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13. ABSTRACT (Maximum 200 words)

An investigation was performed to develop a self-diagnostic technique using a built-in piezoelectric wafer network to detect damage and to identify the extent of the damage in fiber-reinforced composite plates resulting from foreign-object impact. The principle of the technique was to use built-in piezoelectric wafers as actuators to generate stress waves and also use the neighboring piezoelectric wafers as sensors to receive the propagating waves. The difference in sensor measurements before and after the introduction of impact damage, referred to as scatter, contains information about the location and size of the impact damage.

Accordingly, the proposed technique consists of signal generation, signal processing, and damage identification. In the first part of the study, focus was on thin to moderately thick composites where identifying damage in the thickness direction was ignored and only a single piezoelectric wafer network through the composite plates was used. Diagnostic signals were selected for built-in piezoelectric actuators to generate appropriate Lamb waves to enhance the sensitivity of the sensor measurement to damage and to minimize signal noises due to environments. A signal-processing scheme composed of a smooth filtering and a joint time-frequency analysis was utilized to overcome noise interference and convert sensor measurements into sensor and scatter spectrograms in the time-frequency domain. Based on the time-of-flight information obtained from the scatter spectrograms, an identification algorithm was developed to estimate the location and the extent of impact damage in composite plates. The proposed technique was implemented into a PC-based hardware system. Extensive experiment was conducted to verify the technique and the system predictions. The overall predictions of location and size of impact damage agreed well with the experiment for thin to moderately thick composites.

In the second part of the investigation, a feasibility study was performed to use built-in multi-layer piezoelectric wafer networks to identify interior damage, in depth, in very thick composites. A multiple-layer ceramic-composite armor panel was fabricated with two piezoelectric wafer networks embedded through the thickness. The panel was then subjected to multiple ballistic impact loads. Again, results showed that the system could clearly identify the debond damage through the thickness inside the ceramic-fiber composite plate. However, in order to quantify the severity of the damage in depth, a further development of the damage identification method from two-dimensional to three-dimensional would be required. The work was conducted in collaboration with the Army Research Laboratory at the Aberdeen Proving Ground and United Defense in San Jose, California.

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1. ## MANUSCRIPTS

a) Conference Proceedings

C.S. Wang and F.-K. Chang, "Diagnosis of Impact Damage in Composite Structures with Built-in Piezoelectrics Network," Proceedings of SPIE, Smart Structures and Materials, Newport Beach, CA, March 4-8, 2000, pp. 13-19.

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c) Dissertation

C.S. Wang, "Built-In Diagnostics for Identifying Impact Damage in Composite Structures," Ph.D. Dissertation, Dept. of Aeronautics and Astronautics, Stanford University, 2001.

2. ## SCIENTIFIC PERSONNEL

PI: Fu-Kuo Chang

Other personnel: Two PhD students, Calvin Wang and J.H. Park, worked on the project during the report period.

3. ## REPORT OF INVENTIONS

None

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4. SCIENTIFIC PROGRESS AND ACCOMPLISHMENT

The project has been completed and all the tasks proposed have been studied and completed. Technologies have been developed based on built-in piezoelectric sensor/actuator networks to detect and identify impact damage in composite structures.

5. TECHNOLOGY TRANSFER

This project has been conducted in a close collaboration with the **Army Research laboratory** (ARL), in Aberdeen, Maryland, **TACOM,** in Michigan, and **United Defense**, in San Jose, CA. Dr. Shawn Walsh is the primary technical contact. TAMCOM (Jamie Florence) and United Defense assisted greatly on manufacturing, impact testing, and delivery of composite panels for the study. During the period, Stanford researchers visited the ARL, United Defense, and ARL researchers visited Stanford. Impact tests on thick composite plates were conducted at both ARL and United Defense and data measurements were made in Stanford's laboratory. In the future, collaboration with the **ARL** and **TACOM** will continue.

Impact Damage Identification of Composite Structures with Built-in Piezoelectric Sensor/Actuator Networks

Final Progress Report for Contract No. DAAD19-99-1-0236

Submitted to:
Dr. Gary Anderson
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Part I: Thin to Moderately Thick Composites

I. INTRODUCTION

Over the past two decades, there has been a considerable increase in the use of fiber-reinforced composite materials for aerospace applications due to their high specific stiffness and strength and excellent corrosion resistance. Nevertheless, a constant concern is the effect of foreign object impact on composite structures because significant damage such as delaminations can occur and yet be undetectable by visual inspection. Such impacts can be an ordinary impact at low velocity, a tool dropped on a part, or a hypervelocity impact of space debris on a spacecraft. Delaminations can reduce in-plane properties, particularly the compression properties, by up to 50-60% [1].

In order to ensure both safety and functionality of structures and prevent catastrophic failure, it is critical to monitor their condition and access both the location and the extent of damage as it occurs. Proper corrective actions can then be taken to temporarily reduce the effects of such damage until structures can be repaired. Currently most composite inspections are performed with nondestructive techniques such as coin tapping, radiography, and ultrasonic scanning. However, these methods can be expensive, time consuming and impractical for in-service monitoring. Furthermore, they cannot be applied to areas where structures are not accessible. Because of the increasing use of composites on commercial jet transports and military applications, it appears that the demand for composite health monitoring techniques will increase. Therefore, an efficient, reliable in-service monitoring technique becomes most significant and is of immediate importance. According to the NASA space transportation policy for next-generation vehicles, vehicle health management and monitoring systems will be required to meet the fundamental goal of affordable access to space [2].

Recent advances in sensing, electronic, and computational technologies have resulted in a significant interest among researchers in pursuing efficient built-in health monitoring techniques for composite structures. These techniques are specifically designed for incorporating actuators and sensors with composite structures for in-situ damage interrogation. Such integrated structures can be automated with minimum human intervention, which offer great potential for reducing maintenance costs and inspection efforts.

In general, damage detection systems with built-in diagnostics can be categorized into two types [3]: passive sensing diagnostics and active sensing diagnostics. A passive sensing diagnostics system relies solely on passive sensor measurements to determine any changes in the condition of the structures. Studies have been conducted in passive sensing diagnostics by embedding acoustic sensors or fiber optics into composite structures [4-7] and aerospace vehicles [8-9]. However, passive sensing diagnostics have difficulty determining local damage because a sensor could only a parameter at a given location such as strain or displacement. Piezoceramics have been adopted for active sensing diagnostics due to their good electromechanical properties. Keilers and Chang [10] have demonstrated that built-in piezoceramics can be used to detect delaminations in a composite beam. Roh and Chang [11] have shown that impact damage can significantly affect transmitted Lamb waves generated by built-in piezoceramics.

In this investigation, an active structural health monitoring system (ASHMS) is proposed for impact damage identification in composite structures using a built-in network of piezoceramics. The system is capable of detecting the presence of damage and identifying the location and the extent of the damage in composite plates. Damage identification goal was achieved by analyzing the difference in sensor signals recorded in two different time states, i.e., the reference state and the damaged state. The difference is referred to as the scatter and is indicative of damage.

In order to perform this analysis, three major components are required for the system; a Signal Generator, a Signal Processor, and a Signal Interpreter, and will be described accordingly in this paper. In addition, the arrangement of piezoceramics based on experimental studies of ultrasonic wave attenuation in composite plates will be discussed. A schematic representation of an ASHMS is illustrated in Figure 1.

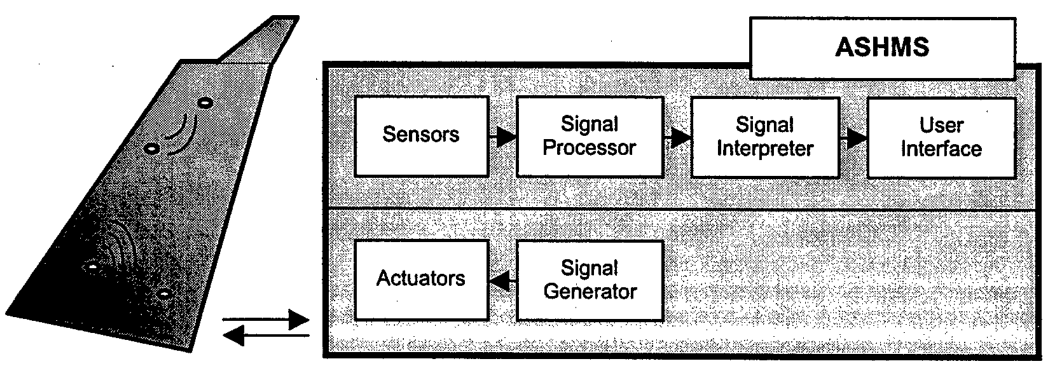


Figure 1. Schematic diagram of the Active Structural Health Monitoring System.

II. METHOD OF APPROACH

Developing an active diagnostic system requires analytical and computational software tools that can create an appropriate diagnostic signal, process raw sensor measurements, and convert these measurements into damage parameters which characterize the impact damage. In addition, these tools must be efficient enough so that the system can be implemented in real time. As mentioned before, the tools are referred to as the three components of the ASHMS shown in Figure 1. Signal Generator produces a diagnostic signal that is capable of propagating in composite plates with minimum signal distortion, and is sensitive to the damage that is of particular concern. Signal Processor manipulates raw sensor measurements into useful information by means of digital filtering and joint time-frequency analysis. Signal Interpreter incorporates the information with an analytical model, and an optimization routine to determine the characteristics of the impact damage, which are the location, size, and orientation. The overall damage identification procedure is shown in Figure 2.

