Fea and Experimental Study of Guided-Wave based Structural Health Monitoring for Identification of Damage in Thin Structures

Nishanth R [1],Lingadurai K[1],Malolan V[2],Gowrishankar Wruti[2],Sreedhar[3]
[1]University College of Engineering-Dindigul, Anna University
[2]Directorate of R&QA, Advanced Systems Laboratory-DRDO, Hyderabad
[3]Center for Non-Destructive Evaluation, Indian Institute of Technology Madras, Chennai

***Abstract* - Structural Health Monitoring (SHM) of aerospace structures has received significant interest as a core component of Condition Based Maintenance (CBM). This paper examines the possibility of using an ultrasonic guided wave system for damage detection in thin metallic plates. Acousto-Ultrasonic methods based on high frequency structural vibrations using piezoelectric transducers (PZT) have been developed to perform damage detection on thin metallic structures.The fundamentalLamb wave modes (A_O&S_O) travel into the structure and are reflected by the structural boundaries, discontinuities, and damage.Thus the presence of defect in the structure can be determined by studying their propagation and reflection. Laboratory level experiments have been carried out on thin Aluminum plates with angular, horizontal and vertical defect. This study provides significant insight into the problem of identifying localized damages in the structure using PZT and dispersion of signal after they interact with different types of damage. The small defects, especially the one with horizontal orientation are missed in time domain analysis can also be clearly identified in a Short Time Fourier Transform (STFT) plot.**

The finite element study on three dimensional model of thin aluminum plate is done on commercial FE package Abaqus/Explicit 6.10 using time-domain simulations to analyze the behavior of Lambwaves in isotropic Aluminum plate. 3D Finite Element (FE) simulations were carried out to understand the propagation of fundamental axisymmetric and symmetric (AO&SO) modes across the Plate , and validated with the experiments.FEA studies show good correlation with experimental results with less than 5% error and demonstrate that it is possible to identify damage position very accuratelyby using signals received from defective structures.

Key Words: PZT, Lamb Wave, Transducers, SHM.

1. INTRODUCTION

Guided elastic waves in plate-like structure, have shown promising potential for structural health monitoring (SHM) due to its high capability to detect and characterize both surface and internal damage in structures and ability of interrogating large areas with a small number of transducers[1-6]. However, many defects are under some coating and/or hidden behind the complex geometries. Some of them can be identified with instruments while many are beyond the reach without partial disassembly. An on-line diagnostic system capable of detecting, locating, and identifying the damage in aluminum and composite materials would improve the safety of the aircraft and reduce life-cycle costs [3]. The structural health monitoring (SHM) methods use a combination of sensors located at the critical locations and data analysis methods with this goal [4].

The objective of this paper is to evaluate the feasibility of Lamb wave methods for detection of defects with different geometrical orientation in thin aluminum plates. Lamb waves were generated and their propagation in a defect-free plate as well as in the presence of defects of different orientation wasstudied.Piezoelectric (PZT) elements were used to excite the structure and the data was collected using oscilloscope [5].The fundamental S_O and A_OLamb wavemodeswereselectively generated. Signal processing technique was adopted for extracting the maximum details from the acquired Lamb wave signals.

2. LAMB WAVES FOR SHM

Lamb waves are guided waves that can be generated in materials having thickness of the order of a few wavelengths.Lamb waves can travel relatively large distances [8]with very less attenuation, offering the advantage of large-area coverage with a minimum number of installed sensors [9].Lamb waves propagate through the thickness of the plate, and have complex vibrational patterns. The propagation of Lamb waves depends on: operating frequency, material thickness, density and elastic properties of the material. Generation of different modes depend on the excitation frequency and entry angle [7-10]. Lamb waves can be classified into two groups based upon the wave motionsymmetric modes and anti-symmetric modes. In symmetric mode, the wave propogates through compression and rarefaction in wave motion direction **(**Fig). This mode can be efficiently produced when the exciting force is parallel to the plate. Here, most of the particle vibration takesplace perpendicular to the plate (Fig).

