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Linear and non-linear analysis of composite plates using guided acoustic waves

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Abstract

Guided acoustic wave techniques have been found to be very effective for damage detection. In this investigation Lead Zirconate Titanate (PZT) transducers are used to generate guided acoustic waves for structural health monitoring of a variety of composite specimens. Multiple sets of composite plate specimens are inspected for impact induced damage detection using PZT transducers. Composite samples are divided into two groups for comparative studies i.e. glass fiber composites and basalt fiber composites. They are damaged by impactors having different levels of impact energy. A chirp signal is excited and propagated through the specimens in a single sided excitation/detection setup to investigate the damages induced by impacts of varying intensity. Signal processing of the recorded signals for damage analysis involved both linear and nonlinear analyses. Linear ultrasonic analysis such as change in the time-of-flight of the propagating waves, Fast Fourier Transform and S-Transform of the recorded signals were tried out while the nonlinear ultrasonic analysis involved the Sideband Peak Count or the SPC technique.

Keywords: Guided ultrasonic waves, S-Transform (ST), Damage detection, Fast Fourier Transform (FFT), Side band peak count (SPC), Lead Zirconate Titanate (PZT), Non-Destructive Testing (NDT), Time of flight (TOF)

1. Introduction

In recent years the use of guided acoustic waves for non-destructive evaluation (NDE) has become increasingly popular for analyzing composite plates. It is often difficult to extract features for monitoring impact damages in composite plates using only traditional linear techniques therefore, this study will present both linear^[1] and non-linear methods^[2] of analysis. Guided acoustic waves are widely used for NDE to extract features for detecting and monitoring damages^[1-10]. Multiple sets of composite plates are fabricated and examined by generating guided ultrasonic waves using Lead Zirconate Titanate (PZT) transducers. The composite plates are fabricated using thermoplastic resins due to their growing popularity in many fields, such as aerospace structures and marine structures.

2. Experimental Procedure

2.1. Materials

The thermoplastic composite plates examined in this study are comprised of two types of reinforcing fibers - glass and basalt fibers. Each plate has 18 plies of reinforcing material which make up 50% of the samples by weight. A total of 6 sets of samples were analyzed. Each set has 3 samples giving a total of 18 samples. The 3 samples in a set are impacted with varying degrees of impact energy. 3 sets are reinforced with glass fibers and 3 sets are reinforced with basalt fibers; however, none of the sets have identical properties. The composite plates have a length of 20 cm a width of 10 cm and a thickness of 3 mm. the densities of the samples and impact energies are summarized in Table.1 (Glass Fiber Samples) and Table. 2 (Basalt Fiber Samples).

Table 1: Summary of Glass Fiber Samples

Glass Set	Number of Samples	Density g/cc	Impact Energy
A	3	1.72	0J (no impact), 20J, 30J
B	3	1.72	10J, 20J, 30J
C	3	1.84	10J, 20J, 30J

Table 2: Summary of Basalt Fiber Samples

Basalt Set	Number of Samples	Density g/cc	Impact Energy
X	3	1.94	10J, 20J, 30J
Y	3	1.82	10J, 20J, 30J
Z	3	1.82	10J, 20J, 30J

Figure 1: Photo of Glass Fiber Samples with Varying Impacts

All sets of composite plates are impacted at the center of the samples with varying degrees of impact energy. A single set of glass fiber samples are shown in Figure.1. It can be seen in Figure. 1 that the impact energy increases from

right to left. Additionally, a set of basalt fiber samples are shown in Figure. 2. Comparing these two sets of samples one can conclude that different failure mechanisms cause these damages in the two sets of samples although they are impacted in the same manner.

Figure 2: Photo of Basalt Fiber Samples with Varying Impacts

2.2. Instrumentation and Methods

The instrumentation and methods used in this study is summarized in Figure. 3. A computer controlled arbitrary function generator produces an electric pulse that is converted to an ultrasonic pulse by the transducer (excitation). The ultrasonic pulse then propagates through the composite plate specimen. At the receiving end, the ultrasonic pulse is detected and then converted back to an electric signal by a second transducer (detection). The PZT transducers that were used for this experiment ^[5-6] have a diameter of 3.50 cm and a thickness of 0.02 cm. The transducers are attached in direct contact with the composite samples when exciting and receiving the signal. For data acquisition, longitudinal guided wave modes are generated and propagated through the samples. TiePie engineering handy scope (HS3) is used as the arbitrary function (wave form) generator and transient recorder. The transient recorder has two channels that can record signals with a sampling frequency of 100 MHz, 8 bit resolution, and a memory of 131060 samples per channel. The arbitrary function generator is connected to a standard notebook PC that is used to log the data. The interfacing between the arbitrary function generator and synchronized transient recorder is programmed using LabVIEW®.