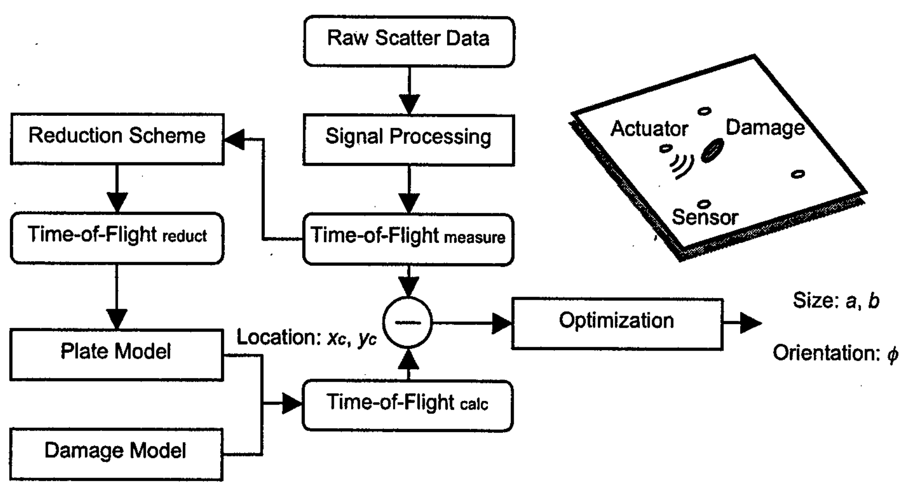


Figure 2. Schematic block diagram of damage identification procedure. The pizeoelectric actuator generates a diagnostic signal which interacts with damage. Scattering effect is produced due to the damage and detected by piezoelectric sensors.

2.1 Signal Generator

Waves propagating in composite plates are dispersive, i.e., propagation speeds of Lamb wave modes depend on frequencies. As a result, the shape of the input signal would be distorted as it propagates over a certain distance. Dispersion is caused mainly by two distinct mechanisms. The first mechanism is viscoelastic dispersion due to the viscoelasticity of the medium. The second mechanism is geometry dispersion due to the characteristic dimensions of the structures. A comparison between two representative signals that contain spectral contents distinctly different from one another is shown in Figure 3. Obviously, the sensor waveform is nearly preserved in the bottom row. Therefore, any change in the waveform can be clearly identified and interpreted in the time domain. The corresponding actuator signal is called narrow-band windowed signal, which was adopted throughout the research.

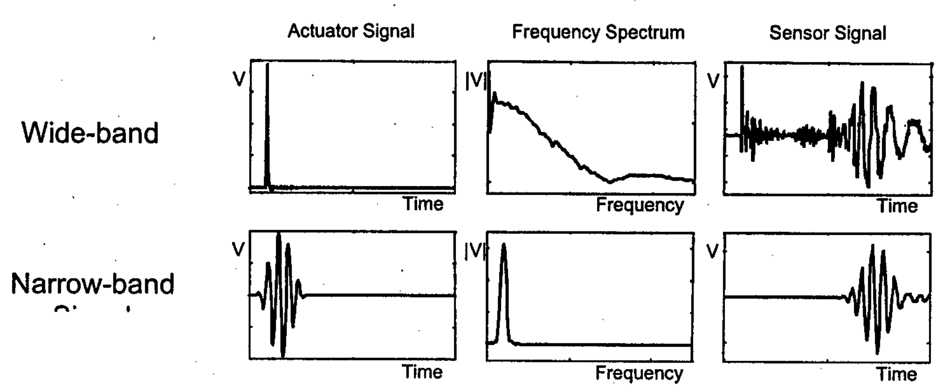


Figure 3. Comparison of sensor signals produced by corresponding actuator signals in a composite plate. Narrow-band signal vs. Wide-band signal.

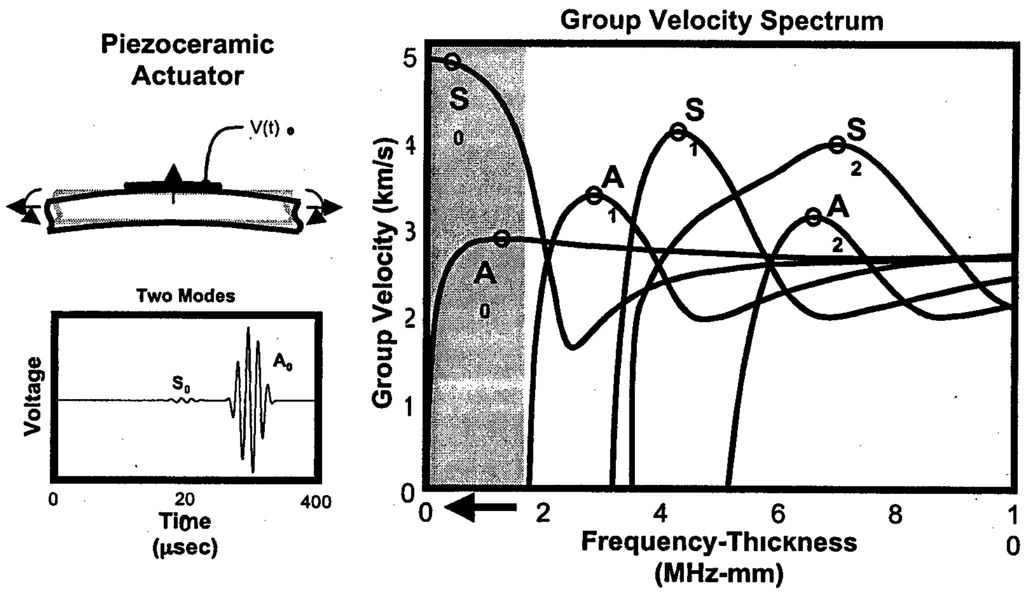


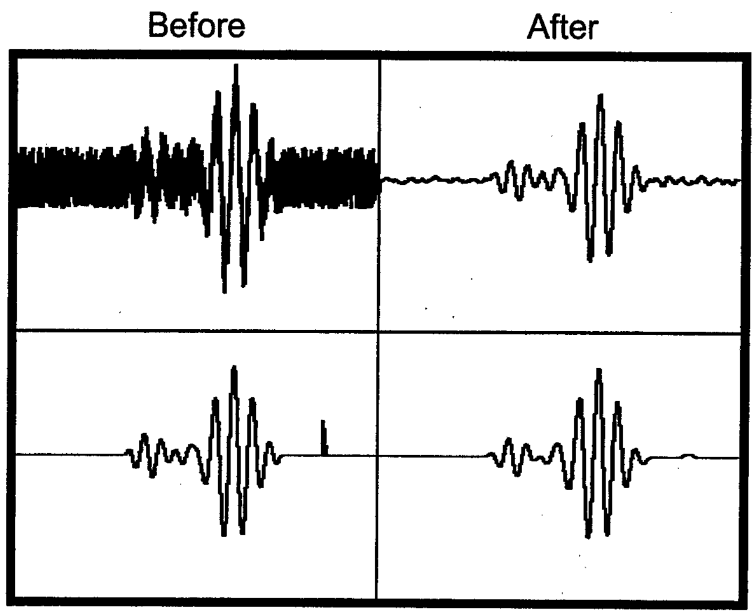
Figure 4 Lamb waves in So and Ao modes generated by built-in piezoelectric actuators and used in the study.

2.2 Signal Processor

In graphite/epoxy composite structures, the signal level is usually small (< 1 VDC), and sensor data can be highly contaminated by noises. Therefore, it would be desirable to apply a smoothing filter to reconstruct the underlying smooth function and increase the signal-to-noise ratio. A smoothing algorithm based on least-squares in time and the QR factorization was developed and efficiently programmed. The typical CPU time to implement this algorithm on a Pentium 200 MHz computer is less than one millisecond corresponding to 1000 data points.

Figure 5 Comparison of measured signals with and without the application of the proposed smoothing algorithm.

In order to characterize impact damage from changes in sensor measurements, diagnosis at a specific frequency may not be sufficient. A swept frequency method was adopted to generate sensor responses over a wide range of frequencies as



Comparison of CPU Consumption Times*

n	Smoothing Filter	Moving Average
10^3	0.006 sec	0.39 sec
10^4	0.036 sec	4.55 sec
10^5	0.344 sec	77.93 sec

*CPU Time is based on 200 MHz clock rate.

shown in Figure 6. The multi-frequency sensor responses were processed by joint time-frequency analysis, which utilized the short-time Fourier transform to calculate spectral components of time-domain signals as a function of time. As a consequence, a three dimensional plot of spectral amplitude information in the time-frequency domain, which is called the spectrogram, can be obtained, and the peak amplitude of each sensor signal of a particular frequency can be determined as shown in Figure 7. This method has been successfully applied to aluminum plates [12].