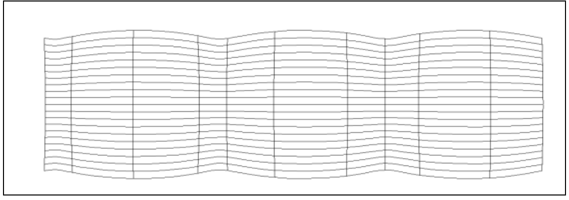

Fig 1: Symmetric mode S_O of Lamb wave in 2mm thick Al plate.

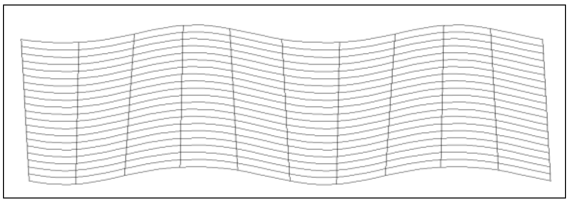

Fig 2: Anti-symmetric mode A_O of Lamb wave in 2mm thick Al plate.

Selection of optimum operating mode

Two important concepts to be understood in wave propagation are dispersion and attenuation. Dispersion is the change in wave speed in a material with respect to frequency and Attenuation is the change in amplitude of a traveling wave over a given distance. The most descriptive way to represent the propagation of a Lamb wave in a particular material is with their dispersion curves, which plot the phase and group velocities in terms of product of the excitation frequency and plate thickness[11]. A particular Lamb wave can be excited if the phase velocity of the incident longitudinal wave is equal to phase velocity for the particular mode [12].

Dispersion curves generated by Disperse software[13] helped to identify and evaluate the possible modes of guided waves and its propagation characteristics in the sample. The analysis was done for an Aluminium plate of thickness 2mm, density is 2700 Kg/m^3 and Youngs modulus is 70 GPa. The plots of group velocity vs frequency, phase velocity vs frequency were generated. The resulting dispersion curves obtained using disperse software are shown in **Error! Reference source not found.**gure3& Figure4

