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Damage Inspection and Online Monitoring using Lamb Waves: A Comparative Study on Aluminium and Composite Plate Structures

Royson Dsouza [1,a], Anil Sequeira [1,b], Marian Jose [2] and Gautami Golani [2]

[1] School of Engineering and IT, Manipal University Dubai, Dubai, UAE.
[2] Mechatronics Department, School of Engineering and IT, Manipal University Dubai, Dubai, UAE.

E-mail: [a] roysonnitk@gmail.com, [b] anil.sequeira@manipaldubai.com

Abstract: Structural damage is an important criterion that can affect the system performance and degrade its ability from its original condition. When it comes to an aircraft, it is the wings of the aircraft that is prone to more damages compared to the body since the wings provide overall structure stability to the aircraft. It is thus mandatory to monitor the surface of the aircraft wing periodically in search of new damages or changes occurring in the wing structures. The term Health Monitoring systems is introduced in these precepts, that are useful in identifying damages in aircrafts, space crafts and mechanical infrastructures by taking periodic measurements with the help of various transmitters and sensors. Waves are allowed to propagate through the wing surface and the deviations occurring in the frequency of the waves are recorded and compared which helps in determining the various types of damages that occur. Yet another consideration is that the sensors embedded to the aircraft wing must be light weight, cost effective, user friendly at the same time provide accurate results for easy diagnosis of the problem. This is achieved by making use of lamb waves (also named as guided plate waves). The proposed work aims at the health monitoring of aerospace and mechanical structures, by using the wave propagation method and the use of piezo-electric wafer active sensors. Results have been validated by experimental and analytical calculations and the proposed method shows enhanced performance in the detection of cracks on the structural surfaces.

1. Introduction

Health monitoring signifies a system which can determine undesirable conditions or damages in the structure so as to improve its durability and life-cycle, at the same time reducing the overall maintenance cost. The aerospace industry uses this health monitoring system as regular inspections and repair of aircrafts can prove to be very expensive. To reduce costs, composite materials are being increasingly used as they have excellent specific strength and specific modulus characteristics. Along with this, they are lightweight, resistant to corrosion and chemical attack and also offer better performance than most metals at high temperatures. Damage detection in composite laminates is difficult due to its anisotropy. Non-destructive evaluation (NTE) methods are used for assessing the safety of the composite. One such method is C-scan, but it is unrealistic for the examination of large components. Others like Eddy Currents, Visual inspection, X-ray radiography and Ultrasounds are expensive, time-consuming and can be performed on surfaces that are accessible only.

Lamb wave based structural health monitoring is widely used in recent times. Lamb waves are guided acoustic waves that propagate in the plane of the structure, which according to its displacement patterns, it can be divided into symmetric Sn and anti-symmetric An lamb waves with respect to the mid-plane of the structure [1]. Lamb wave find its potential application for a large area Non-Destructive Investigation (NDI) due to the advantage of Lamb wave being able to transmit and receive for long distances.
Some of the universally used transducers for non-destructive testing are angle piezoelectric wedge transducers [2] [3], comb transducers and electromagnetic acoustic transducers (EMATs) [4]. Also used are Hertzian contact transducers and lasers. These transducers are efficient for performing maintenance checks when the structure is offline for servicing, but not compact enough to be permanently mounted on-board the structure. Surface-bonded or embedded piezoelectric wafer transducer is one of the very universally used transducers for structural health monitoring. Piezoelectric transducers are inexpensive and are manufactured in sizes of incredibly low thickness, and can thus be easily integrated into structures without causing much obstruction or inconvenience. They further couple the electrical and automated behaviour of the material being monitored. The piezoelectric effect and its inverse effect act as the principles that manage their operation. The major materials universally offered are lead zirconium titanate ceramic, also known as PZT and a polymer film namely, polyvinylidene fluoride (PVDF), designed by Monkhouse [5] [6]. Therefore, PZT is the very commonly used for health monitoring [7] [8] [9] [10].
An acoustic based structural health monitoring (SHM) system was developed for composite structures [11]. The construction of Low Profile Acoustic Transducer (LPAS) is similar to angled wedge ultrasonic transducers that are used for offline NDT. These are used to generate Guided Waves (GWs). The size of these transducers are much smaller when compared with conventional ultrasonic transducers, and thus they possess higher possibility of using them as on-board SHM transducers.

