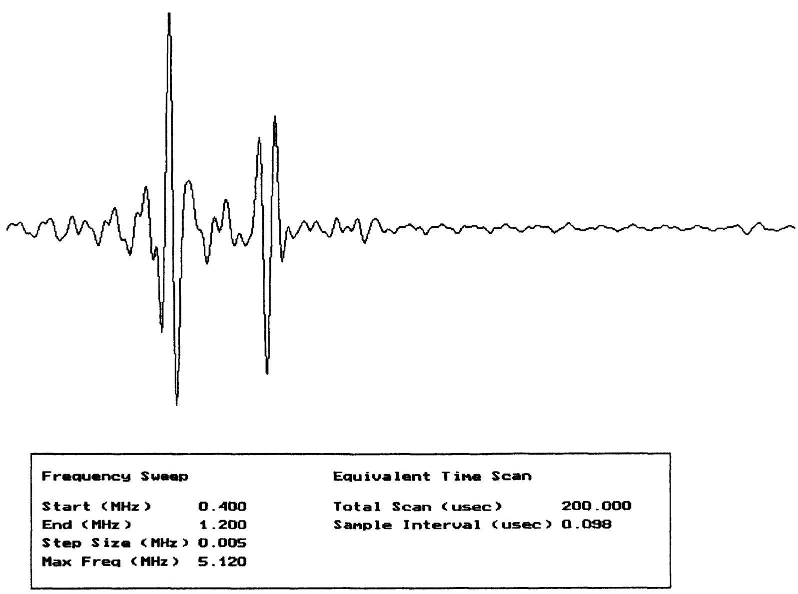

Figure 8. Waveform from 1" thick fiberglass panel - 0.5" insert 0.5" deep

ACKNOWLEDGMENT

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