

Non-destructive Inspection of Multi-layered Composites Using Ultrasonic Signal Processing

S.C. Ng¹, N. Ismail^{1,2}, Aidy Ali¹, Barkawi Sahari^{1,2}, J.M. Yusof², B.W. Chu²

¹Intelligent System and Robotic Laboratory, Institute of Advanced Technology, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

²Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

³Sports Engineering Research Group, Sports Academy, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

Email: ngsokchoo@gmail.com

172 word abstract

1. Introduction

A composite [1] takes advantage of the inherent properties of each phase that is combined to form laminates or sandwich structures. For example, glass fibre-reinforced plastics (GRP) are widely used in structural applications such as vessels, ships and tanks due to their high tensile and compressive strength, and corrosion resistance properties. However, composite structures can encounter damage under mechanical loading and temperature degradation. Typical failure modes in a laminated composite are delamination, matrix cracks and fibre fracture [2][3]. The defect that is most commonly found in composites is delamination that occurs parallel to the surface of the structure [1]. Typically, delamination can be caused by several factors: (1) air that is trapped between prepreg sheets in the lay up process and failure of carefully removing the prepreg backing film during manufacturing [1], and (2) external loads during in-service. These failure modes affect the mechanical properties of the composite structure. The growth of delamination at the internal part of a structure is inaccessible to human visibility until severe damages propagate to the surface of the structure that could cause unbearable loss to company and industry. Thus, non-invasive damage evaluations are needed to inspect the failure in composite materials for the purpose of ensuring the integrity of a structure.

Various non-destructive testing (NDT) methods [4-7] were designed to control and ensure the integrity of parts and structures. The adoption of these methods in an application is highly dependent on the material

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properties and nature of the flaws. Over the last decades, ultrasonic techniques have been the most widely used non-destructive testing and evaluation (NDE&T) method to analyze internal defects occurred inside a structure. Ultrasonic testing is based on the detection and interpretation of reflected ultrasonic waves by defects [3]. By taking into account the maximal amplitude of ultrasonic echoes, the nature, size and orientation of defects can be characterized. Nevertheless, the detection of defect in composite materials poses a great challenge to ultrasonic non-destructive testing due to the high attenuation of ultrasonic signals that could probably caused by the properties of the constituent materials, fibre orientation and the stacking sequence of the composite materials. The inhomogeneity of composite materials makes the ultrasonic testing complicated. Based on the preliminary study, the technique of providing high signal-to-noise ratio (SNR) [8] has been utilized to detect the flaws in large grained and highly attenuative materials. However, it is difficult to locate the flaws due to interference caused by the grain echoes. Kraus and Goebbels [9] applied the signal averaging technique to improve the signal-to-noise ratio by transmitting many different narrow band signals for the purpose of enhancing the flaw-to-grain echo ratio. In recent research work, signal processing techniques such as wavelet transform [10] and split spectrum processing (SSP) [11] were proposed to improve the localization of the defects in highly attenuative materials. The aim of the current study is to investigate the detection of damage in multi-layered composite materials. Ultrasonic testing is applied to detect the delamination in a multi-layered composite material. Normal-incidence pulse-echo method was used to detect the damage in laminates. A-scan was performed on a multi-layered composite to obtain the time domain data. SSP technique [8][11] were then used to carry out the frequency analysis of the ultrasonic waveform. The remainder of the paper is organized as follows. Section 2 describes the experimental system to detect the internal damage of a multi-layered composite. Section 3 shows the utilization of SSP algorithm to process the ultrasonic signals. The results of the experimental work were presented in section 4. Section 5 concludes the work and explores promising directions for future work and development.

2. Experimental system

A single transducer operating on pulse-echo mode acted as transmitter and receiver of ultrasonic signals. Figure 1 shows the experimental set up of the ultrasonic testing. Two different types of four-layered GRP laminates of 2.5mm thickness were prepared. One was perfect and the other has Teflon-induced delamination at the thickness 1.25mm from the front surface of the specimen. A transducer centered at 5MHz with diameter of 12.5mm was used to transmit and receive the ultrasonic signals.



Figure 1. Pulse-echo ultrasonic testing experimental set up

The ultrasonic testing system worked as follows: The transducer, working on piezoelectric effect [6], transformed electrical pulses into mechanical vibrations to generate ultrasonic waves (pulse). The transducer was placed onto the GRP specimen and the pulse generated was transmitted into the test object (GRP). The pulse travelled through the specimen and responded to the object's geometry and mechanical properties. The returned signal (echo) was then transformed back into electrical pulses that can be observed on an oscilloscope. Figure 2 shows the behaviour of the propagating ultrasonic wave as it encounters a boundary (i.e. voids, cracks or delamination). When there is a discontinuity in the ultrasonic travelling wave path, part of the wave energy will be reflected back from the flaw surface. A 50MHz sampling rate was used to acquire the signals from the receiver.

