Lamb Wave Based Tomography for Damage Detection in Aluminium Plate

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Abstract
This paper presents an experimental study on Lamb wave based tomography for damage detection in thin aluminum plate. Tomography is the process of creating an image of the test specimen using the propagation parameters of wave passing through the specimen. Here, Lamb wave is used for the purpose and are generated and recorded using piezoelectric patches as transducers. The array of patches required for the experiment is studied and modified cross-hole geometry is used. The reconstruction algorithm used is MART 2. Prior to the experimental study, a FE simulation was carried for defect-less plate and is validated with the experimental results. Later, the experiments were conducted for different forms of damages, namely, lumped masses of different sizes and orientations, and notch. The experiments proved that the method is successful in predicting the presence of defects, orientation and size using time-of-flight (ToF) data of the propagating Lamb wave.

Keywords: Lamb wave, tomography, structural health monitoring

1. Introduction

Structural health monitoring (SHM) has attracted a lot of attention [1], also in the aerospace community, in the last one decade because of it's relevance in safe service of an aircraft. Lamb wave has been identified as a potential candidate for in-service damage detection of aircraft structures. The reasons being the ability of Lamb wave to traverse large area without much attenuation, ease in generation and detection unlike the conventional non-destructive techniques. There are, however, challenges arising due to multiple reflections from discontinuities and edges, dispersive nature and existence of multiple wave modes [2]. This has motivated the development of several damage detection schemes for Lamb wave.

Several non-destructive damage detection techniques, including those based on Lamb wave propagation, requires expertise and advanced knowledge. However, often there is a requirement of a technique which can be implemented and analyzed without the help of an expert. In this context, imaging techniques like tomography are found to be much user-friendly. The conjugation of tomography with Lamb wave allows exploitation of the benefits of Lamb wave based damage detection while preserving the ease of analysis of imaging based techniques [3]. Though damage detection using Lamb wave based tomography has been studied by several researchers [4-8], there are several challenges particularly for implementation in realistic cases.

In this paper, Lamb wave is generated in a thin aluminium plate with and without defect, using piezoelectric (PZT) patches as transducers. The experimentally measured Lamb wave response is validated with the corresponding responses simulated using two-dimensional finite element model. The time-of-flight (ToF) required for the Lamb wave to travel between one actuator-sensor pair is used as input to a reconstructive technique to obtain the tomogram. The reconstruction algorithm used in the present work is the multiplicative algebraic reconstruction technique (MART) [9]. The data is collected for each actuator-sensor pair following modified cross-hole geometry [4]. Such tomographic images are developed for plates containing lumped masses of different sizes and orientations, and notch representing damages. The images are used to predict the position, size and orientation of the damages.
The paper is organized as follows. Section 2 contains a brief description of the experimental set-up. The next following section summarizes the reconstruction algorithm used. Section 4 presents the results and discussions. The paper ends with some important conclusions.