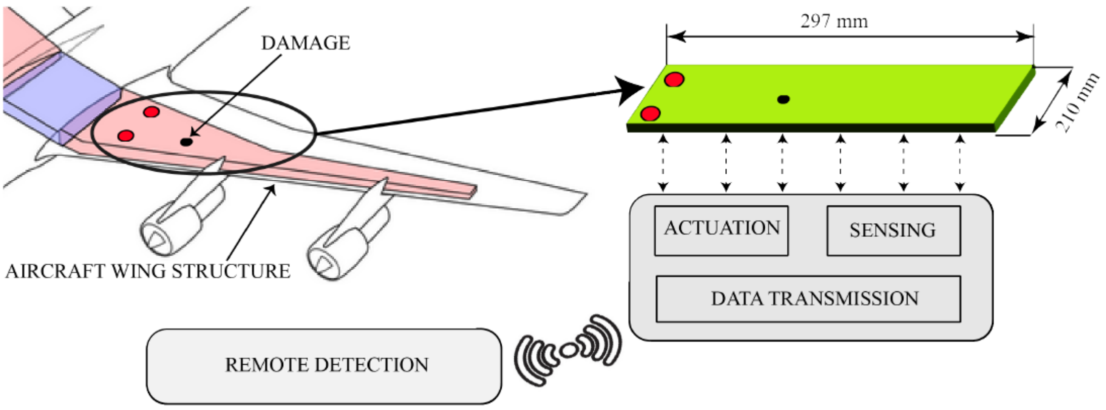


Figure 1. Concept of Structural Health Monitoring using Lamb Waves

The use of guided waves in structural health monitoring and its effects of elevated temperature in internal spacecraft structures is studied and presented [12]. A detailed review on the use of non-linear guided wave in the structural health monitoring on real-time implementation of industry problems is carefully studied [13]. The authors in [14] have shown the creation of damage index for evaluating the extent of damage in composite laminates using guided waves. The debonding effect is more precisely investigated with mathematical simulations and experimental models on the piezo-induced wavefield [15]. The concept of structural health monitoring using lamb waves is shown in Figure1. A detailed study on actuation and sensing properties of Piezoelectric surface mounted transducers at various temperatures is carried out for Lamb wave based damage detection. Experimental validation is also provided for the same [16].
The primary objective is to fabricate Carbon Fiber Reinforced Plastics (CFRP) plates (297×210mm) of 4-ply and propagate lamb waves through these plates with and without crack and later interface the signal that is output from the digital oscilloscope to a laptop with LabView installed in it to detect the

position of the crack. ABAQUS 6.14 is used for simulation of the lamb waves through the CFRP plates in order to match the ABAQUS results with the experimental results and later identify the percentage error or the deviation occurring of experimentally generated results from the theoretical.
The Aluminium plate (thickness 1.2mm) tested results are also compared with the CFRP plates in order to study the wave nature of both the materials. The experiment was also performed on Aluminium and CFRP plates of varied plys by subjecting linear wave scans on them. The transmitted and reflected waves were monitored with circular disk type piezoelectric sensors. ABAQUS models have been developed to select actuator configurations that are ideal for the actuating signals generated in the experiments.
The experimental and theoretical results have been compared among the models developed and they have been used to identify the percentage error that helps in predicting the damage detection capabilities. The techniques employed using Lamb wave provide localized information about the structural and are thus well suited for health monitoring applications.

2. FEA Modeling and Analysis
A 3D Finite element modelling and analysis was carried out using Abaqus FEA software to determine and analyze the response of Aluminium and CFRP specimens subjected to damage and undamaged conditions. Dynamic explicit module being chosen for a time instance of 0.5ms. Approximate global size of 0.001 is selected for Global seed mesh size. The excitation direction is provided along the axis of the plane. The FEA is performed for both Aluminium and CFRP specimens.