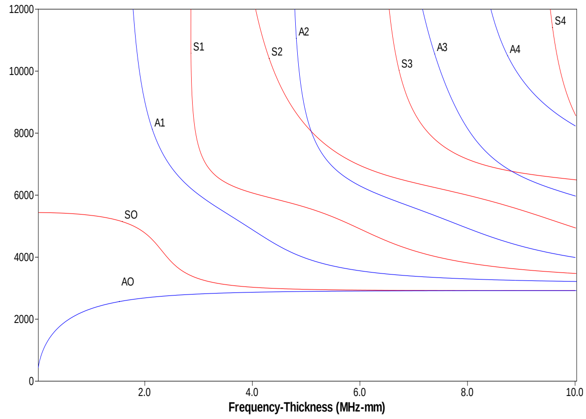

Figure 3: Phase velocity dispersion curve

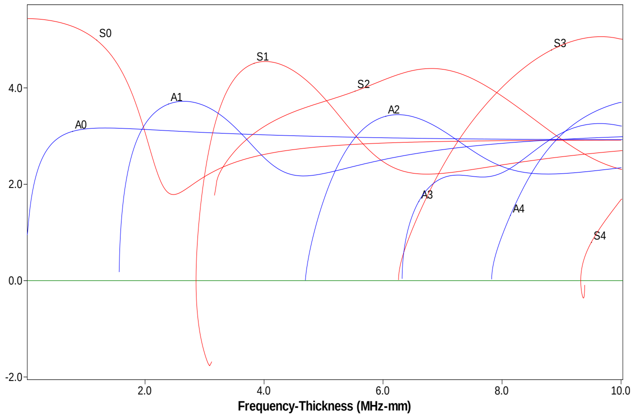

Figure 4: Group velocity dispersion curve

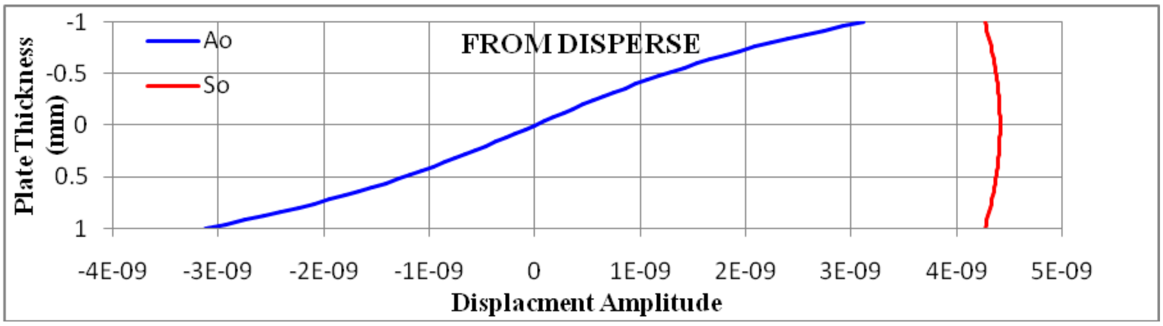

Figure 5:Mode Shape From Disperse

The product of the wave frequency and structure thickness falls in the range of 0–10 MHz mm, in which at least two Lamb modes, A_O and S_O, exist simultaneously.Dispersion curves generated helped to identify and evaluate the possible modes of guided waves and its propagation characteristics in the sample.Selection of the optimum operating mode, required a compromise between lesser number of modes, less dispersion and shorter wave length. It is done to improve the sensibility and simplicity on the signals received.the mode shape obtained from disperse is shown in figure 5.When the experiment is being done the peak identification also plays a major part. The Finite Element Analysis is carried out using ABAQUS 6.10 yields that a frequency range of 300 KHz defines the ideal conditions to carry out the experiment on the Aluminum plate. In the present case, A_O mode at a frequency of 300 KHz was selected. The results of this study were used for further analysis using STFT.

3. EXPERIMENTAL SETUP

The experimental setup for the Lamb wave based SHM is shown in Figure 6. It consists of two PZT (S1&S2), S1for excitation and S2 for sensing. The Agilent 33220A arbitrary waveform generator (AWG) was used to generate the excitation signal and the sensory signals were monitored and recorded by using Agilent DSO 6032A digital oscilloscope. The dimensions of the Aluminum test plate was 400mm x 200mm with 2mm and the defect are through the thickness and measures 50mm length x 5mm wide. The Aluminum test plates used for experiment are shown in figure6a.The transmitterand the receiver probes were placed at a distance of 100mm and 140mm from the edge as shown in figure 6b.The Wave Generator was used to produce a 5-Cycle hanning Window signals at the central frequency of 300 KHz. The S1 is excited to generate the Lamb wave and the waves arriving to the S2 generated the voltage variations and used as sensors the obtained sampled signals are then transferred to PC for further analysis. The same experimental setup as shown in figure 7 is used for evaluating all the plates. The setup is designed such that reflections from the boundaries would not interfere with the first reflected pulse received by the sensor. All the four test plates can be analyzed in this procedure making the defect free plate waveform as reference and comparing it with the vertical, horizontal and angular defect plate waveform. All the signals were analyzed by using the Matlab program and the A-scan results obtained are shown in fig7.The obtained A-scan results are further processed for time frequency analysis. Based on the processed data, the state of the structure and the defect is diagnosed.

