NDT&E International 68 (2014) 43–52

Contents lists available at ScienceDirect

NDT&E International

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

A probabilistic approach for the optimisation of ultrasonic array inspection techniques

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ARTICLE INFO

Article history:
Received 15 April 2014
Received in revised form
14 July 2014
Accepted 30 July 2014
Available online 7 August 2014

Keywords:
Ultrasonics
NDT
Phased arrays
Imaging
Optimisation
Defect detection
Genetic algorithms

ABSTRACT

Ultrasonic arrays are now used routinely for the inspection of engineering structures in order to maintain their integrity and assess their performance. Such inspections are usually optimised manually using empirical measurements and parametric studies which are laborious, time-consuming, and may not result in an optimal approach. In this paper, a general framework for the optimisation of ultrasonic array inspection techniques in NDE is presented. Defect detection rate is set as the main inspection objective and used to assess the performance of the optimisation framework. Statistical modelling of the inspection is used to form the optimisation problem and incorporate inspection uncertainty such as crack type and location, material properties and geometry, etc. A genetic algorithm is used to solve the global optimisation problem. As a demonstration, the optimisation framework is used with two objective functions based on array signal amplitude and signal-to-noise ratio (SNR). The optimal use of plane B-scan and total focusing method imaging algorithms is also investigated. The performance of the optimisation scheme is explored in simulation and then validated experimentally. It has been found that, for the inspection scenarios considered, TFM provides better detectability in a statistical sense than plane B-scan imaging in scenarios where uncertainty in the inspection is expected.

1. Introduction

The use of ultrasonic arrays for non-destructive evaluation (NDE) applications has grown rapidly in recent years. Arrays have key advantages over single element transducers in terms of sensitivity and inspection performance. The take-up of array technology has been across a wide range of industrial sectors including power generation, aerospace, oil and gas and automotive. For example, in the power generation industry, Mahaut et al. [1] describe the inspection of welds in thick (30–50 mm) steel plates using a conformable array. They show the use of an array to steer the beam through a range of angles thus ensuring sensitivity to a range of crack angles in geometrically complex components.

Some attempts have been made to optimise ultrasonic array systems for radio frequency and medical ultrasound applications where it is reasonable to assume the array elements emit into an infinite fluid filled half-space. For example, the classical work of Dolph [2] demonstrates how array elements weighting can be used in order to minimise main lobe beam width for a given side lobe level. Nikolov and Behar [3] use a simulated annealing algorithm to find these element weighting functions that achieve the optimal image contrast (i.e. signal to imaging artefact ratio) and lateral resolution. Matte et al. [4] and Ergun [5] investigate the optimal array geometry and frequency for harmonic imaging and therapeutic ultrasound respectively. However, both authors focus on a small number of parameters, and hence can plot optima on 2D and 3D graphs. Martinez-Graullera et al. [6] and Raju et al [7] investigate the optimisation of imaging performance metrics using sparse arrays. They both use sparse patterns described by a small number of parameters to simplify the optimisation problem and then perform the optimisation by completely exploring the resulting parameter space.

Forward modelling is increasingly used to inform and improve array inspections for NDE. For example Mahaut et al. [8] and Zhang et al. [9] use hybrid approaches in which the wave propagation through the body of the component is modelled as a ray (or pencil beam) and the scattering from a defect is modelled using analytical or finite element approaches. To date these forward models are used pragmatically to inform the array inspection process, rather than to fully explore the relevant parameter space to find optimal configurations. The one recent exception being the work done by Puel et al. [10] who have demonstrated array optimisation

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http://dx.doi.org/10.1016/j.ndteint.2014.07.007

of a simple amplitude-based cost function using a commercial ultrasonic modelling package CIVA (which is developed by the CEA, French Atomic Energy Commission) as their forward model. One of the problems in the optimisation approach adopted in their work is that deterministic forward models have been used to optimise the array inspection for the imaging of a particular defect at a particular location within the considered specimen. In most inspection scenarios, certain levels of uncertainty occur related to the type, size, and location of the defects to be detected or the properties and geometry of the material that need to be inspected.