2.1 Aluminium plates without and with damage
Preliminary analysis is carried out on a Aluminium plate of 1.5mm thickness and dimensions 297mm×210mm attached with a piezo-electric wafer active disk type actuator and a sensor of diameter 7mm. When voltage is applied on to the actuator at a frequency of 150 KHz, lamb waves are generated in omni-direction to the surface and these waves collide with the edges of the plate scatters all over the plate and reaches the sensor which receives these waves.
Lamb waves generated from the piezo-electric actuator propagate through the surface of the plate and spreads all over the plate. When these waves meet the region where damage is present the waves collides and gets reflected as shown in Figure 2. To simulate the damage a hole of 20mm was created exactly at the centre of the plate.

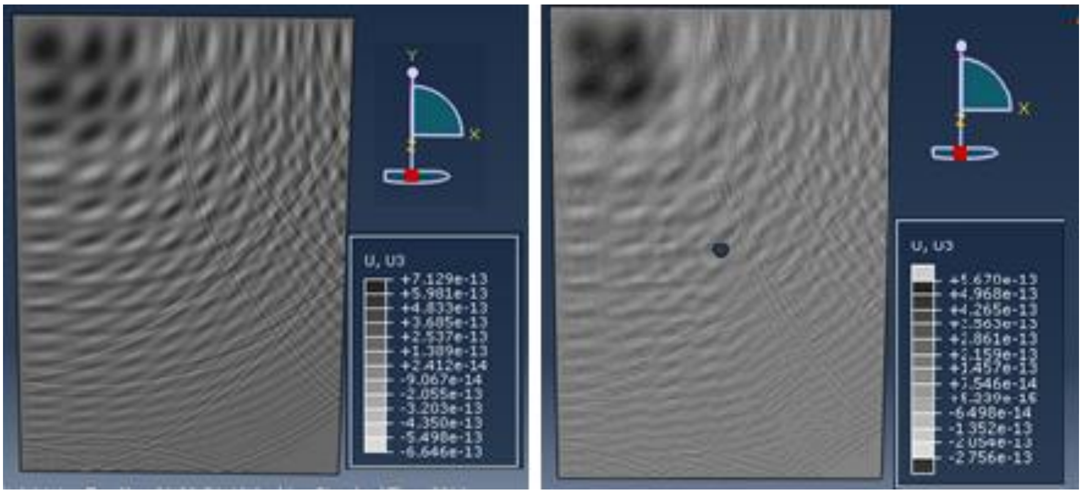


Figure 2. FEA Simulations of Aluminium specimen without and with defect

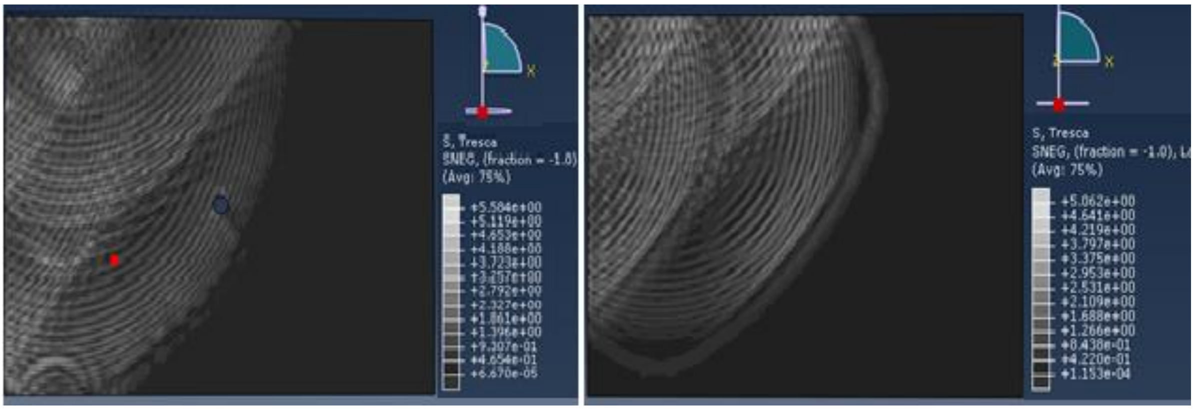


Figure 3. FEA Simulations of CFRP specimen with and without defect

The location of the crack is given by Equation1.

