NDT and E International 92 (2017) 1–9

Contents lists available at ScienceDirect

NDT and E International

journal homepage: www.elsevier.com/locate/ndteint

Multipath exploitation for enhanced defect imaging using Lamb waves

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ARTICLE INFO

Keywords:
Sparse reconstruction
Lamb waves
Multipath exploitation
Structural health monitoring

ABSTRACT

This paper presents a multipath exploitation approach for defect imaging in thin-walled structures using Lamb waves under the sparse reconstruction framework. An image of the defects in the region of interest is obtained by inverting a multipath propagation model via group sparse reconstruction. This permits accurate imaging of regions close to the structure boundary without the introduction of 'false' defects or ghosts. Real-data measurements of defects close to the edge of an aluminum plate are used to demonstrate the effectiveness of the multipath exploitation scheme.

1. Introduction

Use of Lamb waves is emerging as a primary means for the assessment of the integrity of thin-walled structures [1–4]. Lamb waves are the unique solutions to the elastic wave equation for a thin plate with traction free surface conditions [5]. These solutions are multimodal in nature, with the modes being separated into sets of symmetric (S) and antisymmetric (A) modes. The number of distinct propagating modes in a given structure is a function of the plate thickness and the excitation frequency. Transducer size also affects the relative strength of the individual modes. As such, the propagating wave can be reduced to a single dominant (A or S) mode by an appropriate choice of the transducer and the excitation frequency [6].

A number of approaches have been developed for imaging defects in thin-walled structures using guided Lamb waves generated by arrays of ultrasonic piezoelectric transducers [7]. An efficient technique is the use of an array of ultrasonic transducers that generate and receive guided waves in a pitch-catch configuration. Signals received by the transducers in the array can be processed with appropriate algorithms to reveal the presence of defects. Among these, the delay and sum algorithm is simple to implement, though it is prone to imaging errors [8]. Tomographical methods have been developed as well, but these techniques require a dense array of transducers [7]. Sparse reconstruction methods have emerged recently as viable techniques to image defects using a sparse array of transducers [9,10]. For a small number of defects, these methods have been shown to be robust in reconstructing the images of defects in the structure.

When interrogating a structure such as a plate with single-mode Lamb waves, the received signals not only contain the direct scatterings from the structural defects, but also the secondary reflections arising due to wave interactions with the defect and plate boundaries. These multipath reflections have typically been avoided by restricting the region of interest (ROI) to only the interior regions of the plate under examination [8–11]. However, this hinders the localization of defects in regions close to the structure boundaries. Some recent work using data-driven model-based approaches has shown robustness in examining regions in the presence of accounted-for and unaccounted-for interference from edge reflections [12,13]. However, these authors have not attempted to exploit the additional information provided by edge reflections. To address this issue, we propose a Lamb wave based sparse reconstruction method to exploit the defect information in multipath reflections to provide enhanced localization capability in regions close to the structure edges.

Multipath contributions have been utilized in the recent past for defect imaging in nondestructive evaluation (NDE) and Structural Health Monitoring (SHM) applications [14–17]. In Ref. [14], the authors exploited the multipath returns in delay-and-sum beamforming to reveal shadowed parts of the defects, thereby enabling defect perimeter detection in ultrasonic NDE. In Ref. [15], the authors proposed a multipath guided wave imaging method, which generates an enhanced image of the ROI by comparing, via deconvolution, the received signals with a database of scattered signal estimates. The latter were obtained from

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http://dx.doi.org/10.1016/j.ndteint.2017.07.008
Received 21 November 2016; Received in revised form 20 June 2017; Accepted 10 July 2017
Available online 13 July 2017
0963-8695/

wavefield data collected with a scanning laser vibrometer. Time-reversal methods were applied in Ref. [16] to exploit multipath propagation in SHM. In Ref. [17], multiple ultrasonic echoes caused by reflections from the plate's boundaries are considered and an analytical model is proposed to estimate the envelope of scattered waves. Correlation between the estimated and experimental data is used to generate images. However, the aforementioned methods do not utilize the sparsity property of the defects in an otherwise pristine structure for image reconstruction. This provides the motivation for our work which exploits multipath propagation to enhance defect imaging within the sparse reconstruction framework.

This paper focuses on the formulation and experimental validation of a sparsity-based multipath exploitation scheme. It significantly extends previous preliminary work by the authors [18] which presented results based on simulations. Our scheme is based on a signal model that considers several multipath signals in addition to the direct path signal. The fundamental anti-symmetric mode (A_0) is utilized to collect real-data measurements from an aluminum plate with one and two symmetric defects. Using the group sparsity constraint, image reconstruction is performed jointly across all signal contributions.