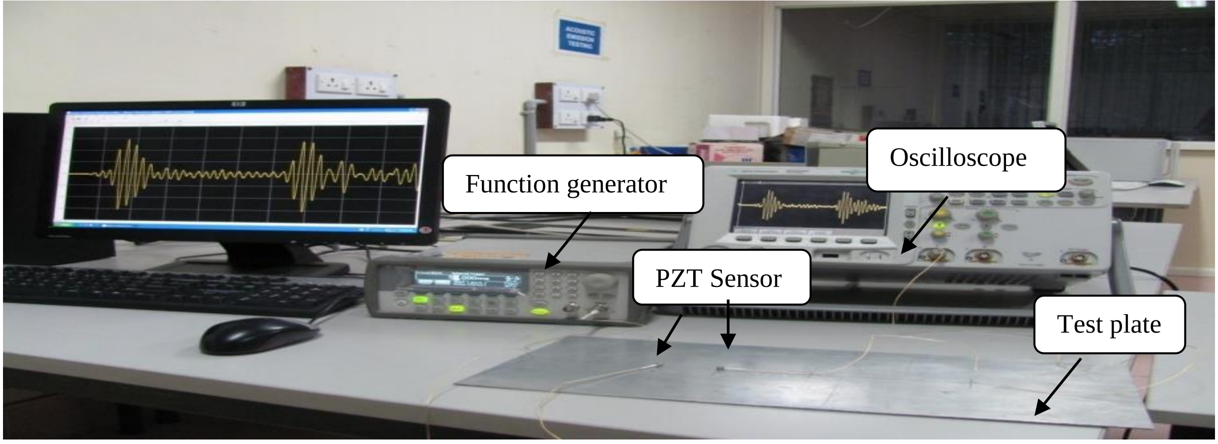

Figure 6: Experimental setup for SHM

Figure 7 a: Defects and Defect free Plate

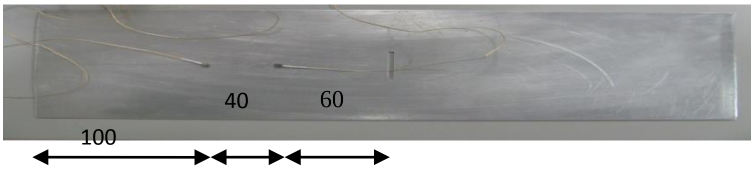

Figure 7b: Placing of sender and receiver on the test plate (All dimensions are in mm)

4. RESULTS AND DISCUSSION

When the PZT is excited at 300 KHz Lamb wave is generated and the reflections from the edges are received by the PZT and displayed in the oscilloscope. The obtained wave form was saved as a text file and imported into MATLAB for further analysis. Similarly the wave form data's of all the plate'swere collected and compared. The raw waveform with useful information carries along lot of other noises due to interference, coupling etc. To avoid such unwanted noises and disturbances filtering of the signal is done using the Savitzky-Golay filtering [16]. Finite element model is developed in ABAQUS to simulate PZT actuation and Lamb wave propagation in the plate and the results are shown in figure 8. It can be seen from the A-scan in figure 8 that the reflection amplitude increases with increase in the size of the defect depth. The reflection energy calculated for the gated region also increases with increase in the defect depth. The reflected energy from the defect, for the simulated FE model, was compared with the experimental results and the variations are less than 10%. The animations obtained from the FE simulation of wave propagation helps in understanding the guided wave characteristics in complex geometries.