$$\alpha = \frac{L\Delta t_{dam}}{\Delta t_L} \tag{1}$$

Where, Ld= Location of the crack from the left hand edge of the specimen.
L=Length of the specimen.
Δt=Time taken by the reflected lamb wave on the reference specimen.
Δtd Time taken by the reflected wave on the specimen with crack.
From the Figure 4, it is seen that the amplitude peak due to the first reflected wave is seen at a time period of 0.31×10^{-3}s. In graph 4.2, an amplitude variation due to crack is seen at 0.15×10^{-4}s the time taken by the reflected wave. Substituting the parameters the location of the crack is found to be 148mm. Figure 4 clearly shows the amplitude time domain signals of FEA simulation results. The transmitted signal and reflected signal can be clearly distinguished alongside the change of amplitude with respect to time. A change in amplitude is clearly observed when the aluminium plate specimen is subjected to damage. The output response of Aluminium plate specimen without damage is taken as reference signal as shown in Figure 4(a). When the plate is subjected to damage the change in the amplitude is observed in Figure 4(c). Arithmetic difference is the difference between the current signal with the reference signal. Figure 4(d) shows a appreciable arithmetic difference between the signal of Aluminium plate specimen with crack and reference signal.

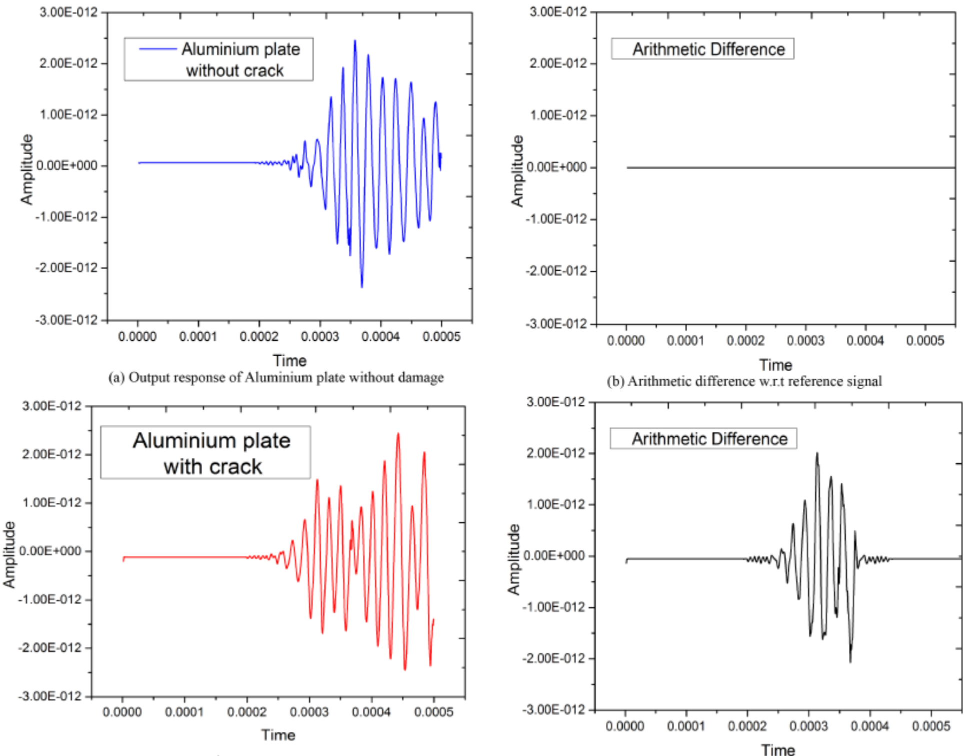
2.2 Carbon Fibre Plate without and with damage