Figure 3: Schematic Diagram of the Experimental Setup

2.3. Methods

As explained earlier, data acquisition is done in transmission mode. A chirp signal is excited in a range from 50 kHz to 250 kHz. In Figure. 4 a transient response is shown for the 0J impact energy sample of glass set A (see Table 1). Similarly, responses for all samples are recorded and processed. Transient signals are normalized to 1 for better comparative studies.

Figure 4: Transient Response of Glass Fiber Set A with 0 J Impact Energy

3. Results and Discussion

3.1. Linear Analysis

3.1.1. Fast Fourier Transform

A fast Fourier transform (FFT) is an algorithm that samples a signal over a period and divides it into its frequency components. In Figures 5 and 6, FFT's of three transient responses for sets A, B and C of glass fiber samples and for sets X, Y and Z of basalt fiber samples are presented, respectively. Intensity changes are compared by normalizing all data to that corresponding to the sample impacted by the lowest impact energy.

Figure 5: FFTs of All Glass Fiber Samples

Figure 6: FFTs of All Basalt Fiber Samples

Clearly, the magnitudes of the peaks and frequency response change with varying impact energy. The FFTs, used in this study to perform the nonlinear ultrasonic analysis based on the Sideband Peak Count (SPC) that will be discussed later, are also useful in determining how sensitive the samples are to specific frequencies.

3.1.2. S-Transform

The S-Transform is a combination of both Short Time Fourier Transform and Continuous Wavelet Transform. The S-Transform of a signal can be seen as a modified Short Time Fourier Transform with a Gaussian window of varying width and height as a function of frequency. It can also be interpreted as a modified wavelet transform (WT) with the phase correction in the mother wavelet. This modified wavelet ignores the wavelet's admissibility criterion of having the zero mean and, hence, cannot be considered as a Continuous Wavelet Transform.

Figure 7: S-Transforms of Glass Fibers Set A

The Different peaks of the S-Transform plots shown in Figure. 7 represent the wave packets that are present in the transient signal. In details, the top left plot of Figure. 7 is obtained from the transient signal that can be seen in Figure. 4. These different peaks in the S-Transform plots are monitored and changes in TOF, frequency, and magnitude of the peaks are summarized and shown in Table. 3. All plot magnitudes are normalized with respect to the values obtained from the sample impacted by the lowest impact energy.

Table 3: Highest Peak values from S-Transform plots for Glass Fibers Set A

Sample	Frequency (MHz)	Time (Millisecond)	Magnitude
0J	0.118	0.06966	1
20J	0.118	0.06895	0.81497
30J	0.106	0.06812	1.004

Data of S-Transform plots for sets B and C, not shown here, are summarized in Tables 4 and 5, respectively. The tables show information obtained from the most dominant peak for each sample that has approximately the same frequency. By examining the dominant peaks at a frequency, any shift in time of that peak can be attributed to the effect of the varying impact energy.

Table 4: Highest Peak Data from S-Transforms of Glass Fibers Set B

Sample	Frequency (MHz)	Time (Millisecond)	Magnitude
10J	0.1	0.0751	1
20J	0.102	0.07281	0.96313
30J	0.102	0.0717	0.84099

Table 5: Highest Peak Data from S-Transforms of Glass Fibers Set C

Sample	Frequency (MHz)	Time (Millisecond)	Magnitude
10J	0.102	0.06194	1
20J	0.108	0.07317	1.4826
30J	0.108	0.06868	1.1836

Figure 8: S-Transforms of Basalt Fibers Set X

The S-Transform plots of the basalt fiber (set X) samples are shown in Figure. 8. As before, the data corresponding to the dominant peaks with approximately the same frequency are recorded and summarized in Tables 6-8.

Table 6: Highest Peak Data from S-Transforms of Basalt Fibers Set X

Sample	Frequency (MHz)	Time (Millisecond)	Magnitude
10J	0.106	0.07132	1
20J	0.108	0.06956	1.1727
30J	0.112	0.06809	0.8111

Again, data from S-Transform plots of the basalt sets Y and Z, not shown here, are summarized in Tables 7 and 8. In this case, it is observed that the magnitude of the peaks decrease with the increase in impact energy.