2. Experimental Set-up

The experimental set-up used to generate Lamb wave in an aluminium plate specimen consists of a Tektronix AFG 3021B arbitrary signal generator, a Tektronix TDS 1002B digital storage oscilloscope, a power amplifier NF BA4825 and a computer connected through USB interface as shown in Fig. 1. The specimens used are Al-5052 aluminium plates of dimension 1.25 m X 1.25 m X 1.6 mm. The material properties are, Young’s modulus $E= 70.3$ GPa, Poisson’s ratio $\nu = 0.33$, density $\rho = 2.63$ g/cc. The PZT patches used as sensors and actuators are wafer-type PZT (material type SP-5H) transducers of size 7 mm$^2$ and 0.5 mm thick, and are bonded to the plate using a commercially available cyanoacrylate based. The array of transducers is made by placing eight PZT wafers on each of the four sides, totalling to 32 transducers. The distance between two adjacent PZT patches on a side is 6.25 cm. The area of investigation is 0.5 X 0.5 m$^2$ and hence, the total area is divided into 64 equal pixels as can be seen in Fig. 2(b). The input signal is a 8-cycle Hanning window modulated sinusoidal pulse of central frequency 100 kHz 20 V peak to peak value generated using the signal generator. The triggering interval is kept at 400 ms. The output from the signal generator is given as input to the power amplifier with an amplification factor of 10. The amplified signal is given to the PZT patches, and the Lamb wave after travelling through the test specimen is received by the sensor. The response is monitored in the oscilloscope. The ToF data for each wave response is recorded and $S_0$ mode is used to calculate the ToF. The procedure is repeated for all the independent rays, with different propagation path. As mentioned earlier, the data are collected using modified cross-hole geometry as shown in Fig 2(a). This ensures maximum utilization of the test area. In addition, modified cross-hole geometry offers better angular coverage compared to conventional cross-hole geometry [6], with fewer transducers. For the present case, the number of independent rays is 384.
These recorded ToF data are given as input to the reconstruction algorithm, MART 2 which is explained in the following section. Following reconstruction, a field value is obtained for pixel, which is a measure of the material properties, in other words, an indicator of the health of the specimen in the particular pixel. The values of each pixel are used to make the image of the test area of the specimen. The image thus formed is called tomogram, and it can be analyzed for damage prediction.

![Figure 2: (a) modified cross-hole geometry (b) PZT transducers array](image)

The defects are created either by gluing extra masses, or by making a notch. A tomogram was created for several cases of such damages, to emphasize the efficiency of the scheme. The comparison between the baseline data of the defect-less plate and the damaged plate helps in predicting the location, size and orientation of the damage. For ease of damage identification, tomograms are constructed by considering the ratio of field values of the defect free specimen to that of the specimen with defect.

3. Reconstruction Algorithm

Here, the algorithm used for reconstruction is the multiplicative algebraic reconstruction technique (MART) [9]. In this section, the MART algorithm is explained briefly. In MART algorithm, the image is formed as a linear combination of number of vectors called image vectors. The region to be reconstructed is divided into a grid of square regions. The length of intersection of \(i^{\text{th}}\) ray with the \(j^{\text{th}}\) pixel is denoted by \(w_{ij}\) as shown in Fig. 2(a). Here, \(i\) varies from 1 to \(M\) and \(j\) varies from 1 to \(N\), where, \(M\) is the ray number and \(N\) is the pixel number. \(w_{ij}\) represents the contribution of the \(j^{\text{th}}\) pixel to the total attenuation of the \(i^{\text{th}}\) ray, and is known as the weight factor of that ray-pixel pair. The weight matrix thus formed of \(w_{ij}\) will be of size \(M \times N\). This matrix is given as an input to the reconstruction algorithm.

The total amplitude of a ray can be calculated as the line integral of the amplitude function along the ray propagation path. It is given as,

\[
\phi_i = \sum_{j=1}^{N} f_j w_{ij} \quad i = 1, 2, \ldots, M
\]  

(1)

The initial approximate value of \(\phi_i\) is calculated using Eqn. 1, with an initial assumed field value \(f^0\). The variants of MART algorithm is given as,
The iterations are continued till,

\[
\frac{f^{k+1} - f^k}{f^k} \times 100 \leq \varepsilon
\]  

(5)

where, \( \varepsilon \) is the stopping criteria. The inputs required for the algorithm are the weight matrix \( w_{ij} \), the projection data matrix, \( \phi \), and the initial assumed vector \( f^0 \). The iteration or a \( k^{th} \) iteration steps are as follows,

1. Calculation of \( \phi_i \) for each ray \( i \)
2. Calculate the number of rays passing through each pixel
3. Compute the product of all correction factors for each cell, considering all the rays passing through the cell
4. Final correction is applied to each cell multiplicatively using the expressions of MART algorithms

The iteration is continued until the stopping criterion is satisfied. The input wave matrix has to be accurate for algebraic reconstruction. For reconstruction purpose, initial field value is taken arbitrarily and pixels simulating flows are given a zero value. The root mean square (RMS) value of error in MART is considered for convergence. In the present work, the MART 2 algorithm given by Eqn. 3 is adopted considering convergence, computational time and accuracy.