Carbon fibre reinforced plastics (CFRP) of 4-ply are tested without crack initially and the generated waves travel through the cross-ply and matrix and reach the piezo-electric sensor which outputs the signal to the wave order to compare the results with the crack formation. Lamb waves generated from the piezo-electric actuator propagate through the surface of the CFRP plate and spreads all over the plate. When these waves strike the region where the two cracks are present the waves collide and get reflected as shown in Figure 3. These reflected waves are obtained at the receiving sensor and transferred to the digital oscilloscope which saves the output waveform. Later, the waveforms obtained on the CFRP plate with crack and the plate without crack is compared and the location of the crack is obtained. Substituting the values of variables from the graph in Equation 1 the location of the crack is found to be 147.5mm. Figure 5 clearly shows the amplitude time domain signals of FEA simulation results. The transmitted signal and reflected signal can be clearly distinguished alongside the change of amplitude with respect to time. A change in amplitude is clearly observed when the CFRP plate specimen is subjected to damage. The output response of CFRP plate specimen without damage is taken as reference signal as shown in Figure 5(a). When the plate is subjected to damage the change in the amplitude is observed in Figure 5(c). Arithmetic difference is the difference between the current signal with the reference signal. Figure 5(d) shows a appreciable arithmetic difference between the signal of CFRP plate specimen with crack and reference signal.

3. Experimental Setup

Keeping the input and output requirements, an experimental setup is designed to investigate the behavior of lamb waves in CFRP plate specimen in comparision with Aluminium plate specimen subjected to damage and no damage. The schematic diagram of the experimental setup is shown in Figure 6.The testing for damage has been carried out using Aluminium plates and Carbon Fibre Reinforced Plastics (CFRP). Lamb waves are generated on specimen of size 210×297 mm by applying a sinusoidal wave of 11Vp-p voltage at a frequency of 240KHz to a piezoelectric disc operated in the longitudinal mode by using Scientec 4061 Signal generator. The experimental setup was placed as shown in Figure 7. When voltage is supplied to the piezoelectric disc it expands and contracts parallel to the surface of the plate which produces a bending moment that generates the lamb waves.

The propagation of the generated lamb waves are used for identifying the location of the damage on the basis of time delay caused by the subsequent reflected waves from the specimens boundaries. Tests were performed on specimens made of Aluminium of size 210×297×1.2 mm having density=2.580g/cm^3,shear modulus=23GPa, youngs modulus=72GPa. The plate was instrumented using two piezoelectric discs of size 20 mm diameter made of commercial brass backed piezo ceramic resonators where one PZT was used as an actuator (PZT 1) and the other used as a sensor (PZT 2) bonded at the end of the plate as shown in Figure 6.



(a) Output response of Aluminium plate without damage

(b) Arithmetic difference w.r.t reference signal

(c) Output response of Aluminum plate with damage

(d) Arithmetic difference w.r.t reference signal and (c)

Figure 4. FEA Simulated response Arithmetic difference between the response signals of the Aluminum specimen