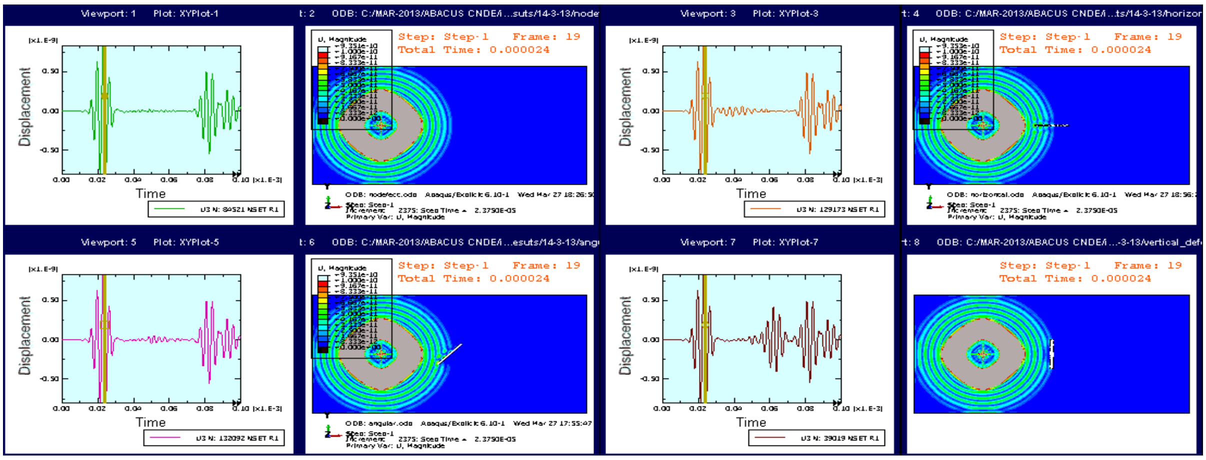

Figure 8: Analytical A-scan results of guided Lamb wave propagation in plate

The filtered A-SCAN results of horizontal, vertical and angular defect and the defect free plate are plotted and compared as shown in figure 9a-9b. From the filtered waveform, edges of the plates are identified using the reflection peaks. In the waveform generated two distinct reflections of S_O and A_O mode are visible. The first transmitted S_O mode is seen at 0.15×10^{-4}s and reflected at 0.42×10^{-4}s similarly the transmitted A_O mode is seen at 0.2×10^{-4}s and the reflected wave at 0.75×10^{-4}s. Since the S_O mode waves are faster, the reflection peaks occur much earlier.TheA_O mode reflection is much stronger, while the S_O mode reflection appears to be much weaker due to its highly attenuating nature. Hence S_O signals will not be useful to identify the damage characteristics. So, more care is needed to be taken such that the reflections from the defects have to occur after the S_O edge reflections. Fig. 9a shows the waveform from a defect-free plate. We can see the first reception peak (received from the transmitter) of the wave by the receiving sensor occurs at 0.2 $\times 10^{-4}$s and the next reflection peak (reflected from the edge) occurs at 0.75×10^{-4}s, these two peaks can be taken as reference and any other reflections from defect will occur within this interval. Fig. 9b shows the waveform from a plate with horizontal defect. The waveform peak corresponding to the defect occurred around 0.5×10^{-4} s. The amplitude of the peak is quite low on comparison with

the reflected wave peak and the detection of horizontal defect becomes difficult as the defect is very small.