4. Results and Discussions

First, the experimental results are validated with simulated Lamb wave responses using a two-dimensional finite element models developed using ANSYS. The element used is four-noded PLANE 82 and the time integration is done using Newmark’s scheme. The velocities of both \( S_0 \) and \( A_0 \) modes for different frequencies of excitation, obtained from experiments and simulations are compared for validation. These velocities match well with the error not exceeding \( \pm 5.5 \% \).

Next, tomograms are developed first for defect-less plates and plates with different damage configurations from experimentally measured responses. These tomograms are next used for damage detection. In this section, these experimental tomograms are presented for two cases of damage following the experimental and simulated tomograms for defect-less plates.
Figs. 3(a) and (b) respectively presents the tomograms of the defect-less plates obtained using the ToF data of simulated and experimentally generated Lamb wave response. Fig. 3(c) presents the ratio of the field value of the simulated and experimental data. It can be seen from Fig. 3(a) that the plot is axisymmetric. This symmetry is expected for a defect-less plate. However, the field values are found to be different from each other, even though it satisfies the symmetry condition. This is due the difference in number of rays passing through each pixel, which is more at the centre compared to the corners. Fig. 3(b) presents the corresponding tomograms obtained using experimental data. The experimental tomogram also exhibits the symmetry and variation in the field values. To monitor the difference in experimental and simulated field values, a tomogram with ratio of experimental and simulated field values is presented in Fig. 3(c). The difference in the experimental and simulated field values can be attributed to experimental error, manufacturing defects, variation in material properties, which also resulted in a difference in the simulated and experimental wave velocities.
Fig. 4(a) shows a damage configuration, where two additional masses are bonded to the specimen. These masses are of 23 mm diameter, 2.5 mm thick and the material is a copper-nickel alloy. Fig 4(b) presents the tomogram obtained using experimentally recorded ToF data, and Fig. 4(c) presents the corresponding tomogram obtained using the ratio of field values of the defected and defect-less plates. It can be seen from Fig. 4(c), that the pixels corresponding to the additional masses show higher field values. The defect detected at the corner, made the shadowing effect on the adjacent pixels unlike the more centralized defect. This is again due to the reason that less number of rays traverse through the corner pixels. This shows that the tomograms can predict the presence of defects prominently for centralized defects, and has a more smearing effect for defects at the corners.
Figure 5 (a) damage configuration (notch) (b) enlarged view of the damage (c) tomogram of ratio of field values of simulated & experimental data

Figs. 5(a) and (b) show a damage configuration, which is a notch made at the central region of the plate. The notch is 4 mm in width, 0.8 mm in depth and with a length of 53 mm. Fig. 5(c) presents the corresponding tomogram obtained using the ratio of field values of the defected and defects-less plates. It can be seen from Fig. 5(c), that the pixel corresponding to the additional masses shows higher field values. As mentioned earlier, the defect being at the center, it is prominently detected by the tomogram. This shows the efficiency of the scheme even in detecting smaller damages.

4. Conclusions

The paper presents an experimental and theoretical study to detect damages using Lamb wave based tomography in aluminium plate. The time-of-flight data for $S_0$ mode is used to calculate the field values. The study is done for several damage configurations and the scheme is found to effective, particularly for damages located at a centralized position of the transducer array. The transducers used are piezoelectric patches bonded at regular interval over a square area to be investigated. First, the results are validated by comparing the wave velocities obtained experimentally and through finite element simulations. Comparisons and validation are also done between the tomograms obtained from the simulated and experimental field values. Next, tomograms are developed from experimental data for plates with additional masses and notch representing damages. The scheme is found suitable even for predicting multiple damages and damages of smaller magnitude.

References