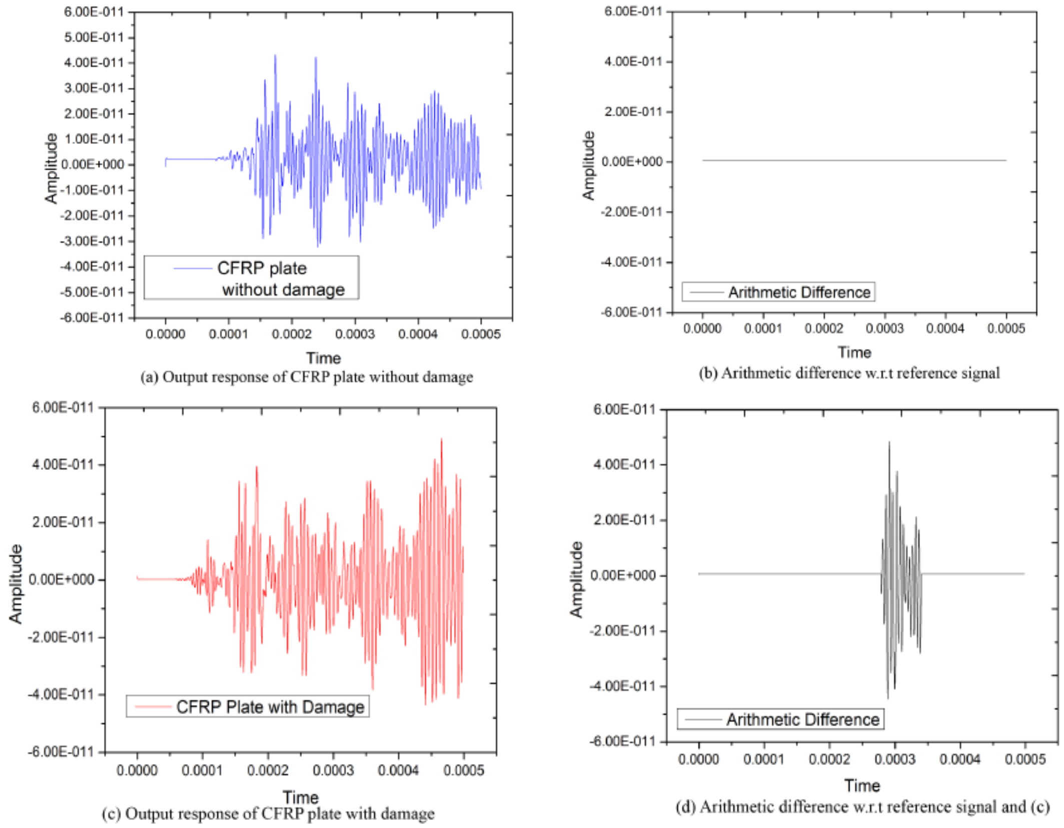


Figure 5. FEA Simulated response Arithmetic difference between the response signals of the CFRP specimen

