Ultrasonic Tomography Using Lamb Wave Propagation Parameters

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Abstract

Tomography refers to the cross-sectional imagining of an object from either transmission or reflection data collected by illuminating the object from different directions. In this work, an ultrasonic tomography system based on Lamb waves, developed in our laboratory, is presented. We discuss the inverse problem of tomography imaging using data collected from ultrasonic plate waves interacting with a discontinuity. Here the main focus is on improving the quality of tomography maps using two reconstruction techniques (backprojection and MART). Results of experiments for defect reconstruction on a thin plate are presented. It was found that MART can provide a better reconstruction image than the backprojection technique, with minimal distortion, of a two-step circular discontinuity embedded in an aluminum plate.

Keywords: Ultrasonic Lamb waves; tomography; defects; time-frequency representation.

1. Introduction

Defect detection and characterization are critical tasks for structural health monitoring of engineering structures. Physical aging during routine operation inflicts deterioration and generates hidden internal and/or superficial defects in these structures. Typically, real time monitoring of engineering structures requires scanning large areas in a short period of time. Lamb waves have the ability to propagate long distances in plates and pipe-like structures, offering a potential solution to defect detection in these types of structures [1].

Several approaches have been proposed to achieve tomography reconstruction on different types of structures. Leonard, et. al. [2], discuss the use of a square perimeter array of transducers to achieve tomography reconstruction of aircraft structures. Malyarenko & Hinders [3] present a methodology for tomography reconstruction with ray bending correction for imaging of objects with moderate ultrasonic scattering. Volker et al. [4] reported the use of ultrasonic tomography for corrosion-type discontinuities reconstruction in pipes using Lamb wave traveltime parameter.

In this work, the application of ultrasonic tomography using Lamb waves for reconstruction of artificial discontinuities in aluminum plates was studied. The objective in this study is to improve Lamb wave ultrasonic tomography reconstruction of an artificial discontinuity using...
the ray tracing theory. The implementation of a parallel projection tomography scheme as a data gathering process is used to compare amplitude reconstruction using a backprojection algorithm with traveltime reconstruction and MART algorithm.

2. Tomography theory

Ultrasonic tomography can be studied in a similar way as x-ray tomography if wave refraction and diffraction phenomena are ignored in a transmitter-receiver configuration of transducers [5]. In both cases, a line integral (Figure 1) of the attenuation or traveltime values can be estimated on the far side of the object by,

\[ P_\theta(t) = \int_{(\theta,x)\text{line}} f(x, y) ds. \]  
\[ T^P = \int_P s(x, y) dl^P, \]  

where \( P_\theta(t) \) is the projection amplitude as a function of positions \( t, \theta \) is the projection angle, \( f(x, y) \) is the inspected object function, \( ds \) is the distance from the projection axis \( X_\theta \) to the position \( (x, y) \) in the object, \( T^P \) is the travel time along an arbitrary path \( P \) that connects a given transmitter and receiver position, \( s(x, y) \) is the slowness distribution of the propagation media and \( dl^P \) is an infinitesimal distance along the path \( P \). A more detailed description of equations (2.1) and (2.2) is presented in next sections.

In Figure 1, the generation process of a projection \( P_\theta(t) \) from several ultrasonic signals propagating through an inspected object, \( f(x, y) \), is shown. The amplitude or traveltime values taken at multiple transmitter-receiver transducer positions and a specific angle \( \theta \), generate a single projection.

In theory, if an infinite number of projections are obtained, the object function can be entirely recovered. Tomography process involves many wave-matter interactions when input signals travel from the transmitter to the receiver transducer and are affected by the propagation media.
The use of Lamb waves, to perform tomography reconstruction process involves interaction of guided waves with discontinuities. The interaction of guided waves with discontinuities affects the attenuation and velocity properties of the ultrasonic signals. The problem of Lamb wave propagation in a plate with thickness reduction (discontinuity) is schematically described in Figure 2.

Theoretically, an infinite number of dispersion Lamb wave modes can be excited in the plate. A discontinuity similar to that shown in Figure 2a changes the behavior of the dispersion curves (Figure 2b). Due to dispersion phenomena, interpretation of Lamb waves and identification of propagation parameters requires additional signal processing. Multiple dispersion modes can be found in a typical Lamb wave signal and arrival time for specific frequencies cannot be resolved in the time-domain representation. Recently, Short Time Fourier Transform (STFT) has been reported for mode identification of guided waves [6]. Here, amplitude and travelt ime parameters are obtained by implementing STFT analysis.