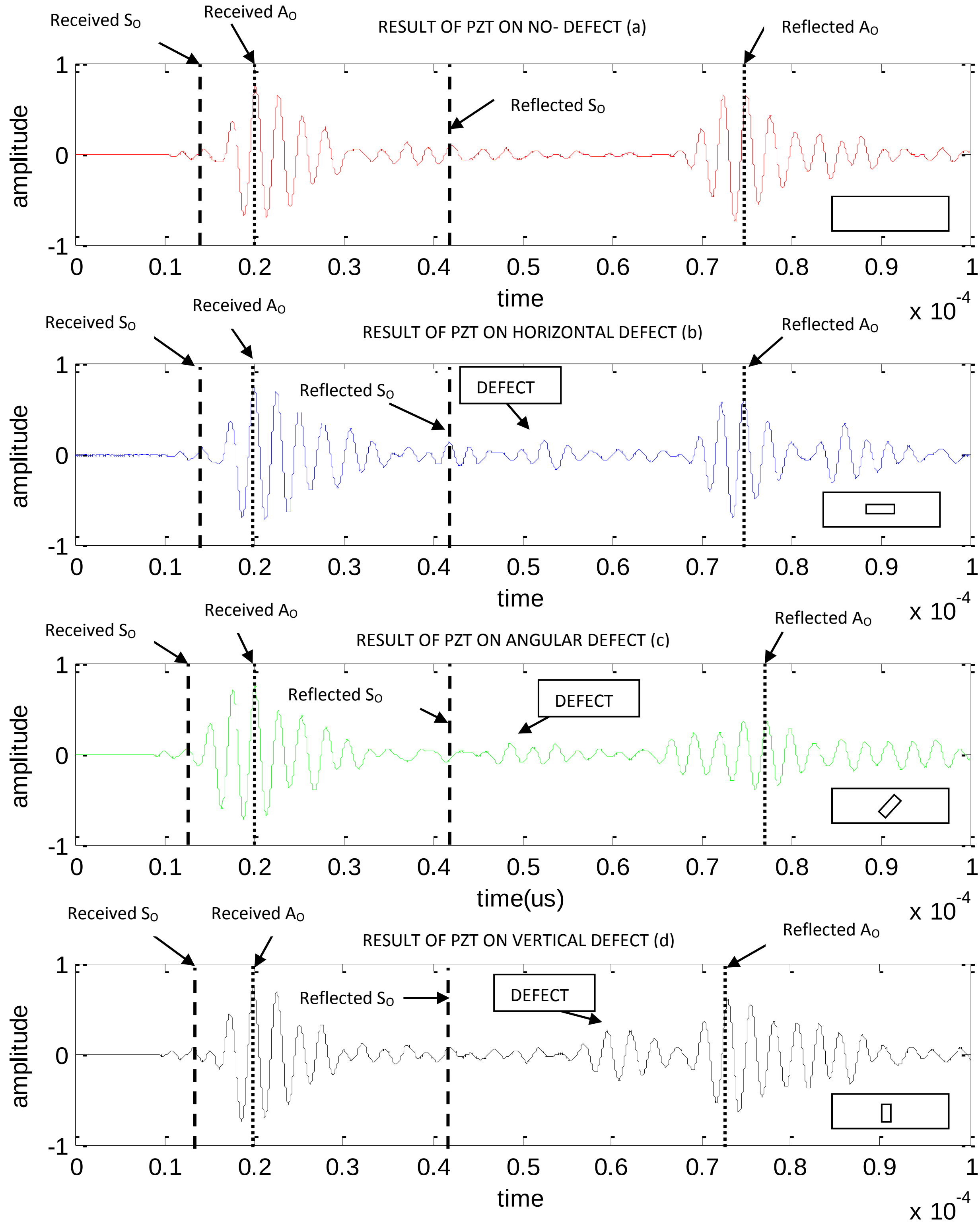

Figure 9a-9d: Comparison of Experimentally obtained waveform

Fig. 9c shows the waveform from a plate with angular defect. The waveform peak corresponding to the defect occurred around 0.65x10^{-4}s. The amplitude of the peak is high when compared to both the amplitude of horizontal defect and reflected wave.

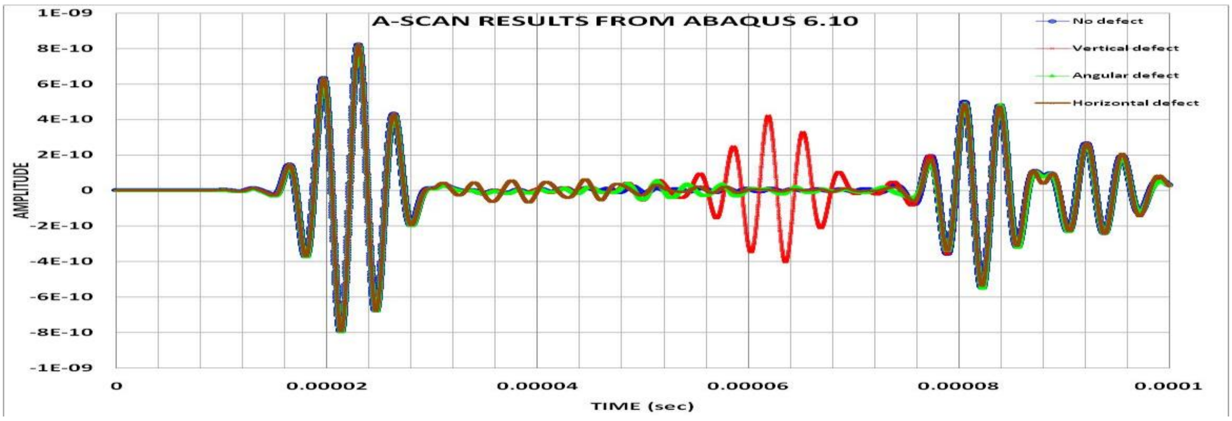

Fig. 9d shows the waveform from a plate with vertical defect. The waveform peak corresponding to the defect occurred around 0.57x10^{-4}s. The amplitude of the peak is quite equal on comparison with the reflected wave peak.

The comparison of defect and defect free waveform shows that all three types of defects are detected in which the angular and vertical defect can be identified easily since the amplitude of the peak is appreciable on comparison with the reflected wave peak. The detection of horizontal defect becomes difficult as the defect is very small.

4a-TIME- FREQUENCY ANALYSIS

The dispersive and multimode characteristics of Lamb waves complicate the interpretation of Lamb waves. Meanwhile, various interferences such as the ambient vibration and natural structural vibration and the measurement noise are also inevitably contained in the sampled signals. For this reason, appropriate signal processing methods [14-21] must be applied to the acquired raw signals. Currently time-frequency analysis methods, especially wavelet transform (WT) and short time fourier transform (STFT) are most popularly used for Lamb waves signal analysis due to its adaptive time-frequency resolution characteristics [17,18]. In the frequency domain analysis, we lose the time information, such as arrival time, wave packet dispersion etc. It is found that though the most often used signal processing method is the Fourier Transform, this approach has the serious drawback that it loses all the time information and hence it is not an appropriate tool for non stationary signal analysis. They proposed using short-time Fourier transform (STFT), which corrects the deficiency of Fourier transform by using a windowing technique, i.e., by cutting the signal into sections and only analyzing a small section at a time.