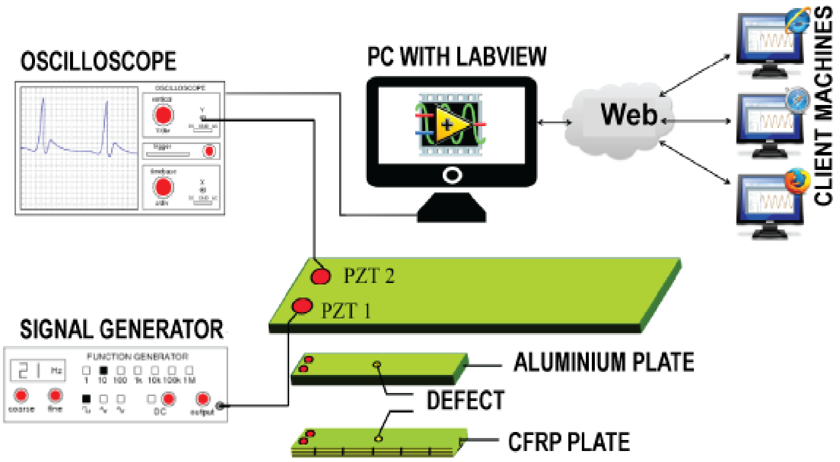


Figure 6. Schematic diagram of the experimental setup

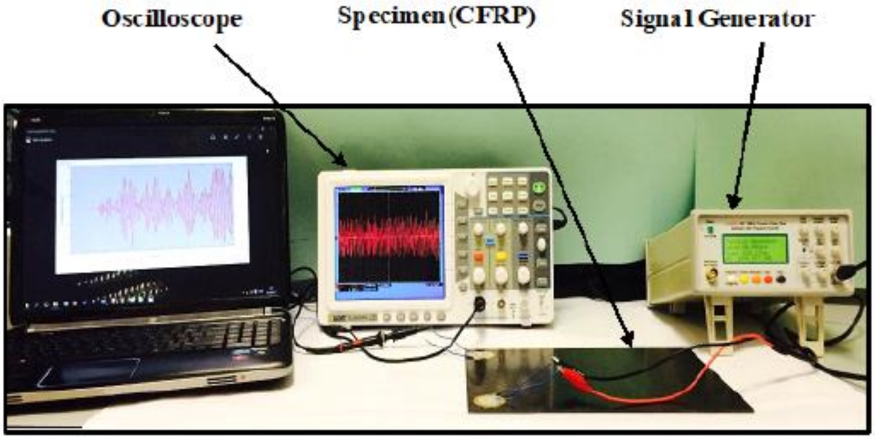


Figure 7. Experimental setup

The same experimental setup and procedure used for the analysis of Aluminium plate is used for the testing of Carbon fibre. All the four test plates were tested by following the aforementioned procedures and the waveform obtained by the defect-free plate was used as the reference and compared with the waveform obtained by the plate having the defect. The resultant waveform signals were analyzed using LabVIEW. Arithmetic difference of the signals, display of location of crack is developed in front Panel of LabVIEW. The application is then deployed to the webserver which is then remotely monitored using Ethernet Communication.

4. Results and Discussions

Tests are carried on Aluminium specimen and CRFP specimens as mentioned above. The response graphs are recorded in Labview and subsequent graphs are plotted for the same and are discussed in following sections.

4.1 Experimental Result Analysis of Aluminium specimen

Figure 8 shows the response signals of the tests carried on Aluminium plate subjected to damage and without damage. From the 2 graphs it is very evident that there is a change in response signal from the damaged plate to the undamaged plate at a given time interval. Location of the damage can be found using the Equation 1. From Figure 8 it is very evident that the amplitude peak due to the first reflected wave is seen at a time period of 0.33×10-4s and amplitude variation due to crack is seen at 0.16×10-4s the time taken by the reflected wave.Using Equation 1 the location of the graph is found to be 144mm. Figure 9 clearly indicates the arithmetic mean difference of the Aluminium specimen with and without defect.