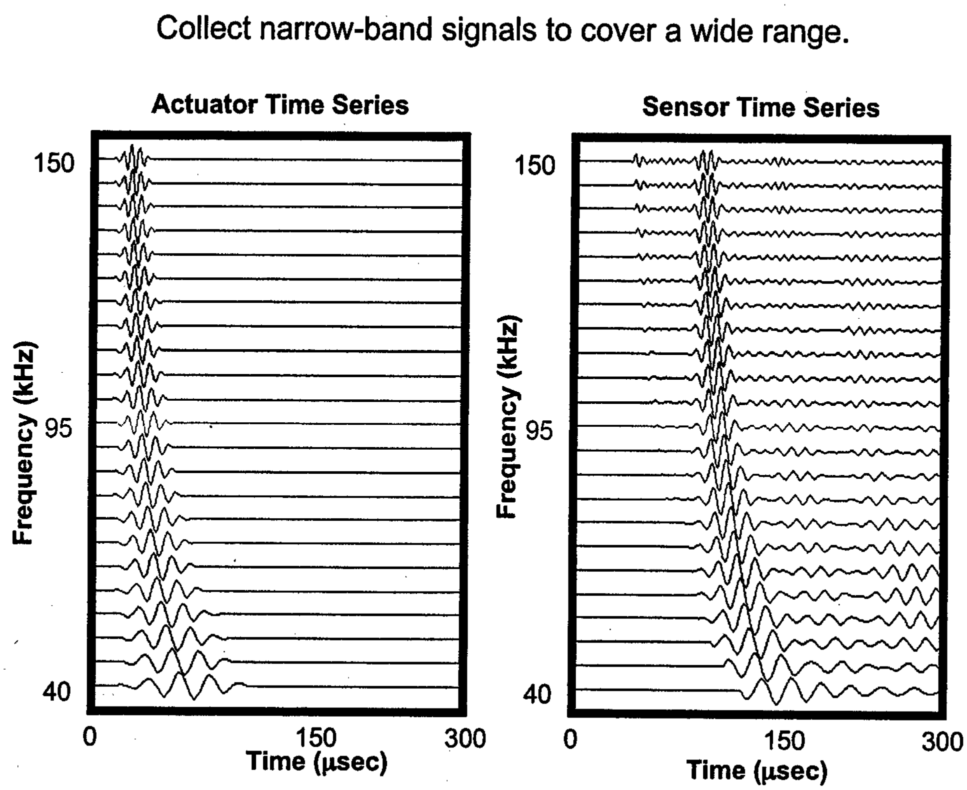


Figure 6 A frequency sweep of narrow-band signals over a wide range was used to generate diagnostic inputs.

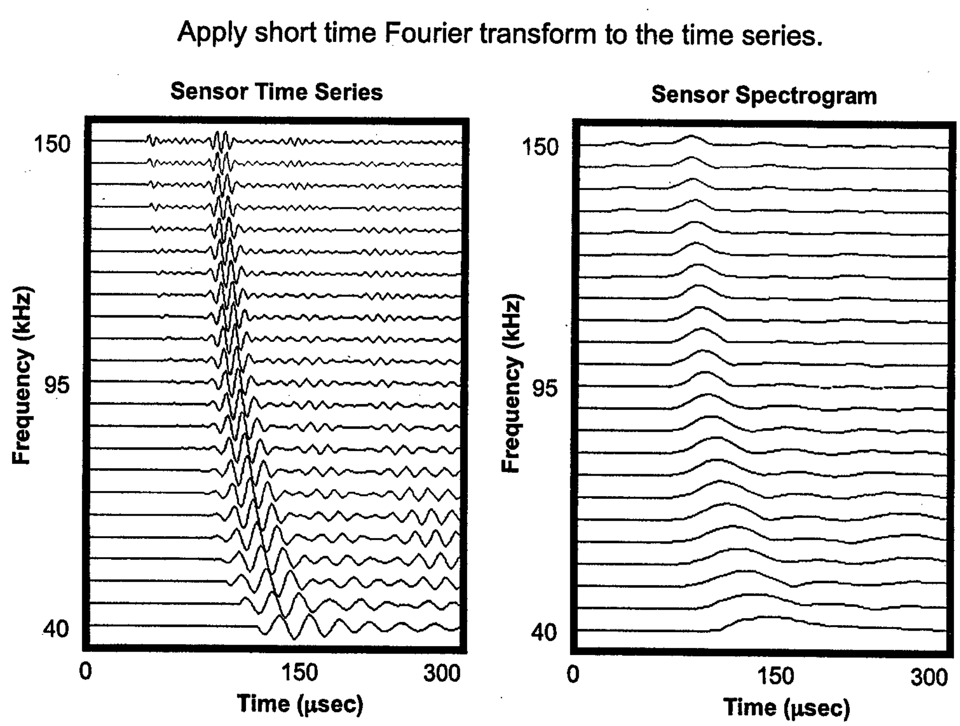


Figure 7 Conversion of signals to spectrogram using short time Fourier transform.

The spectrogram offers great advantages in finding time-of-flight of narrow-band wave packets. By definition, the scatter is the difference in two sensor signals recorded at two different time states, i.e., the reference state and the damaged state. Therefore, the scatter spectrogram can be obtained by subtracting the baseline sensor spectrogram from the sensor spectrogram after damage is introduced. The time-of-flight of the scatter can be determined by comparing the scatter peak amplitude to the actuator peak amplitude. This time-of-flight represents the time that the signal takes to propagate from the actuator to the sensor via damage, which is the key information to the damage identification problem. Figure 8 shows typical spectrograms from actuator inputs, sensor signals, and scatters of a composite plate with damage from the study.

2.3 Damage Identification

In the damage identification procedure, it was assumed that the damage to be identified is located with the domain encompassed by the four piezoceramics, which form a unit damage identification cell (UDIC). The UDIC contains six actuator-sensor (pitch-catch) diagnostic paths. Therefore, six scatter spectrograms can be generated and six sets of time-of-flight can be obtained accordingly. The resulting time-of-flight measurements were related to the location projected into a two-dimensional plane (no depth), and the size of damage. Accordingly, the proposed technique focused only on thin to moderate thick composites where damage location in the thickness direction is not a major concern.

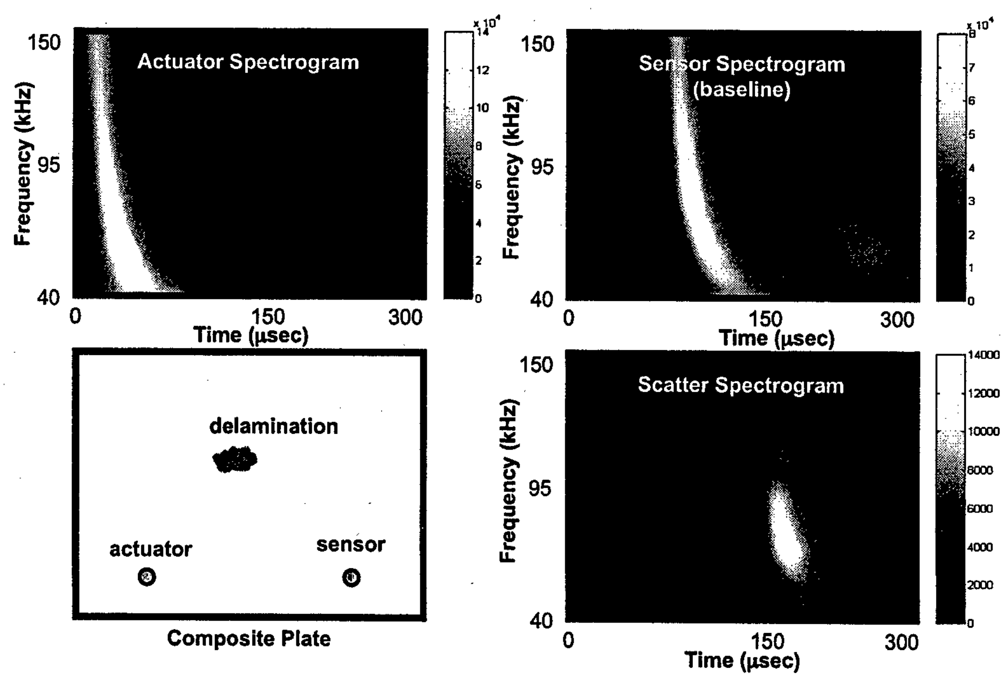


Figure 8 Spectrograms of actuator signals, sensor signals, and scatter signals used in the study.

A damage identification algorithm was developed to use the time-of-flights measured from 6 scatter spectrograms in a 4-piezoelectric sensor network as shown in Figure 9 to estimate the center location of impact damage and the extent of the damage located within the region encompassed by the four piezoelectric sensors in a composite plate. Assumptions were made in the model; the shape of the damage was assumed to be circular, material degradation was assumed to be uniform over the damage area, and the diagnostic signals were primarily scattered off from the boundary that encloses the damage area. However, it was not known if the scatter was generated mainly from the front edge of impact damage or from the rear edge of the damage.

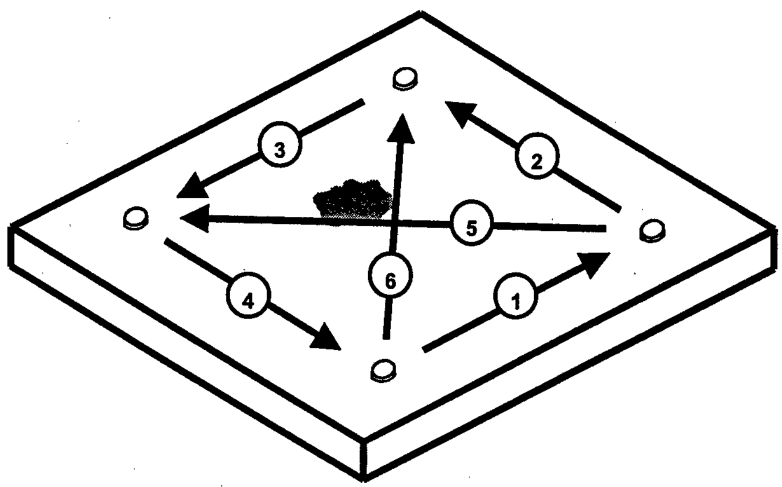


Figure 9 Six possible diagnostic actuator-sensor paths for a four-piezoelectric wafer network.