A schematic of the data generation and gathering processes performed in our experiments is illustrated in Figure 3. Once the ultrasonic signals are captured and signal parameter
identification process is carried out, the input data for the tomography reconstruction algorithms can be obtained.

Figure 3. Scheme for the data gathering process for the two experimental setups.

2.1 Backprojection algorithm

In principle, to perform a tomography reconstruction, a summation of all the projections is needed in either frequency or space domain. The sum of all projections realized in the space domain is called the backprojection algorithm [5].

Conceptually, the complete steps of filtered backprojection algorithm are described in Figure 4.

Figure 4. Block diagram of backprojection algorithm scheme.

In this study, the backprojection algorithm to reconstruct an artificial image (shown in Figure 4) was implemented on synthetic data that simulates a two-step thickness reduction in a plate (see Figure 5a). This is used to model a discontinuity with corrosion-like shape. Smooth (Figure 6a) and irregular (Figure 6b) profile discontinuities could be a challenge in tomography reconstruction process because of the scattering effects produced by Lamb wave propagation interaction with the discontinuity.
A set of 19 projections, with 100 rays each were artificially obtained from 0° to 180° in increments of 10° emulating the parallel projection scheme on thickness reductions (Figure 5a). The artificial discontinuity was divided in rectangular cells to generate a figure matrix; for each projection, the value of each cell was taken into account to generate the amplitude projection matrix.

Reconstruction results using the backprojection algorithm are shown in Figure 5b. It was found that the backprojection algorithm is able to reconstruct the shape and thickness gradient of the original image; however, there is a distortion (reduction in size) on the reconstructed discontinuity of about 30%. The incorrect sizing could be critical for defect characterization of engineering structures; if actual size of discontinuities is not correctly resolved, a good insight on health condition of the inspected object cannot be achieved.

Straight-ray propagation of ultrasonic signals introduces errors in the image reconstruction (as shown in Figure 7a). Thus, tomography reconstruction should account for acoustic waves bending (curved paths) in plates with refracting objects (see Figure 7b). This phenomenon is called ray bending [7]. In order to improve tomography reconstruction and to overcome the ray bending problem, a ray tracing algorithm is proposed. The basic idea of ray theory is to calculate the ray path, with minimum traveltime, of ultrasonic signals from the transmitter to the receiver transducer. The implementation of ray tracing theory uses a reconstruction algorithm with traveltime input parameter taken from ultrasonic signals. The fundamental theory of traveltime tomography reconstruction algorithm is described next.
Figure 7. a) Straight ray tomography; b) Ray bending problem.

2.2 MART algorithm

Several ray tracing algorithms have been developed to overcome the ray-bending problem in tomography reconstruction. Anderson and Kak [8] presented a review of digital ray-tracing, using the Fermat principle and eikonal equation, for applications in ultrasonic computerized tomography.

In this study, a Multiplicative Algebraic Reconstruction Technique (MART) [7] for traveltime tomography reconstruction is used. To achieve traveltime tomography reconstruction of ultrasonic signals, it is necessary to reconstruct the slowness distribution $s(x, y)$ in the propagation media at certain location. The slowness distribution is the inverse of Lamb wave phase velocity $c_p(x, y)$ in propagation media at point $(x, y)$. Data for slowness distribution calculation is obtained by traveltime parameter determination for each transmitter-receiver positions.

The time of flight (TOF) of an ultrasonic signal from a transmitter transducer position to a receiver transducer position can be obtained by applying the following line integral,

$$T_p = \int_P s(x, y) dl^p.$$  \hspace{1cm} (2.3)

Theoretically, the slowness distribution $s(x, y)$ can be calculated by implementing the following equation,

$$s_{m+1}(x_i, y_j) = s_m(x_i, y_j) \frac{t^i}{\hat{t}^m} \hat{\lambda}_m,$$  \hspace{1cm} (2.4)

where

$$\hat{\lambda}_m = \frac{l_{ij}}{\left( \frac{1}{l} \sum_{j=1}^{l} l_{ij} \right)}, \quad \hat{t}^m = \sum_{i=1}^{l} s_m(x_i, y_j) l_{ij}, \quad l_{ij} = \sqrt{1 + y'_{ij}^2} \Delta x.$$  \hspace{1cm} (2.5)
From equations (2.4) and (2.5) the \((x_i, y_j)\) parameter correspond to the cell index in the discrete representation of the slowness distribution, \(l_{ij}\) is the traversed distance over the \((x_i, y_j)\) cell, \(t_i\) is the measured TOF for the receiver-transducer position, \(t_{im}\) is the minimum TOF obtained for the generated slowness distribution with minimum TOF \(s_{m}(x_i, y_j)\) and \(\Delta x\) is the size of the sample grid to be used to reconstruct the image. The sub-index \(m\) in equations (2.4) and (2.5) refers to the parameters obtained when the minimum TOF for an ultrasonic ray path is found.