Table 7: Highest Peak Data from S-Transforms of Basalt Fibers Set Y

Sample	Frequency (MHz)	Time (Millisecond)	Magnitude
10J	0.106	0.07054	1
20J	0.106	0.06494	0.62351
30J	0.110	0.06177	0.53175

Table 8: Highest Peak Data from S-Transforms of Basalt Fibers Set Z

Sample	Frequency (MHz)	Time (Millisecond)	Magnitude
10J	0.100	0.06302	1
20J	0.112	0.06748	0.86572
30J	0.112	0.06173	0.70451

3.1.3. Time of Flight

The change in the signal arrival time, or in other words the change in time of flight (TOF), is first investigated. From the S-Transform plots, the variations of the TOF for damaged specimens relative to a reference specimen (which is the least damaged specimen) are plotted in Figures 9 and 10 for the most dominant peaks. The plots show the variations of TOF as the impact energy changes, for all investigated samples.

Figure 9: Time-of-Flight Plot of All Glass Fiber Sets

Generally speaking, it can be seen that TOF decreases with the increase of the impact energy. However, sets C and Z exhibit a trend that is not monotonic, presumably due to the occurring failure mechanisms.

Figure 10: Time-of-Flight Plot of All Basalt Fiber Sets

3.2. Non-Linear Analysis

3.2.1. Sideband Peak Count

The non-linear analysis of the samples is performed using sideband peak count (SPC). The SPC technique counts the number of peaks in the FFT plots for given threshold values. In general, a linear material shows fewer peaks compared to a non-linear material. Therefore, SPC values for linear and nonlinear materials should be different. The composite plates examined in this study show some non-linear behavior to start with. Increasing impact energy causes more damage in the material, and causes the material more non-linear. Obtaining sideband peak count or SPC values requires relatively simple signal processing tools that are implemented to count the number of peaks observed for a given threshold value. First, the total number of peaks in the FFT plot are counted for all signals shown in Figure. 11. Then, a threshold is set, and the number of peaks below the threshold are counted. Finally, the number of peaks above the threshold are calculated by subtracting the number of peaks below the threshold from the total number of peaks.

Figure 11: Visualization of FFT and Threshold of SPC

The threshold value can be increased or decreased which is useful for studying the full spectrum of peaks. For example, a threshold value of 20% will only analyze the peaks that go up to 20% of the FFT's peak magnitude value. Therefore, peaks at 20% threshold are 0 since the peaks above 20% are disregarded. This can be useful in finding the range of peaks that are more influenced by the impact energies. A threshold value of 100% is always examined. However, may not always show a clear trend. Figures 12 and 14 show the SPC of both glass and basalt fiber composite sets, respectively, at a threshold value of 100%. In the case of the basalt fibers a trend can be seen for all sets at a threshold of 100%. The least damaged sample generally has a lower peak count than the samples with more damage.

The sets of glass fibers do not show a clear trend at a threshold of 100%. Therefore, the SPC plots are again plotted at a threshold of 20% where a trend is clearer. As explained earlier these changes in threshold values can be due to the different material and different failure mechanism. Further studies are required to select proper thresholds for certain materials or failure mechanisms. The sets B and C show a trend of increasing peaks for higher impact energies however, set A does not demonstrate the same behavior. At a threshold of 20% as shown in Figure. 13 the trend can clearly be seen in set A however, it is not as clear in sets B and C.

Figure 12: SPC of All Glass Fiber Sets at 100% Threshold

Figure 13: SPC of All Glass Fiber Sets at 20% Threshold

Figure 14: SPC of All Basalt Fiber Sets at 100% Threshold

4. Conclusion

To conclude it is observed that both linear and non-linear ultrasonic techniques show some promising results in monitoring damages in composite plate specimens. The linear S-Transform based TOF analysis seems to be capable of detecting samples with higher impact energies. The decrease in TOF can be related to the impact energy and induced damage. The TOF technique is advantageous since it is not sensitive to the bonding condition between the transducers and composite plate samples. Furthermore, the non-linear SPC technique shows clear distinctions and trends with varying impact energies. However, more studies are needed to determine which threshold values and what peaks are affected by certain failure mechanisms.

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