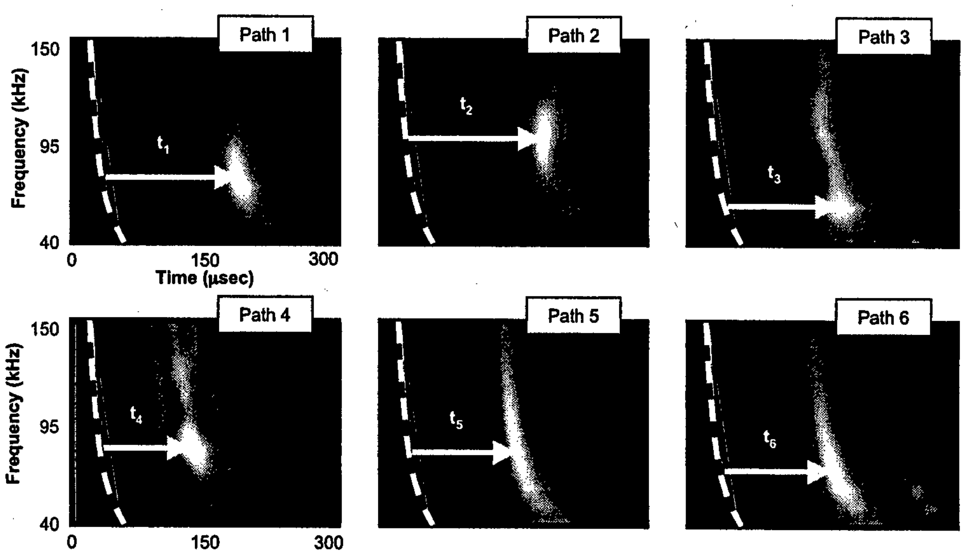


Figure 10 6 scatter spectrograms generated from a 4-piezoelectric sensor network with time-of-flights measured from each spectrogram.

Accordingly, extensive experiment was conducted to measure time-of-flight of scatter signals from impact damage with various sizes. Time arrival was measured for a fixed actuator-sensor geometry by varying the damage size as shown in Figure 11 where the data clearly showed that the larger the damage, the higher is the time-of-flight for a fixed actuator-sensor distance. The test results strongly indicated that the measured scatter signals were most reflected from the rear edge of the damage, instead of the front edge. This phenomenon can be reasoned as follows: Impact damage causes local reduction of structural stiffness. Accordingly, scatters are generated when propagating waves travel from a soft (damaged) media to hard (un-damaged) media.

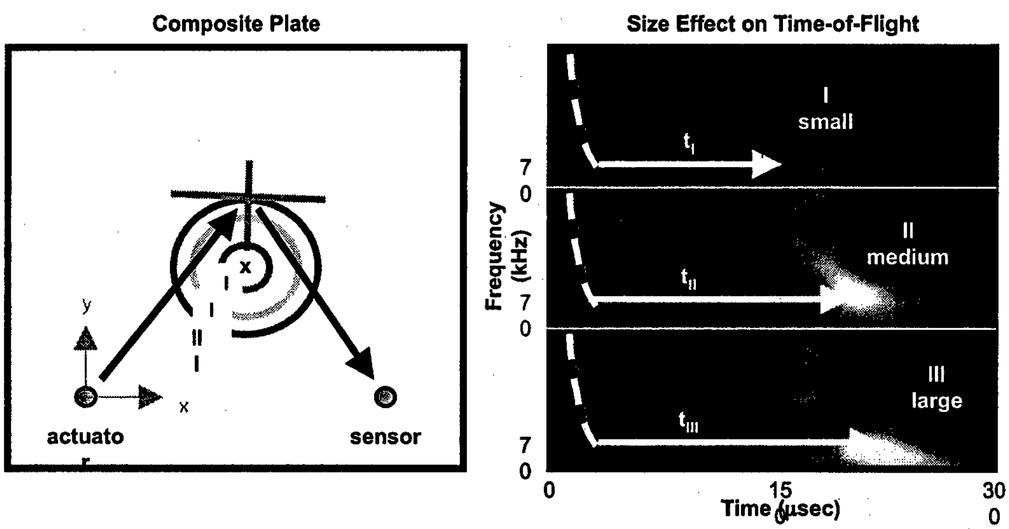


Figure 11 Measured scatter spectrograms and time arrivals for various damage sizes in a composite plate.

Therefore, the measured time-of-flight from a scatter spectrogram is associated with a sum of the distance measured from the actuator to the rear edge of the damage and the distance measured from the rear edge of the damage to the sensor. By limiting damage size to be relatively small to the actuator-sensor network in this study, it was further assumed the effect of local damage on wave speed is negligible. Therefore, the location and rough size of the damage could be estimated from the six time-of-flights if the group velocities of diagnostic waves are known, in all directions, in the composite plates. The best estimate of damage size can be achieved by minimizing the differences between measured time-of-flight and known time-of-flight using an optimization routine. Detail model developments and optimization routine can be referred to [13].

III. EXPERIMENT

Extensive experiments were done on a series of graphite/epoxy (T800/3900-2) composite plates. The ply layups of the plates were shown in Table 1. On each plate, four piezoelectric PKI-400 Lead Zirconate Titanate (PZT) ceramic wafers were mounted on one side of the surface using conductive epoxy, and the whole composite plate was used as a ground terminal. Each PZT was a thin disc with a 0.25-inch diameter and a 0.010-inch thickness. According to [14], the maximum electrical field which can be applied to a PZT without depolarizing it is approximately 250~300 V/mm. Damage was introduced by quasi-static impact on a MTS machine.

For each ply orientation, two damage locations were selected and damage with three different sizes was generated. In total, there were 54 panel tests for all the cases as shown in Table 1.

The Smart Suitcase manufactured by Acellent Technologies [16] was used to generate diagnostic signals from actuators and to retrieve measurements from sensors. Basically, the hardware contains a waveform generator, a sensor amplifier, a PC, and an actuator amplifier as shown in Figure 12.

Table 1 Specimen configurations used in the study for verifying the proposed SHM technology.

	Location (in.)		Size of Damage (in.^{2})					
Specimen Lay-up	I	II	IA	IB	IC	IIA	IIB	IIC
$[0_2/90_2]_s$	(1.4,2.3)	(3.5,2.3)	0.29	0.61	1.21	0.30	0.46	1.75
$[0_4/90_4]_s$	(1.5,2.7)	(3.5,2.4)	0.38	0.84	2.35	0.48	1.03	3.10
$[0_6/90_6]_s$	(1.4,2.2)	(3.5,2.4)	0.46	1.06	3.56	0.37	0.89	1.71
$[0/45/-45/90]_s$	(1.3,2.3)	(3.7,2.2)	0.31	0.55	0.94	0.49	0.88	2.18
$[0_2/45_2/-45_2/90_2]_s$	(1.1,2.9)	(3.3,3.1)	0.52	1.16	2.22	0.39	0.99	1.81
$[0_3/45_3/-45_3/90_3]_s$	(1.2,2.4)	(3.5,2.8)	0.68	2.83	0.64	0.55	1.67	3.88
$[45/-45/0_2]_s$	(1.6,2.6)	(3.7,2.2)	0.12	0.34	0.46	0.23	0.45	1.12
$[45/90/-45/0_2/45/-45/0]_s$	(1.4,2.6)	(3.6,2.8)	0.23	0.47	1.18	0.30	0.59	1.50
$[45/90/-45/0_3/45/0_3/-45/0]_s$	(1.3,2.3)	(3.7,2.5)	0.21	0.38	1.26	0.43	0.48	1.38

Since a UDIC is composed of four piezoceramics and only two of them at a time are selected as the actuator and the sensor, an electromechanical relay circuit is required to perform automatic selection of these elements. A Pentium computer controlled all the devices and performed automatic data acquisition with a high speed GAGE A/D converter plugged in. The schematic representation of the experimental setup is shown in Figure 12.

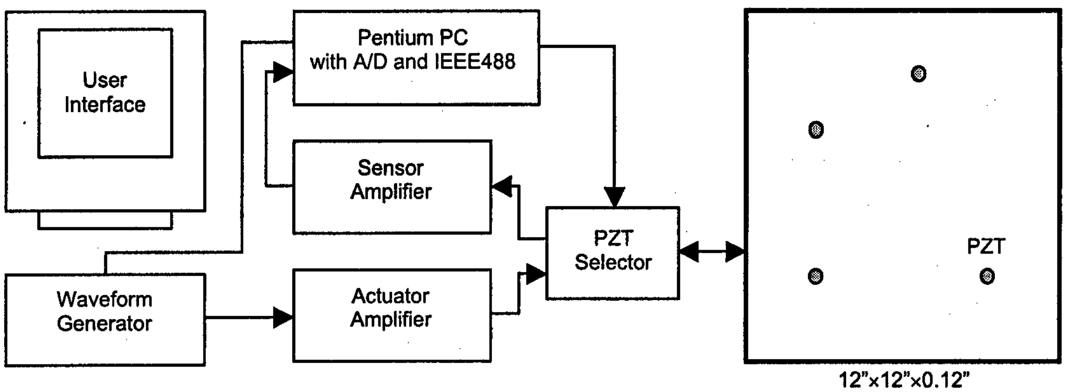


Figure 12. Schematic diagram of composite specimen and instrumentation. Sensor amplifier and piezo selector are powered by a HP DC power supply with +/- 12 volts.

IV. VERIFICATIONS

Diagnoses were performed at carrier frequencies from 40 kHz to 150 kHz. In this range, the fundamental Ao Lamb mode can be detected for the given composite plates. As mentioned before, a UDIC contains six actuator-sensing paths from which six groups of spectrograms can be generated.

In this research, the distances between actuators and sensors range from 4 inches to 8 inches. Figure 13 shows the actuator spectrogram, the sensor spectrogram, and the resulting scatter spectrogram at 70 kHz for a particular path. The region surrounded by the white area in each spectrogram indicates the peak amplitudes of the signals. The maximum peak amplitude is 50 volts in the actuator spectrogram, 1 volt in the sensor spectrogram, and 0.3 volt in the scatter spectrogram. The scatter time-of-flight can be extracted from the plots and used in the identification procedure. The comparison of the identification results and X-ray image for the actual impact damage in a quasi-isotropic composite plate are presented in Figure 14, which shows good correlation between estimated results and the real damage case.