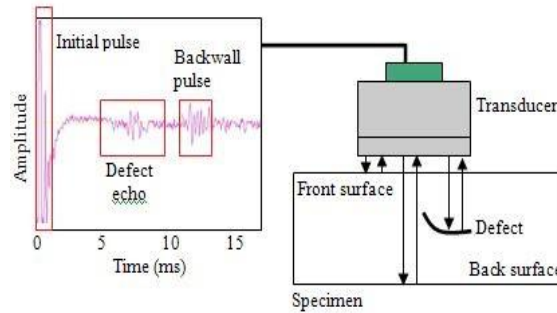


Figure 2. Defect detection by ultrasonic inspection

Pulse-echo method measures the location of a defect by acquiring the time required for the ultrasonic pulse to travel through the thickness of the test material and reflected from the back or surface of a defect to the transducer. The depth of the defect (d) of the test material from the surface is measured by Eq. (1):

$$d = \frac{vt}{2} \quad (1)$$

where v is the velocity of ultrasonic wave in the material and t is time of flight (TOF).

In the inspection of defect in composite materials, the ultrasonic pulse is reflected not only by the defect occurred within the material but by the microstructures and multiple lay ups that can cause the problem of close echoes separation in time as shown in Figure 3. The close spaced echoes cause the difficulty to differentiate the internal flaw reflections and the grain reflections, known as noise in the ultrasonic signals. Thus, post signal processing is needed to resolve the signal drowned in noise for the ultrasonic signals obtained from the experimental system.

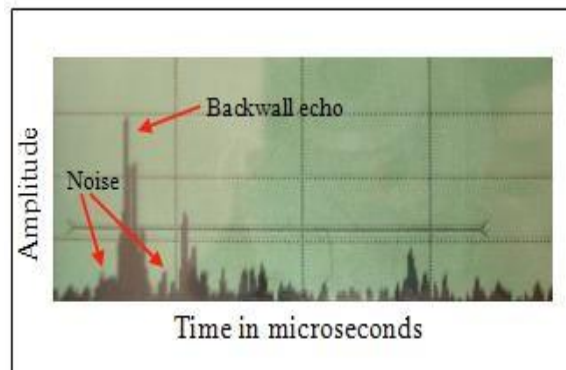


Figure 3. Signal drowned in noise for the response of pristine GPRF

3. Ultrasonic signal processing

To enhance the delamination defect visibility, split spectrum processing (SSP) [11] technique was applied to the received ultrasonic signal. SSP works on the principal of decomposing the received broadband signal into a number of smaller frequency bands by means of digital filtering and finally inverse Fourier transforms each band to obtain the individual frequency shifted signal [12] (Figure 4). This technique can increase the signal-to-noise ratio for the close-spaced echoes. The frequency bands can be represented by a bank of Gaussian band-pass filters. When the bank of filters is applied to the ultrasonic signal, the minimum amplitude for each instance of time is selected to reduce the microstructure signals while retaining the defect signal (minimization). The SSP algorithm [11][13] consists of the following operations:

1. Calculate the signal spectrum of reflected echoes, $x(t)$ by fast Fourier transform.
2. Divide this spectrum into N abjections bands.
3. Calculate the inverse fast Fourier transform of each frequency band to obtain the individual time domain analysis ($y_n'(t)$).

4. Normalize the signal $y'(t)$ to obtain $y(t)$.

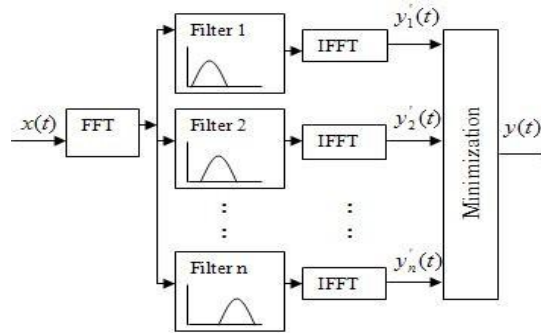


Figure 4. Split spectrum processing process

4. Experimental results

The experiment was conducted on two sets of composite material samples (GRP laminates) in which one set is specimen that has no defect ($S_{pristine}$) while the other is specimen with artificial defect (delamination), S_{defect} at the center of the sample. The dimensions of the samples are 30mm x 65mm x 2.5mm. The sound velocity in this material is $V_{sample} = 2320$ m/s. Figure 5 and 6 show the signal of ultrasonic echoes of $S_{pristine}$ and S_{defect} . In Figure 5, it can be observed that the backwall echo responses at $2.2\mu s$ which approximates the thickness 2.5mm by applying Eq. (1). The defect echo responses earlier than the backwall echo when the ultrasonic wave encounters a boundary (delamination) as shown in Figure 6. Based on the principal of TOF, it can be calculated that the defect distance is 1.27mm which approximates the actual delamination thickness position (1.25mm) of the sample with an error of 1.6%. The fibre constituent and the multi-layered structure of the laminates cause the high absorption of travelling wave in the material. Thus, high SNR is applied to the detection of delamination in the samples.

