



A comparison and extensions of algorithms for quantitative imaging of laminar damage in plates. II. Non-monopole scattering and noise tolerance

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HIGHLIGHTS

- Diffraction tomography is adapted for mixed mode Lamb wave imaging.
- Excellent imaging performance is shown to be compromised by noise sensitivity.
- Strategies to enhance noise tolerance are proposed and investigated.
- Imaging in the presence of structural complexities is demonstrated experimentally.
- Sensor requirements can be reduced by a factorisation approach.

ARTICLE INFO

Article history:

Received 21 July 2015
Received in revised form 6 April 2016
Accepted 7 April 2016
Available online 19 April 2016

Keywords:

Imaging
Diffraction tomography
Beamforming
Time reversed imaging
Inverse scattering

ABSTRACT

A generalisation of diffraction tomography that is applicable for mixed-mode Lamb wave imaging is derived, subject to clearly stated simplifying assumptions. The resulting algorithm is further extended to near-field imaging. This algorithm requires a knowledge of the scattering pattern for an appropriate point scatterer, which needs to be determined separately for each type of damage, and for every combination of incident and scattered wave modes. The procedure for determining this point-scatterer pattern is presented for the case of delamination damage modelled as a flexural inhomogeneity. The performance and limit of validity of the resulting algorithm for the A_0 mode are shown to be comparable with those for the acoustic model, but this excellent performance is accompanied by an increased sensitivity to noise relative to simpler algorithms based on beamforming or time reversed imaging. Several strategies for enhancing the noise tolerance are proposed and investigated. Experimental results are presented to demonstrate the practical implementation and imaging performance. These results also illustrate the use of the distorted wave Born approximation for imaging in the presence of known structural complexities, as well as the use of a factorisation approach to minimise the required number of sensors.

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1. Introduction

This paper continues and completes an investigation into algorithms suitable for quantitative imaging of laminar damage in plate-like structures. In a previous paper [1], three distinct imaging algorithms were systematically derived, assuming that the wave motion satisfies the 2D scalar wave equation. This so-called *acoustic model* has been widely used for deriving imaging algorithms [2,3]. The main conclusions reached in [1] were that: (i) the algorithm based on linearised

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inverse scattering, which is a generalisation of diffraction tomography, is the most rigorous approach from a mathematical viewpoint; (ii) the algorithms based on beamforming and reverse time migration rely on heuristic arguments, but they are much simpler to implement in practice, which accounts for their popularity; (iii) all three algorithms were shown to have a similar mathematical structure in the far-field limit; and (iv) it is therefore possible to derive variants of these algorithms that combine accuracy, for both size and severity reconstruction, with ease of implementation.

The present work is organised as follows. Section 2 describes the imaging setup and problem formulation. This includes a definition of the terms *laminar damage* and *quantitative imaging*, as well as a careful statement of the simplifying assumptions underpinning the present work. Section 3 presents a generalisation of diffraction tomography for mixed-mode Lamb wave imaging, starting with the far-field formulation, and extending that to near-field imaging, following the approach presented in [1] for the acoustic model; a generalisation of time reversal imaging is also presented. Section 4 deals with the special case of scattering by flexural inhomogeneities [4], for which mode conversion can be ignored. An idealised model of delamination damage is used to assess the imaging performance, which is compared with the performance reported in [1] for the acoustic model. Section 5 investigates the noise sensitivity of the imaging algorithm, identifying factors that exacerbate sensitivity, as well as strategies to improve noise tolerance. Section 6 presents experimental results to demonstrate the practical implementation of the imaging algorithms, and in particular to illustrate the implementation of the distorted wave Born approximation and of the factorisation approach [5–7] that can be used to minimise the required number of sensors. Finally, Section 7 provides a general discussion and recommendations for practical implementation, as well as directions for future work.

Although the present work is primarily concerned with the imaging algorithms derived in [1], it is pertinent to mention briefly some recent approaches to the inverse scattering problem that are designated collectively as *sampling methods* [8–12]. These methods are not restricted to weak scatterers, but their implementation requires elaborate computations to evaluate a so-called indicator function, and these calculations need to be repeated for every point within the prescribed imaging domain. In particular, the linear sampling method [8,9] requires the solution of an integral equation whose kernel is constructed from observations of the scattered field, and whose solution is expected theoretically to become unbounded for sampling points outside the support of the scatterer. In contrast, the topological sensitivity approach [10,11] requires the evaluation of the functional derivative for an objective function that is formulated as an integral over the body's external boundary and the time interval of interest, where the integrand involves the solution of the forward scattering problem for an idealised small scatterer located at the given sampling point. Furthermore, these sampling methods are recognised to be *qualitative methods* [12], in the sense that the indicator functions are designed to attain extreme values when the sampling point strikes the scatterer, thereby providing an indication of the scatterer's shape and size, but they do not provide a quantitative image of a contrast parameter that can be correlated with damage severity. By contrast, the algorithms investigated in [1] and in the present work can be implemented straight-forwardly as simple formulae involving the measured scattered field as input, which accounts for their popularity in practice, and they lead to quantitative images [1]. As also noted in [1], these algorithms rely on the weak scatterer approximation, which, however, is the case of greatest practical interest for structural health monitoring, as it corresponds to early damage detection. Furthermore, these linearised inverse algorithms have been shown to perform as well or better than the sampling methods even for cases that would not be considered weak scatterers [13]. Indeed, the modified time reversal algorithm that is presented here in Section 3 has recently been shown to provide excellent images of partially closed cracks, using either the fundamental frequency or the second harmonic component of the scattered field as the input [14].

2. Imaging setup and problem formulation

Consider a plate-like structure that has suffered some form of laminar damage over one or more regions designated collectively by Σ_d , as indicated by the shaded area in Fig. 1. The term laminar damage refers to forms of damage that extend parallel to the plate's midplane, rather than cracks at right angles to the plate surface; examples are corrosion thinning, exfoliation corrosion and delamination damage in fibre-composite laminates.

The plate is assumed to be equipped with point-like sources (actuators) and receivers (sensors), with the sources distributed at discrete locations $\mathbf{X}_j = (X_j, Y_j)$, ($j = 1, \dots, N_s$), and the receivers at locations $\mathbf{X}_i = (X_i, Y_i)$, ($i = 1, \dots, N_r$), as indicated in Fig. 1. If the active elements can be used as both sources and receivers, as in the case of piezoelectric transducers, one would have a coincident source–receiver array. However, even for that case, the index j will be used to identify actuator locations, and the index i to identify receiver locations, with $i, j = 1, \dots, N$, ($N_r = N_s = N$).

The total wavefield due to the action of an actuator at \mathbf{X}_j can be regarded as the superposition of the incident field u^I which would prevail in the absence of any damage, and the scattered field u^S due to the presence of the damage,

$$u(\mathbf{x}, t; \mathbf{X}_j) = u^I(\mathbf{x}, t; \mathbf{X}_j) + u^S(\mathbf{x}, t; \mathbf{X}_j), \quad (1)$$

where $u(\mathbf{x}, t)$ denotes a physical observable such as the transverse deflection [4,15] at location $\mathbf{x} = (x, y)$; the case where actuation and sensing involve an electro-mechanical transduction is discussed in Section 6. The scattered field recorded at receiver location \mathbf{X}_i , due to an actuation at \mathbf{X}_j , can be regarded as the ij th element of a time-domain data matrix,

$$u_{ij}^S(t) = u^S(\mathbf{X}_i, t; \mathbf{X}_j). \quad (2)$$

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