Figures 15 and 16 show the comparison of impact location and size between the actual measurements and the predictions. Overall, the proposed technique can locate the center of impact damage within a 0.5-inch radius. The predicted damage area also correlated quite well with the measurements. However, it can be evident from the figure that the difference in damage area between the predicted and measured enlarged as the damage size increased. This can be attributed to the fact that the effect of damage on the wave propagation was ignored in the model.

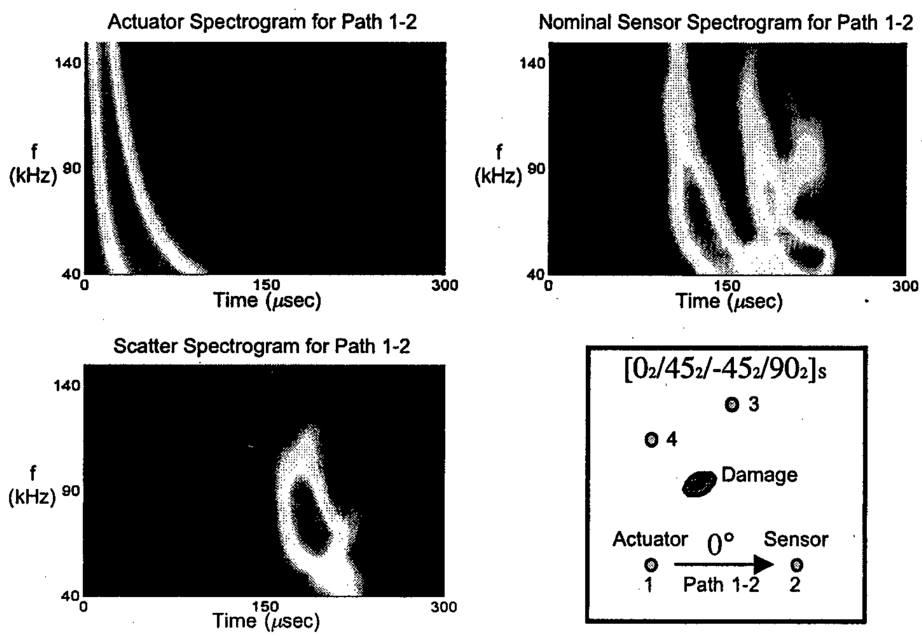
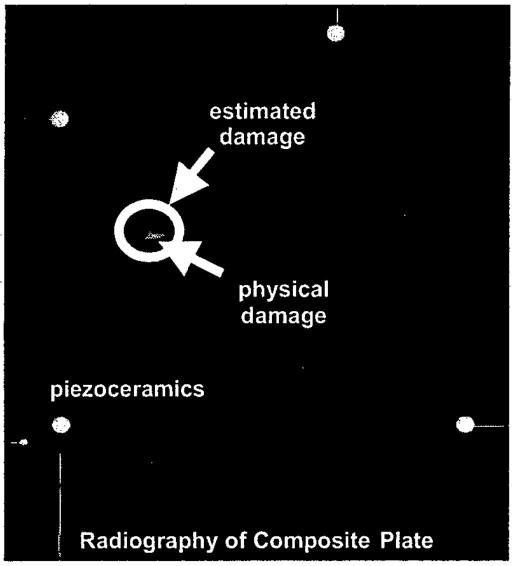


Figure 5. Actuator spectrogram, Sensor Spectrogram, and the resulting scatter spectrogram for path 1-2 along 0° fiber direction in a quasi-isotropic composite plate.



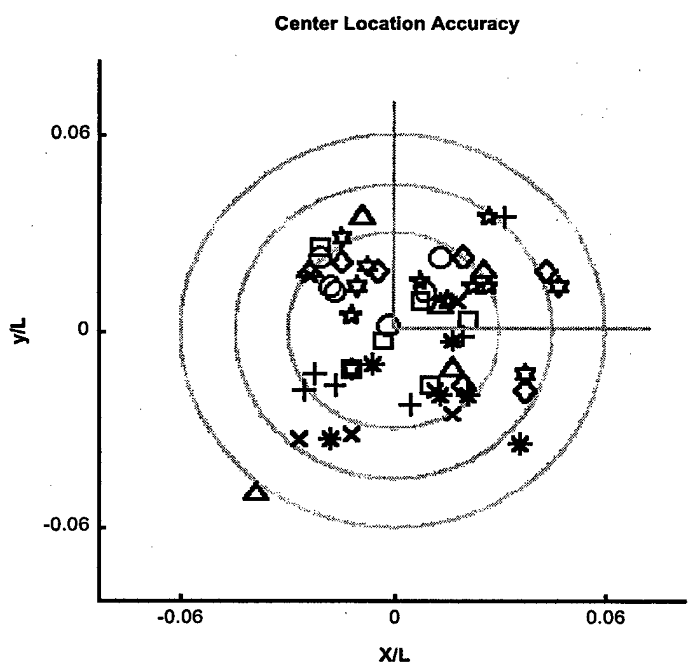
Quasi-isotropic Lay-up
$[0_2/45_2/-45_2/90_2]_s$

	x	y	A
Estimate	0.	3.	1.5
Physical	1.	2.	1.39±0.28

Cross-ply Lay-up
$[0_4/90_4]_s$

	x	y	A
Estimate	1.	2.	2.8
Physical	1.	2.	2.63±0.22

Figure 14 Comparison of measured and predicted impact damage locations and sizes for quasi-isotropic and cross-ply laminates.



L: largest sensor spacing in the network

Figure 15 Damage location errors compared to data. The maximum error was within a 0.5 in radius from the center of damage for a 7-in actuator-sensor spacing.

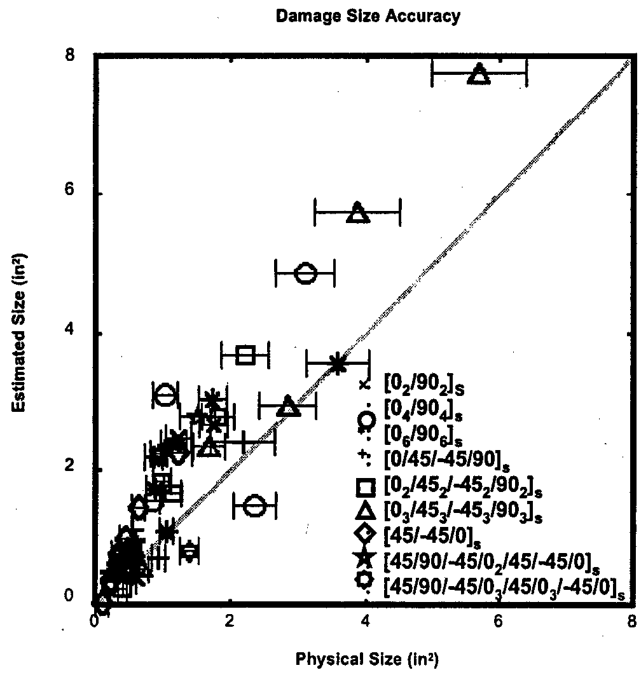


Figure 16 Comparison of damage size between the measurements and the predictions for all the data.

V. DISCUSSION

In order to minimize the number of piezoceramics used for the ASHMS, the area that a UDIC can cover needs to be optimized. In other words, the propagation distance between an actuator and a sensor needs to be large enough. It is limited by wave attenuation in composite laminates. Wave attenuation refers to the energy dissipation associated with the decrease in the stress wave amplitude due to wave scattering and the viscoelastic characteristics of the resin matrix in composite materials, and is generally frequency-dependent.

A study of actuator-sensor spacing was experimentally conducted on a quasi-isotropic $[0_2/45_2/-45_2/90_2]_s$ composite plate. Attenuation measurements were made by comparing amplitudes of the received signals through four different actuator-sensor distances to the amplitudes of the associated input signals. The attenuation curve was obtained by applying a curve-fitting method for these four data points as shown in Figure 17. If V_{IN} is the actuator input voltage, V_{OUT} is the sensor output voltage, then the Amplitude Ratio (AR), which is a function of frequency ω can be expressed as

$$AR(\omega) = 20\times\log \frac{V_{OUT}}{V_{IN}} \text{ dB}$$

In this study, circular piezoceramics with 0.25-inch diameter and 0.01-inch thickness were used. The actuator input voltage was fixed at 50 volts, and the operation frequency range was from 40 kHz to 150 kHz. Figure 16 shows the variation of the Amplitude Ratio versus the change in the actuator-sensor distance along the 0° fiber direction at 70 kHz. The particular frequency was chosen such that the sensor signal reaches its maximum amplitude. In Figure 7, it was observed that the Amplitude Ratio decreases linearly as the actuator-sensor distance increases. However, as the actuator-sensor distance decreases, there exists a significant reduction (~-55 dB) in the amplitude of the sensor signal. This is primarily due to the impedance mismatch and the interfacial bonding condition between piezoceramics and composite materials, which appear to have significant effects on wave attenuation in the experiment.

In general, the signal amplitude needs to be at least ten times greater than the noise level (SN ratio = 10) in order for the signal to be detected and distinguished from noises. In the experiment, the noise level was approximately -105 ~ -110 dB corresponding to a 50-Volt input signal under the laboratory environment. Therefore, the sensor signal level would be greater than –85 dB to be used in damage identification. From Figure 17, the maximum propagation distance between an actuator and a sensor can be determined, which is approximately 27 inches. However, this number can be reduced if the input frequency increases since materials tend to attenuate high frequency ultrasonic waves more than low frequency waves [15].