Here the SHM problem compels one to combine the time domain information along with the frequency domain information resulting in time-frequency analysis. Time-Frequency representation enables one to understand the signal behavior by creating a frequency estimate at each instant in the signal and thus provides a better understanding of the evolution of the frequencies. In many instances, the signal processing can be used as a pre- or post-processing action that enhances the efficiency of SHM techniques. [14,19]In this work, STFT is considered for studying stationary damage and its interaction with dispersive and non-stationary wave. The STFT spectrogram can be viewed as representing the signal in a different frequencies and time positions, but constant time widths. In many instances, STFT may be the more accessible way to achieve quickly the 2-D time–frequency analysis.

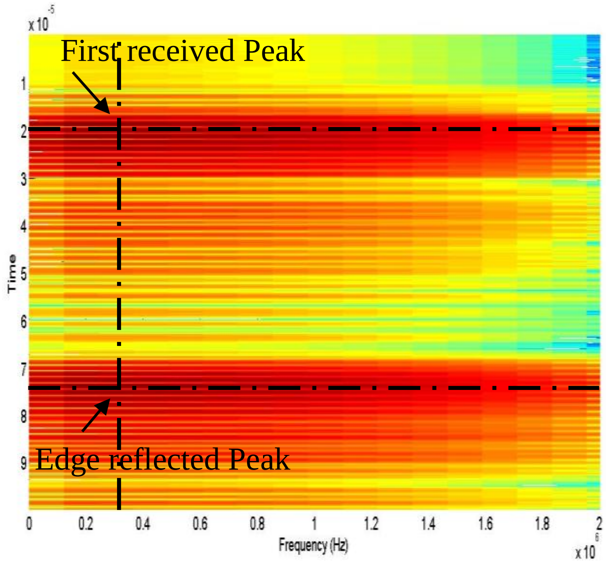

Figure10: STFT of defect free aluminum plate(time-frequency analysis)

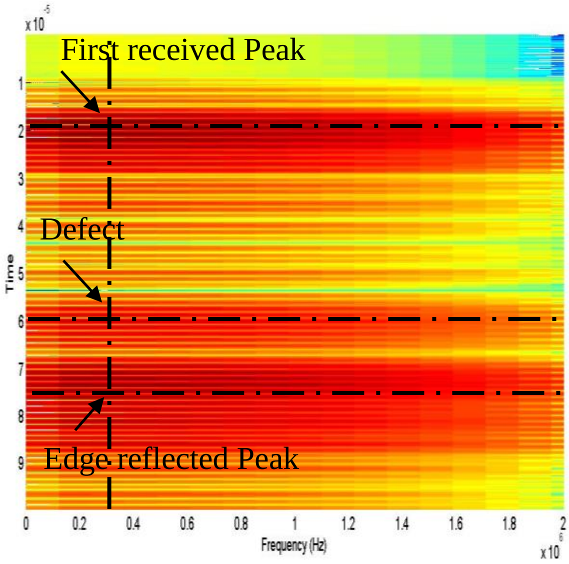

Figure 11: STFT of aluminum plate with vertical defect (time-frequency analysis)

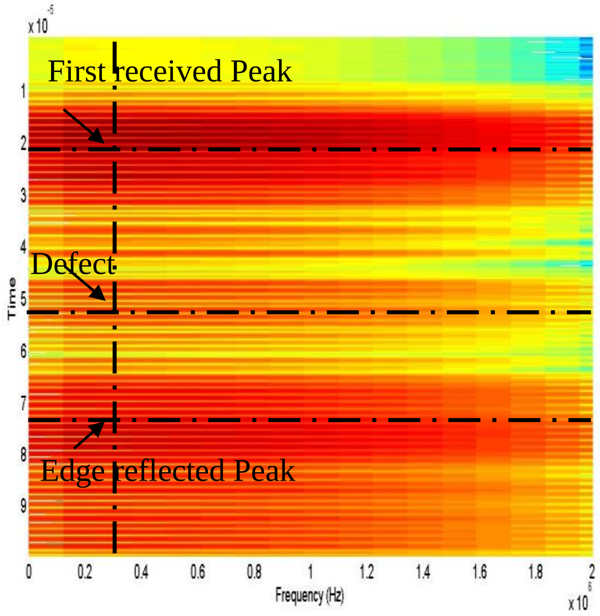

Figure 12: STFT of aluminium plate with angular defect (time-frequency analysis)