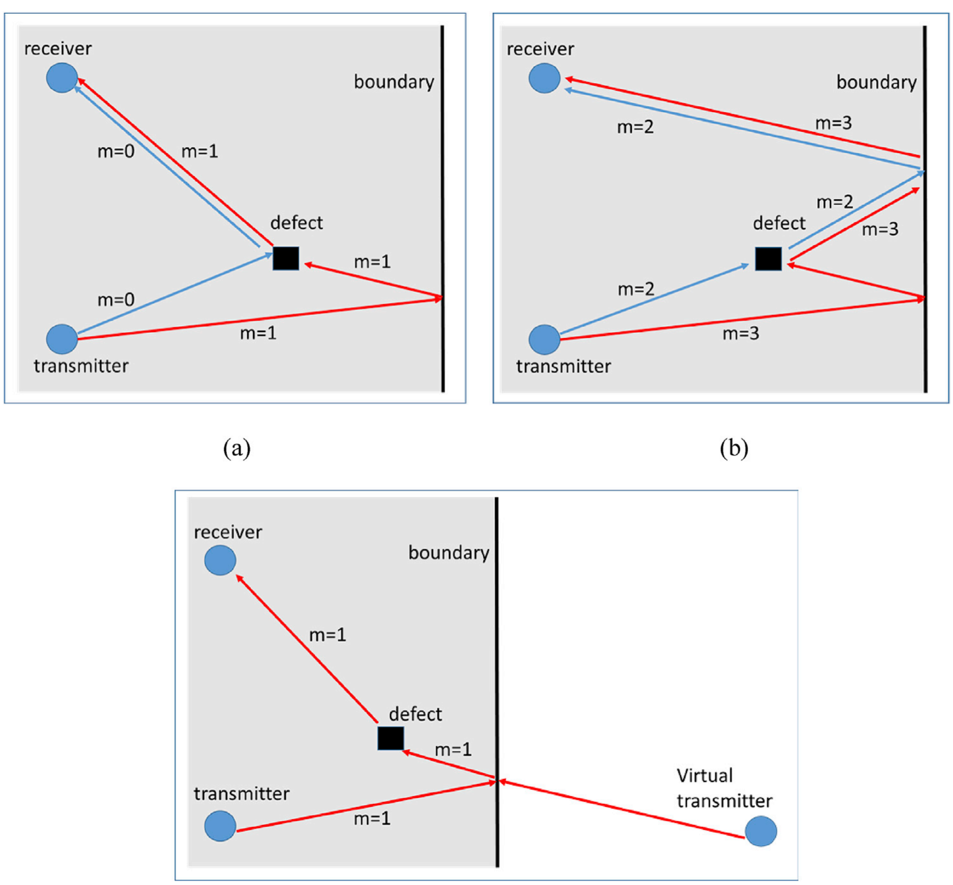
The remainder of the paper is organized as follows. In Section 2, we present the signal model and the group sparse reconstruction framework for the sparsity-based multipath exploitation approach. Section 3 describes the experimental setup and presents the reconstruction results. Section 4 contains the concluding remarks.

2. Signal model

Assume a network of M piezoelectric transducers attached to the surface of a thin plate and operated in pitch-catch mode. These M transducers provide $L = M(M-1)/2$ unique transmitter-receiver combinations. Let the transmitter and receiver locations corresponding to the lth pair be denoted by $\mathbf{t}_l$ and $\mathbf{r}_l$, respectively. Assume the excited waveform, $h(t)$, is a windowed sinusoidal signal, whose frequency is selected to provide a single dominant A_0 mode. Access to baseline signals collected with no defect present is assumed [9,10] and Optimal Baseline Subtraction is employed to minimize temperature-dependent baseline mismatch [19].

Consider P defects present in the plate with the pth defect located at $\mathbf{s}_p$. Let the ROI be divided into $N \gg P$ pixels. For each transmitter-defect-receiver combination, there exists a number of scattering paths due to the structural edge multipath phenomenon. For illustration, we consider the scenario depicted in Fig. 1(a) and (b), where one direct scatter path, two first-order multipath (involving single interaction with the boundary), and one second-order multipath (also referred to as the "W" path involving boundary reflection before and after interaction with the defect) exist between the transmitter and the receiver via the pth defect. The baseline-subtracted received signal, $z_l(t)$, corresponding to the lth transmitter-receiver pair, can be written as

$$z_l(t) = \sum_{p=0}^{P-1} \left[g_{lp}^{0}(t) + g_{lp}^{1}(t) + g_{lp}^{2}(t) + g_{lp}^{3}(t) \right], \quad (1)$$



(c)

Fig. 1. Schematic showing multiple pathways for waves to travel from a transmitter to a receiver after being scattered by a defect and the plate boundary: (a) the direct scatter path ($m = 0$) and a first-order multipath ($m = 1$); (b) a first order multipath ($m = 2$) and a second-order "W" path ($m = 3$); (c) virtual transmitter model; the case of the virtual receiver is constructed analogously. Shaded region represents region of plate.