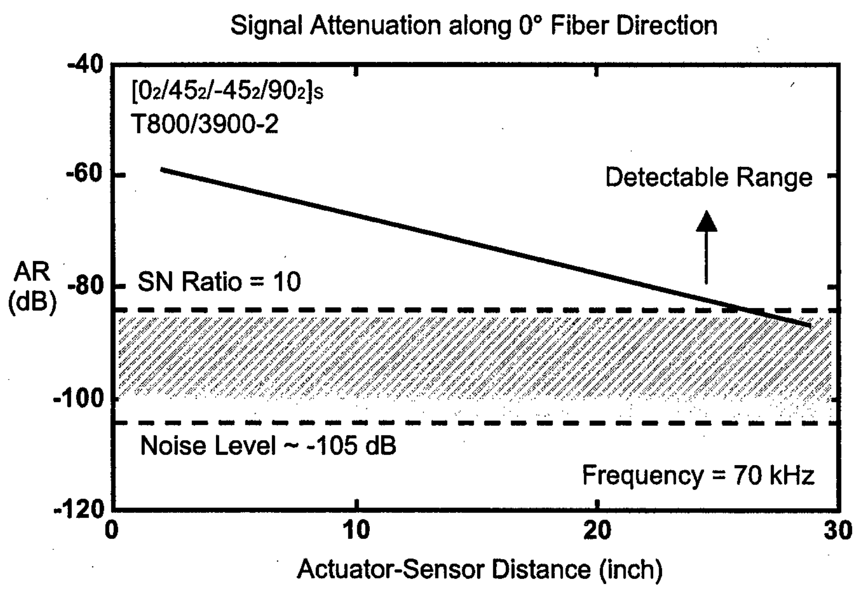


Figure 17. Signal attenuation along 0° fiber direction in a 16-ply quasi-isotropic composite plate. The SN ratio is less than 10 in the gray region. The linear curve was obtained by curve-fitting measurements from four different actuator-sensor distances.

In this research, the damage identification process was based on the scatter signal, which by definition is the difference between sensor signals before and after the damage is introduced. From the experiment, the amplitude of the scatter was 3-6 times smaller (-10~15 dB) than the associated sensor signals. The maximum distance that a scatter signal can propagate from an actuator to a sensor via damage was found to be approximately 10-17 inches in this case. However, the results depend upon the input energy, input frequencies, the size of piezo-ceramics, and the size of damage.

VI. CONCLUSION

This work has demonstrated the feasibility of the Active Structural Health Monitoring System using a built-in network of piezo-ceramics in composite structures. In this research, a narrow-band diagnostic signal was produced and proved to be sensitive to the presence of the damage. Furthermore, a signal processing technique and an interpretation scheme were developed and implemented to determine the location, size, and orientation of impact damage using time-of-flight information from scatter spectrograms. The identification results compared to the X-ray images showed satisfactory agreement. Further studies will be appropriate in developing a structural monitoring system with embedded piezoelectric actuators and sensors.

Part II: Impact Damage in Multi-Layered Thick Composite Structures

1. INTRODUCTION

Traditionally, thin and moderately thick composites are being employed for the construction of space and aircraft structures, such as helicopters. However, thick composites have been demonstrated to possess an extremely high-energy absorption capability for impact loading and have been used for the design of Army ground fighting vehicles. Currently, multi-layered thick composites, embedded with ceramic tiles and other energy absorption layers, are being developed for the design of next generation Army armored vehicles. Because of the thickness and multi-layered properties including tiles, damage or de-bond in the multi-layered composite system resulting from manufacturing or combat situations are nearly impossible to be detected with traditional NDE techniques [17]. However, if undetected early, these hidden damage or defects could grow and potentially lead to severe reduction of mechanical properties such as rigidity and integrity, which are essential for such vehicles in combat situations for controlling mobility and agility and furthermore, for protecting the safety of the crewmen inside.

In addition, the lack of information about the extent of damage in depth and size posts a great challenge for repair and maintenance of the vehicles if they suffer visual damage on the surface in combat. Accordingly, a built-in self-diagnostic technique would significantly improve the reliability and sustainability of the vehicles and the safety of crewmen.

This report summarizes the results of a feasibility study by extending the built-in diagnostic technique developed in Part I to multi-layer thick ceramic/composite structures. Although the aforementioned technique was developed for thin and moderate thick composites, ignoring the thickness effect, many techniques and methodologies previously developed could still equally be applied to thick composites. It was expected that the aforementioned system shall be able to detect damage and estimate its location, but it would not be able to quantify the extent and depth of the damage without further improving the identification algorithms developed previously in Part I. In the second part of the study, the SMART layers which contains an embedded network of piezoelectric wafer network manufactured by Acellent Technologies [16] was adopted because they became available commercially for the study. Using the SMART layers, an investigation was conducted to generate diagnostic signals before and after impact test, and to analyze the signals for interpretation of internal damage buried inside the multi-layer thick ceramic-composite plates.

II. METHOD OF APPROACH

2.1 Damage detection scheme

The scheme developed in Part I of the study was adopted for this part of the study. The principle of the damage detection scheme is based on a change in the state of measured sensor signals generated from a neighboring embedded actuator. The overall procedure is shown again in Figure 1. Using the software, pre-selected diagnostic signals from a designated piezoelectric actuator to its neighboring sensors were generated by the diagnostic unit. The corresponding sensor signals were recorded and compared to a baseline reference, which was previously recorded.

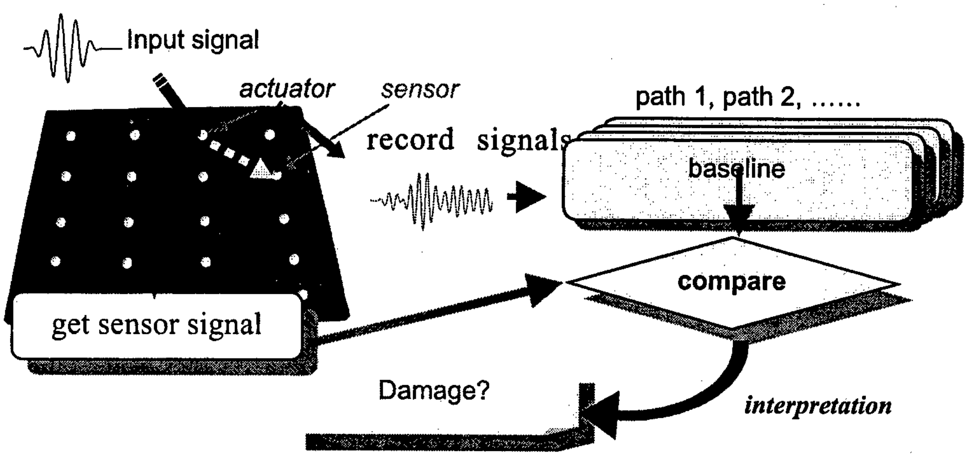


Figure 1. Damage detection scheme used in Part II study.

2.2 Diagnostic Input Signals

Based on the Part I study, a 5 peak burst wave was adopted for generating diagnostic signals to structures. The shape of the signal is shown in Figure 2. This burst type signal has narrow bandwidth in frequency domain. The input signals were generated by the diagnostic unit with the range of the central frequency from 80 to 250 kHz.

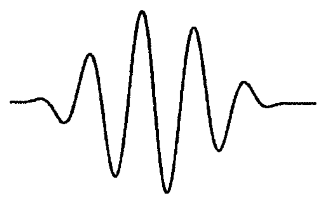


Figure 2. Typical diagnostic input signals.

III. THICK CERAMIC-COMPOSITE PANEL

In order to evaluate damage buried in thick composites for potential Army application, a one-inch thick, 40 in x 40 in wide composite armor panel was manufactured for the study by United Defense in San Jose, California in collaboration with the Army Research Laboratory at Aberdeen Proving Ground. Two SMART Layers were embedded in the panel; one located above two composite plies from the bottom surface and the other is near the center of the thickness below ceramic tiles as shown in Figure 3. The SMART layers were provided by Acellent technologies.

3.1. Thick composite panel with a sensory system

Figure 3 shows the thick composite panel with two SMART layers embedded. Each layer has 20 PZT sensors as indicated by white dots on the right figure below.

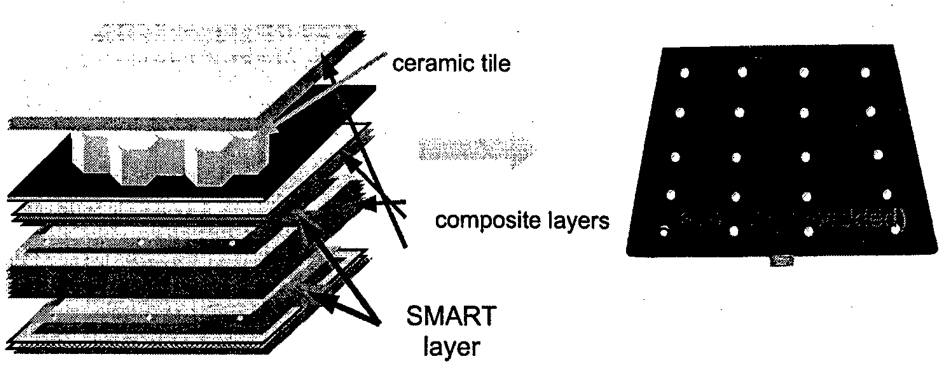


Figure 3. Thick composite structure with SMART layers

3.2. Detecting damage from signal path

With two piezoelectric actuator-sensor networks built into the composite panel, not only could diagnostic signal paths within each network be established, similar to what has been done in Part I study, but also through-the-thickness paths between two networks. Accordingly, three kinds of signal paths were established; from the middle plane network, the bottom plane network, and the through-the-thickness network, which are shown in Figure 4.