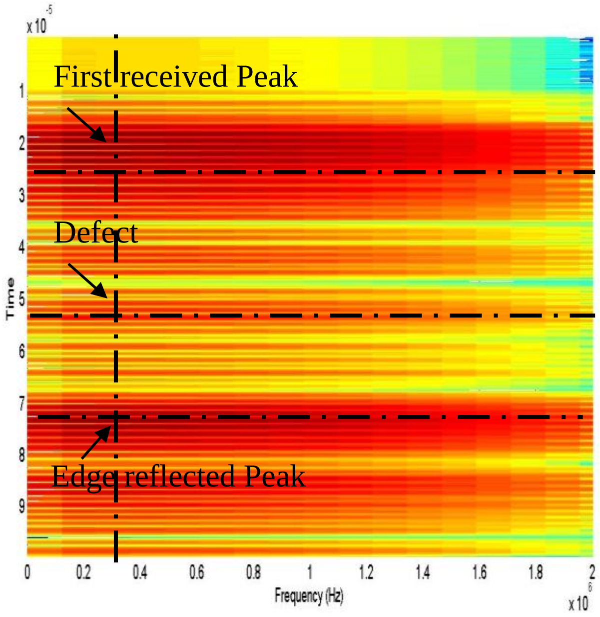

Figure 13: STFT of aluminium plate with horizontal defect (time-frequency analysis)

But STFT also has its own drawbacks, e.g., the fact that the size of the time window is the same for all frequencies. The short time Fourier transform, which is one of the easiest conventional time frequency responses (TFR) to compute, was used by Prasad et al. [4] to extract a suitable parameter for tomographic image reconstruction mapping the Structural defects. Nishanth et al [21]states that, in the STFT time domain- signal spectrum analysis it was seen that the identification of the horizontal defect was difficult among the available other peaks. But in the Frequency-time domain, it can be seen that the horizontal defect has also had a definitive spectral intensity. Since the STFT of time –frequency analysis is performed and the time frequency representation of the waveform are given in figure 10- 13.The STFT plot of the defect free wave form is shown in fig 10 and the STFT for the plot with vertical defect is shown in fig 11.The STFT plot of the angular defect wave form is shown in fig 12 and the STFT for the plot with horizontal defect is shown in fig 13.This presents a more convenient way of analyzing the waveform. It can be seen that the frequency contact of 300 KHz occurs only at these points where power spectrum intensity has been high. The first received peak, edge reflected peaks are all marked with dotted line.

The results in this section show that STFT along with time-frequency analysis methods can extract damage information's like occurrence of defect, distance of defect and type of defect. STFT along with time vs. signal spectrum analysis shows the excitation level of the reflected wave by which the defect can be easily identified since it occurs in between the reference peaks i.e. first received peak and the edge reflected at the outset STFT successfully displayed the arrival time of each frequency band in the waveform spectrum

5. CONCLUSION

Based on the damage detection results presented here, it is shown that Lamb wave based SHM are effective for detecting damage in thin aluminum plates. Clear differentiation between various types of defects has been identified. Numerical simulations using Matlab have also revealed the presence of S_O and A_O Lamb mode with low frequency and low amplitude, and experimental results confirmed this outcome. TheA_O mode reflection is much stronger, while the S_O mode reflection appears much weaker because of which A_O mode is highly useful for damage identification. The frequency range of 300 KHz defines the ideal conditions to carry out the experiment on thin Aluminum plate. Changes in the experimental signals were identified clearly using STFT based Time -frequency analysis on the extracted waveform, those small defects life horizontal defect can also be clearly identified using time frequency analysis . The A-scan results also show that identification of horizontal defect is difficult when compared to identification of vertical and angular defect but can be clearly identified in STFT more precise results can be obtained if wavelet analysis is performed on the obtained waveform. At the outset this experimental study has revealed the complete working and basic requirements needed for structural health monitoring of thin aluminum plates using guided Lambwave.

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