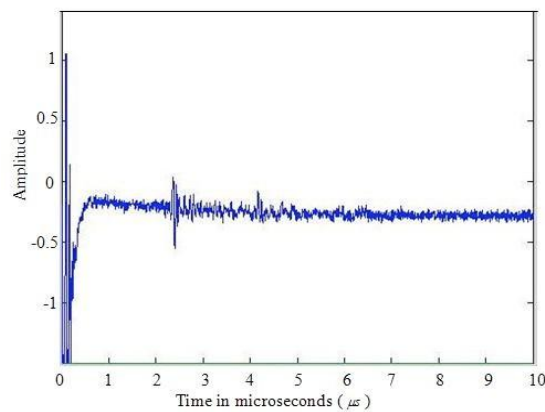


Figure 5. Pristine response of $S_{pristine}$ at 5MHz from receiver

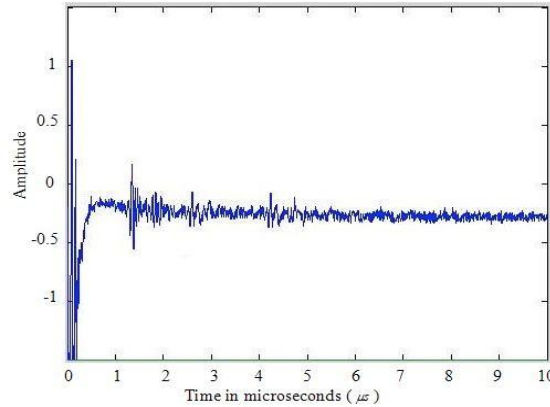


Figure 6. Damage response of S_{defect} at 5MHz from receiver

Figure 6 shows the close spaced echoes that occur between the defect-reflected echo and backwall echo. In Figure 5 and 6, it can be observed that noise signals exist in the receiving echoes due to the reflected signals from microstructure. The signal drowned in noise reduces the flaw visibility. Figure 7 and 8 show the signal of ultrasonic echoes of $S_{pristine}$ and S_{defect} after the process of SSP. The number of filters in the filter bank, N_{filter} is 500. It is noted that the signal drowned in noise is reduced. In Figure 8, the close spaced echoes of the delamination and backsurface are separated after the process of SSP. It can be noticed that in the case of thin thickness composite material, SSP processing is useful to increase the flaw visibility.

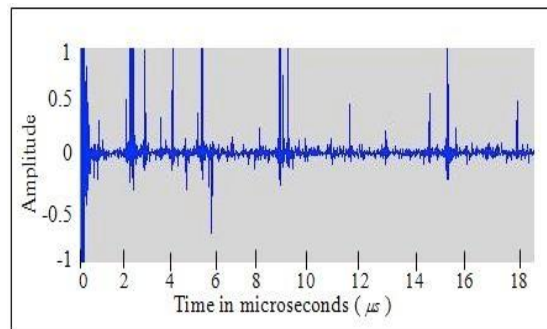


Figure 7. $S_{pristine}$ response obtained by SSP ($N_{filter} = 500$)

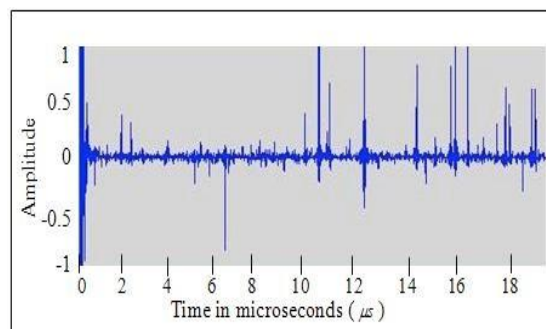


Figure 8. S_{defect} response obtained by SSP ($N_{filter} = 500$)

5. Conclusions

The aim of the present study is to investigate the detection of delamination defect echoes in multi-layered composite structures. A single transducer operating on pulse-echo mode was used to detect the location of the delamination defect in a thin GRP laminate (2.5 mm thickness). SSP signal processing technique has been used to increase SNR by minimizing the signal drowned in noise caused by the microstructure

reflections in the composite materials. SSP realizes nonlinear filtering to eliminate the grain echoes. This technique is based on frequency analysis of the signal spectrum. The time domain of the received signals was Fourier transformed to frequency domain. The spectrum was then split into frequency bands by bank filters to select the minimum output. Each band was finally converted back to time domain by inverse Fourier transform. According to the obtained results, it is proven that SSP technique can successfully improved SNR to increase the flaw visibility. As future work, the localization of the close-to-surface defect (front or backsurface) will be investigated by using SSP.

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