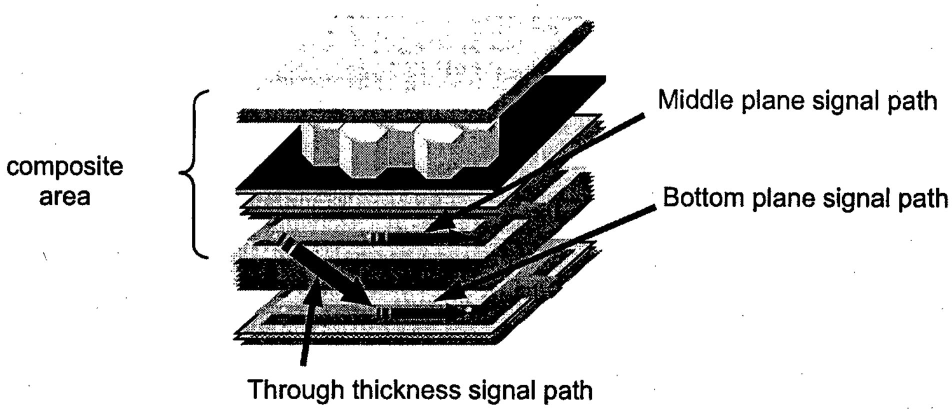


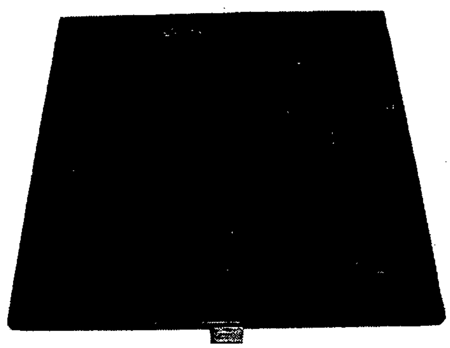
Figure 4. Diagnostic signal paths in a thick composite with two embedded actuator-sensor networks.

By using these signal paths, it was intended to monitor impact damage throughout the panel as follows:

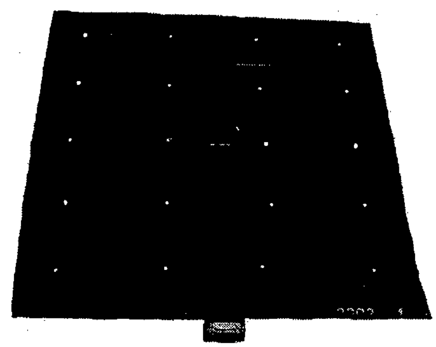
1) The mid-plane network
   - for damage in and near ceramic tiles
2) The bottom network
   - for damage near the bottom layers of the composites
3) Through thickness network
   - for through-thickness damage below ceramic tiles but above bottom layers.

IV. EXPERIMENTAL RESULTS

Ballistic impact test was conducted at United Defense on three specified locations on the composite panel, as shown in Figure 5, where black patches are located (on the right of Figure 5). Due to security reason, the impacted areas were covered by patches so that the inside materials of the structure could not be visualized for the study.



(a) before impact test



(b) after the first impact test

Figure 5. Photographs of the thick composite armor panel before and after ballistic impacts. Black patches indicated the location of impact.

After the impact test, the signals of specific paths were obtained and compared with the base line signals which had been recorded previously. As there were three impact locations on the panel, three areas were mainly examined, with signals obtained. Figure 6 shows these three areas of the thick composite panel with sensor numbering. Each area is the rectangular shape surrounded by four sensors including the impact location.

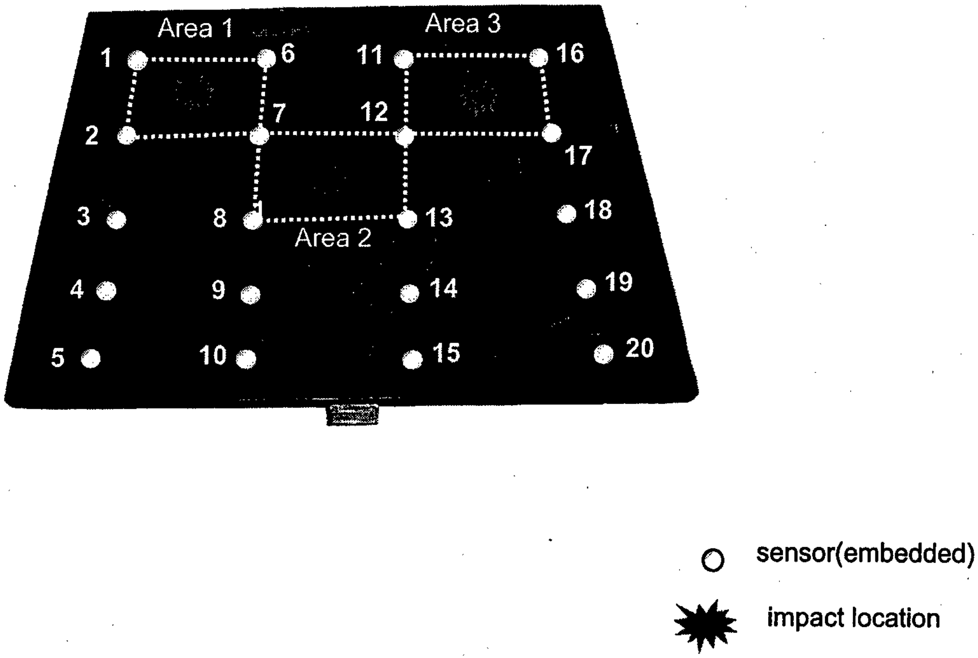


Figure 6. The thick composite panel with sensor numbering

It is worth noting that for the non-damaged area, there was no or little change between baseline signals and after-impact signals. The baseline signals were recorded before the impact tests. Figure 7 shows the signals of path 3-4 in the bottom plane, which means the signal is actuated from sensor 3 and obtained by sensor 4 (conferring the sensor numbering to Figure 6). As this path is away from the damaged area, no noticeable change was recorded as shown in Figure 7. The signals were very repeatable before and after impact for nearly three months.

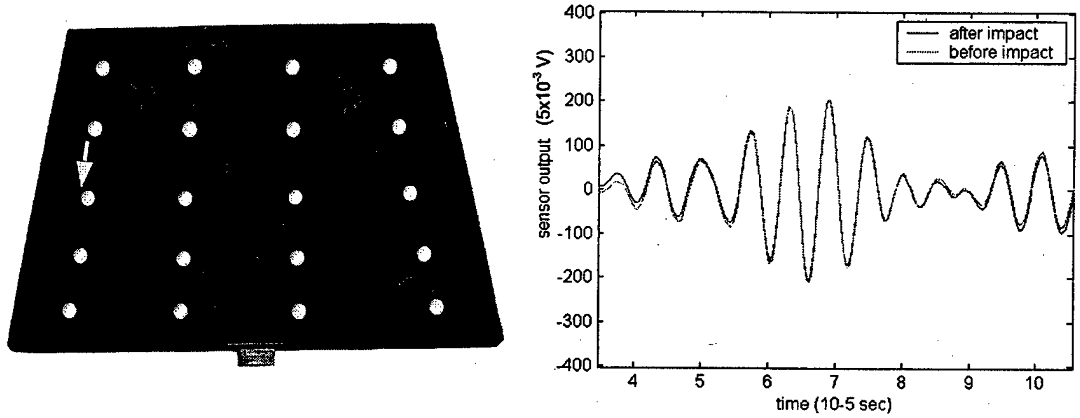


Figure 7 Unnoticeable changes in sensor signals from path 3-4 away from impacted areas.

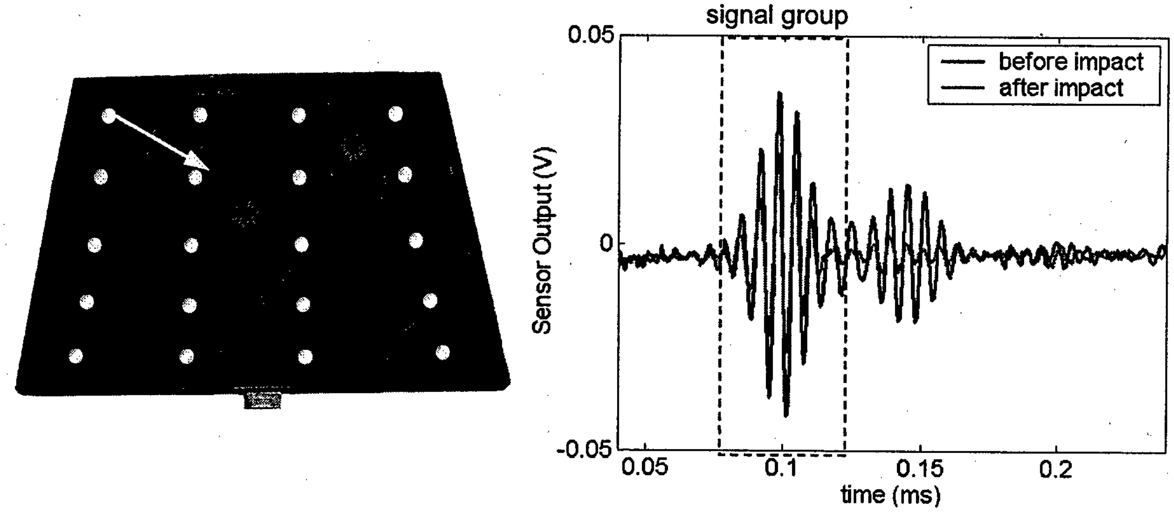


Figure 8. Significant change in sensor output for the path 11-17 which passed through the damaged area.