If ray paths are unknowns, straight ray tomography cannot be applied; therefore an iterative process to compute an approximate slowness distribution is required [7]. As a first step to tomography reconstruction, we assume \(\lambda_m = 1\) in eq. (2.5) (straight ray estimation), and obtain an initial slowness distribution estimation. Then, ray tracing algorithm can be applied to trace the ray paths for all transmitter-receiver positions. Once the ray paths are obtained, bend ray MART reconstruction can be achieved solving equations (2.4) and (2.5). Finally, the ray tracing algorithm is applied iteratively until a desirable image quality is achieved. The minimization criteria to determine the appropriate quality of reconstruction is obtained following equation.

\[
e \leq a,
\]

where \(a\) is an error criteria value and

\[
e = s_{m+1}(x_i, y_j) - s_m(x_i, y_j),
\]

the parameter \(e\) is the error value between the current slowness distribution calculation \(s_{m+1}(x_i, y_j)\) and the previous one \(s_m(x_i, y_j)\).

![Figure 8. Reconstruction from a synthetic figure, white background with two circles in the center. a) Original image; b) Reconstruction using backprojection algorithm.](image)

The same synthetic image (Figures 5a) used for numerical validation of the amplitude reconstruction process was used to validate the traveltime reconstruction. Again, a set of 19 projections were artificially obtained from 0° to 180° with increments of 10° using the
parallel projection scheme. For each projection the sum of each row was obtained to simulate the TOF vector.

The reconstruction of the synthetic figure with MART algorithm is shown in Figure 8. The results indicate that MART algorithm can reconstruct the shape and the two step features of the original images with an error in size prediction of 5% with respect to the original one.

3. Description of experiments and results

The experimental setup to study the sensibility of the proposed tomography reconstruction algorithm is described in Figure 9. An aluminum plate (50 x 50 cm) with a thickness of 2.03 mm was used. A circular discontinuity (25mm in diameter) was artificially machined in the sample plate (Figure 9). For the experiments, two broadband longitudinal normal contact transducers with a central frequency of 1 MHz were used to induce the A1 dispersion mode in the plate. The two transducers were set in a pitch-catch configuration separated by a distance of 25 cm between them. A set of 5 rays (to form a projection) of ultrasonic signals was obtained by a simultaneous and parallel displacement of the transducers in steps of 2 cm (Figure 3). Then, four projections were captured following a 45 degrees clockwise rotation of transducers around the discontinuity.

Signals were further post-processed by applying short-time Fourier analysis [6]. The Fourier transform spectrum can determine which frequencies are present in the detected signal but it does not provide information of time localization of the signal. The STFT evaluates the time-domain signal into a series of small sections of the signal. Then, each of these sections is windowed and the Fourier transform is applied individually for each one. Both parameters amplitude and time can be obtained from the captured signals and can be used as an input for the tomography reconstruction algorithms. In Figure 10, a typical time-domain representation of captured signals for ray #3 (ray crossing the center of the loaded area, see Figure 3) is shown.

Reconstruction of the artificial discontinuity machined on the aluminum plate was obtained with limited data (4 projections with 5 rays each). In Figure 11a, results of backprojection are shown. It is possible to observe that, even for a small number of rays and projections, the discontinuity can be reconstructed. A clear improvement in resolution (Figure 11b) using MART was found where a better agreement in shape and size of the circular discontinuity reconstruction (white area in the center of the figure) was found. Also there is a reduction of artifacts, noise around the discontinuity reconstruction when compared with backprojection results.
4. Conclusions

The effect of bending of ultrasonic rays in tomography reconstruction due to changes in phase velocity and changes in thickness was accounted for by using the MART algorithm. MART algorithm using time of signal data was proved to be more accurate than backprojection using only amplitude. The improvement was verified on synthetic data and on actual data taken from a plate with an artificial discontinuity. Finally, the proposed MART algorithm could be potentially applied for the reconstruction of defects such as corrosion which reduces the thickness of plate-like structures.

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References