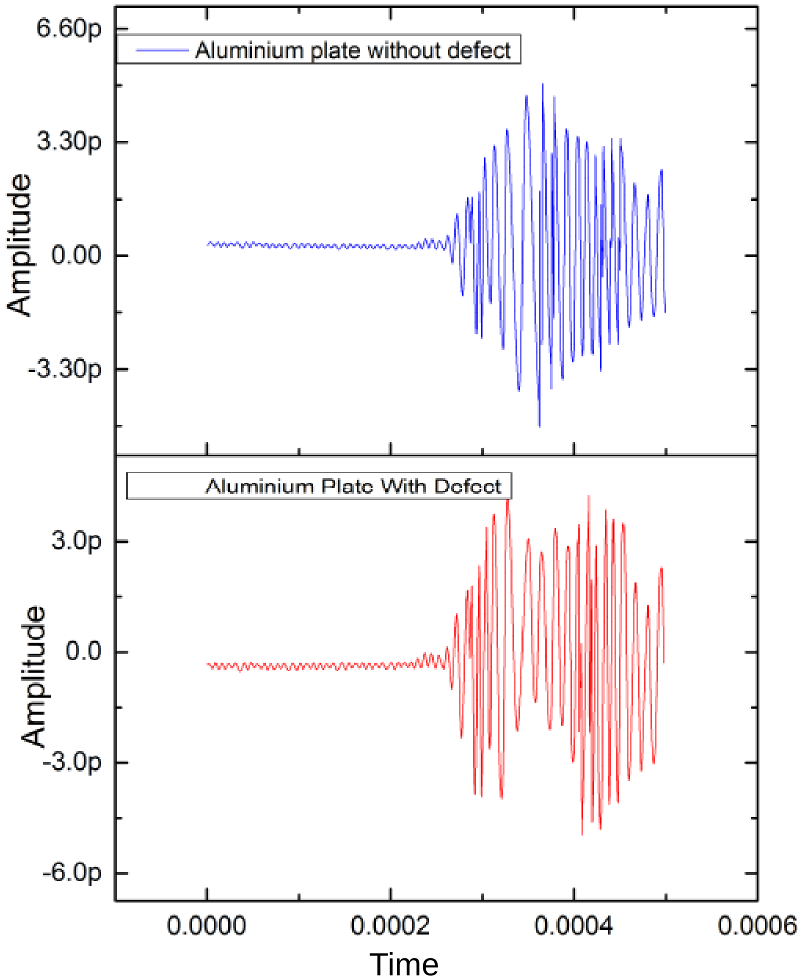


Figure 8. Response signals for the Aluminium plate with and without defect

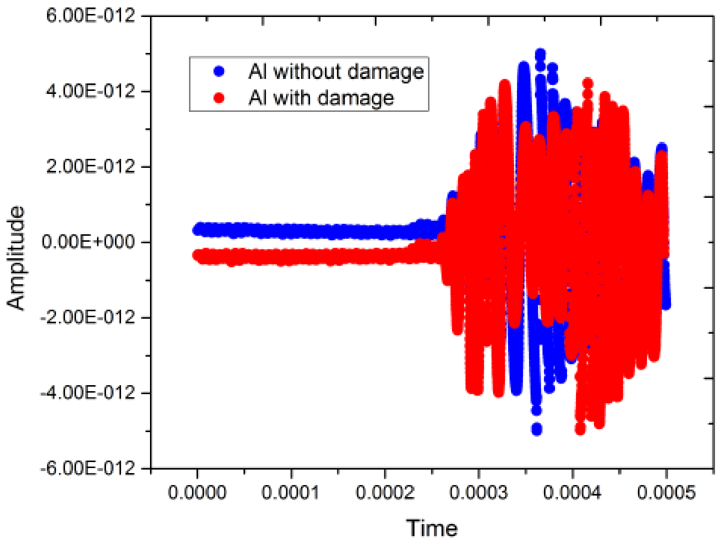


Figure 9. Comparison of response signals from Aluminium plate with and without defect

4.2 Result Analysis of CFRP specimen

From the graph shown in Figure 10, it is seen that the amplitude peak due to the first reflected wave is seen at a time period of 0.25×10-4^{s} and an amplitude variation due to crack is seen at 0.12×10-4^{s} the time taken by the reflected wave. From Equation 1 the location of the crack is calculated to be 142.56mm.

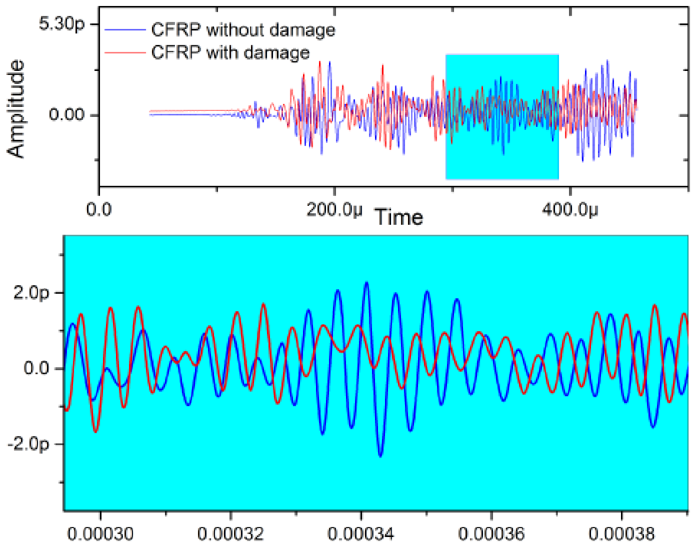


Figure 10. Response signals for undamaged and damaged CFRP specimen

5. Conclusion and Future Work

Health monitoring of composite laminates using piezoelectric wafer active sensors was proven a reliable, robust, light weight and low budget method to generate the lamb waves compared to other costly methods such as ultrasonic methods which require large comb or wedge transducers to carry out the scanning across the plate.

Lamb wave methods have good potential for implementing in health monitoring system. This method provides useful information about the presence and extent of damage in both aluminium and composite materials at the same time hold the capability of determining the location and type of damage which helps to fixed onto a structure with conformable piezoelectric devices.

The major disadvantage of lamb waves is that it is active, it requires voltage supply and function generating signal to be supplied the signal. This can be complicated in a large structure, especially if the health monitoring system is to be implemented wirelessly. Remotely activated PZT using radio frequency waves can be used for future work in order to implement this type of method in a large structure.

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