Compared with the baseline (the blue line), the signal on path 11-17 after the impact test showed significant decrease in amplitude (the red line). The amplitude change was very clear in the first arrive group signal which resembles the 5 peak signal sent from the actuator. This kind of change in amplitude (scatter) is observed clearly in the signals which passed through the damaged area and the rate of amplitude change might indicate the severity of the damage in the area where the path covers.

The amplitude change is expressed as (1),

$$\begin{matrix} amplitude \\ change \end{matrix} = \frac{a-b}{a} \times 100(\%) \qquad (1)$$

where a=amplitude of the signal in baseline, b=amplitude of the signal after impact. Figure 9 shows how the amplitude change was calculated from Equation (1).

As two SMART layers in the thick composite panel provided multiple signal paths on the planes and through-the-thickness planes, more than 300 actuator-sensor paths were examined and the scatters (the difference between the baseline and the measurements) were recorded, particularly in terms of amplitude.

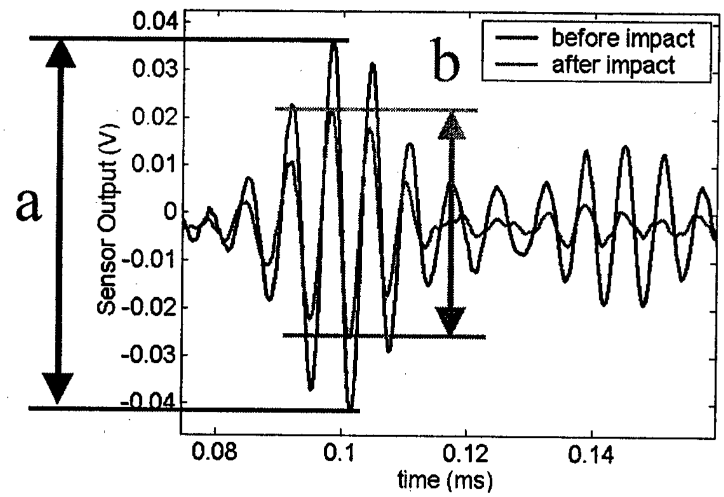


Figure 9. Amplitude change

Using the equation (1), the amplitude change of each signal path can be calculated after the impact test. A linear relationship was assumed between the severity of damage and the amplitude reduction in signal. Figure 10 shows the amount of amplitude change in some selected paths scaled with various colors. The red indicated the highest change in amplitude and the blue implied no reduction in amplitude. Unfortunately, some sensors could not be used in the tests due to grounding problems from manufacturing, as indicated in the Figure also.

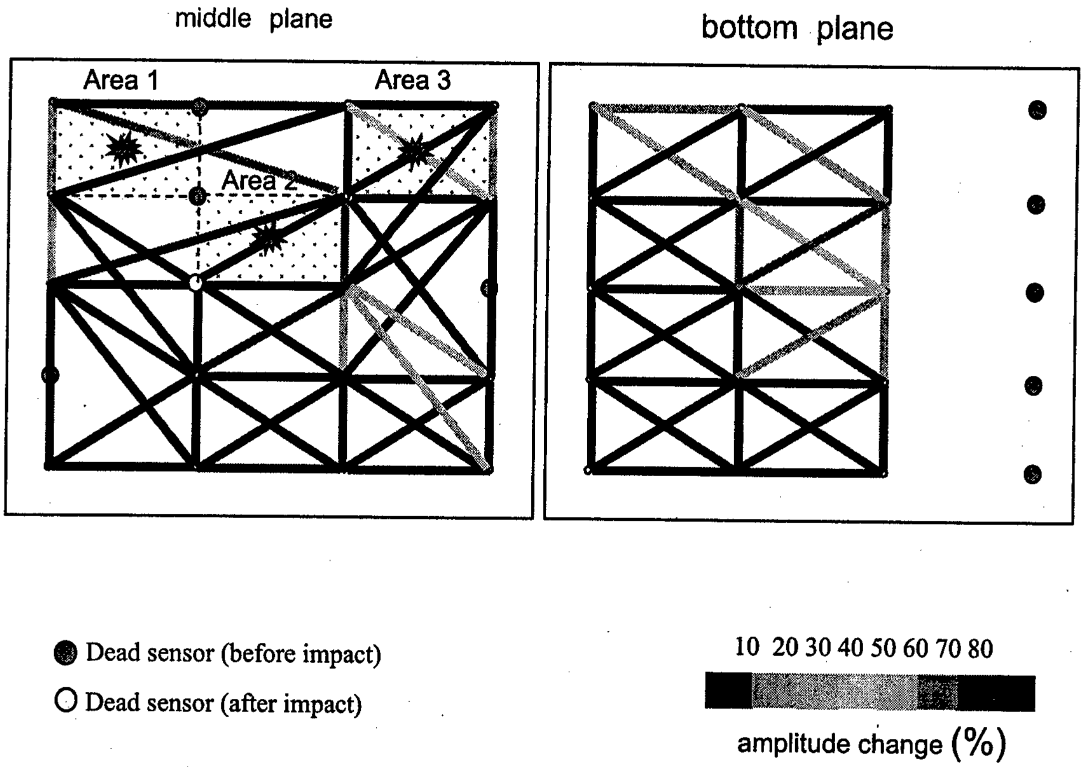
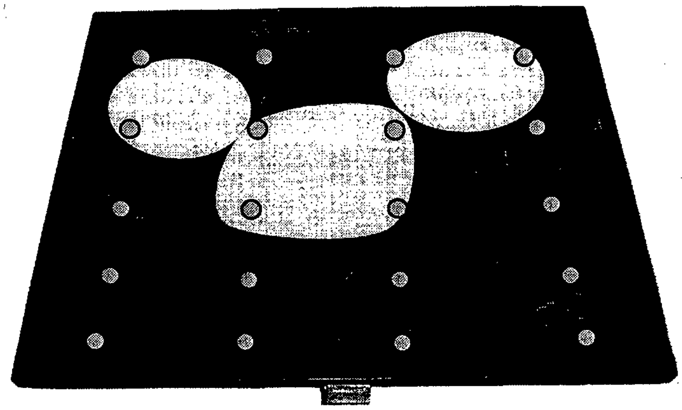
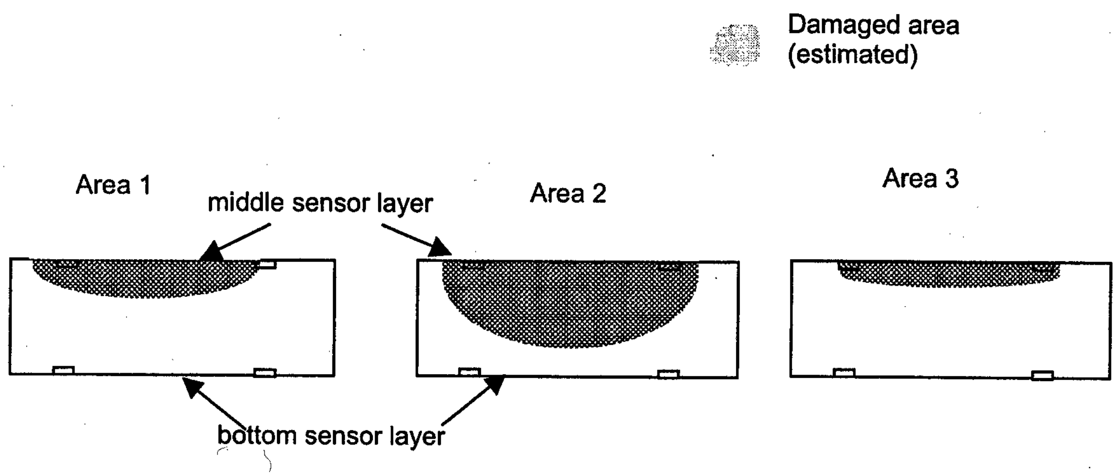


Figure 10. Amplitude change in middle and bottom plane

With the assistance of Figure 10 and a linear relationship assumption between damage and amplitude reduction, the extent and the depth of the damage in each impact area were roughly estimated and sketched out as shown in Figure 11. No attempt was made to use the identification method proposed in Part I to predict the damage size, since the method was only applicable for Lamb waves propagating on plates. The signals generated from the thick composites are truly three dimensional stress waves. Further study would be needed in order to properly interpret the change of signals in terms of damage size and depth.



(a) tile and upper layers



(b) thickness direction

Figure 11. Estimated damage sizes and depths in multi-layered thick armor panel after the impacts.

V. CONCLUSION

Built-in active sensing diagnostic technique developed in Part I of the study has been applied to assess damage in a multi-layered thick armor composite panel. Two sets of piezoelectric sensor/actuator networks were embedded inside the panel at different locations through the thickness to form a 3-dimensional sensor-actuator interrogation network for the thick composite.

Significant changes in sensor measurements, particularly the amplitude, have been found near the region where the panel has suffered from ballistic impact with even minimum surface damage. Based on the results of 3-dimensional interrogation, the extent and depth of invisible damage in the thick composite resulting from ballistic impact were created in a three-dimensional map.

Unfortunately, due to Army security reason, the contents of the materials and the actual damage in the composite could not be either obtained or examined. Therefore, no comparison was possible between the prediction and the actual damage.

However, the results of the study showed a significant promise of the proposed approach for interrogation of damage in multi-layered thick composites. Further studies would be necessary to develop further physics-based identification algorithms and to perform more experiments to correlate with the predictions.

ACKNOWLEDGMENT

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