Here we present a general framework for the optimisation of ultrasonic array inspection techniques in NDE. Both forward deterministic and statistical modelling of the inspection are used to formulate the optimisation problem and incorporate inspection uncertainty information. The array produces an image of the interior of the test structure and these images can be used for both detection and characterisation. This work follows the approach presented by Flynn and Todd [11] who present a theoretical framework based on detection theory for optimal sensor placement in structural health monitoring (SHM) applications using ultrasonic guided waves. Here we explore a simple inspection set-up in which defect detection has been defined as the main inspection objective and use this to assess the performance of the optimisation framework. Experimental measurements are carried out for benchmarking and validation.

2. Optimisation framework

In this study, the defect detection problem is expressed in the form of an optimisation problem. Optimisation problems can be described in a general form as follows: Given a set of variables $\boldsymbol{X}$ (*decision vector*) and a function $Y:\boldsymbol{X}\rightarrow\mathbb{R}$ (the *objective function*), the aim is to find $\boldsymbol{x}^*\in\boldsymbol{X}$ such that for all $\boldsymbol{x}\in\boldsymbol{X}$, there holds $Y(\boldsymbol{x})<Y(\boldsymbol{x}^*)$. This problem can be extended to solve multi-objective functions. Multi-objective functions are expected to produce conflicts and hence trade-off design parameters have to be considered. In this study only single-objective functions are addressed.

In the current ultrasonic array inspection problem, the array location, propagation mode(s), coupling method, array size, number of elements, etc. are considered as the decision variables. For a deterministically defined inspection problem, the imaging signal amplitude, SNR, etc. can be considered as objective functions whereas for a stochastic problem, a statistical parameter such as the mean, median, minimum, or cumulative probability above a threshold for the signal amplitude or the SNR can be considered as an objective function. These objective functions will be chosen depending on the aim of the inspection (i.e. detection, characterisation, or both), and they will depend on the component geometry, material properties, defect type, location, and orientation. Some of these parameters might be precisely known and well-defined while some others might be uncertain.

Here we address the stochastic problem by using deterministic forward models to calculate realisations of these objective functions, and a Monte Carlo approach to heuristically simulate uncertainty in the inspection. In many cases, these objective functions are expected to be fairly challenging to maximise and contain multiple maxima. Therefore, global optimisation algorithms, such as the genetic algorithm (GA), simulated annealing (SA), or Monte Carlo Markov Chains (MCMC) can be used to solve these optimisation problems.

Fig. 1 shows a flowchart of the proposed optimisation framework. The following sections will describe the main components of this optimisation framework which will then be used to optimise the inspection in two specific examples. The optimisation results will also be validated experimentally.

2.1. Forward model

In this optimisation framework, a frequency-domain far-field hybrid modelling approach is used to simulate the forward problem. In this hybrid model a ray-based model is used to simulate the propagation of ultrasonic waves through the body of the structure while a scattering coefficient matrix is used to model the response of the defect. The ray model analytically incorporates the effects of beam divergence, phase delays, refraction, and mode conversion at interfaces. The scattering coefficient of a defect describes its far-field ultrasonic response as a function of the angle of incidence and scattering. These scattering coefficients can be calculated using analytical or finite element (FE) methods [8,9].

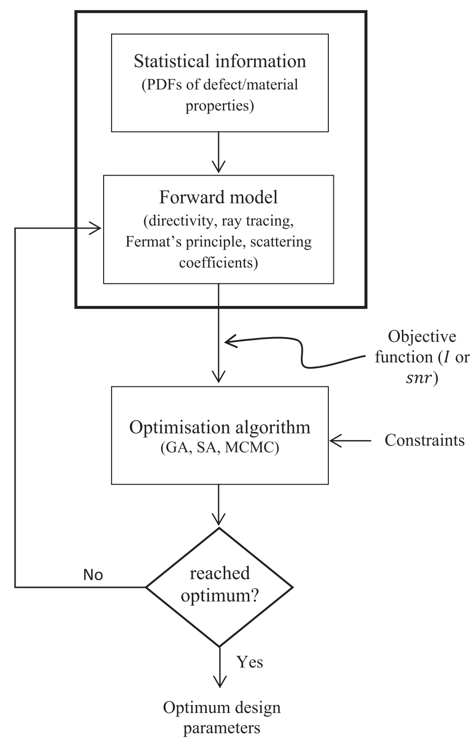

Fig. 1. Flowchart diagram of the proposed optimisation framework.

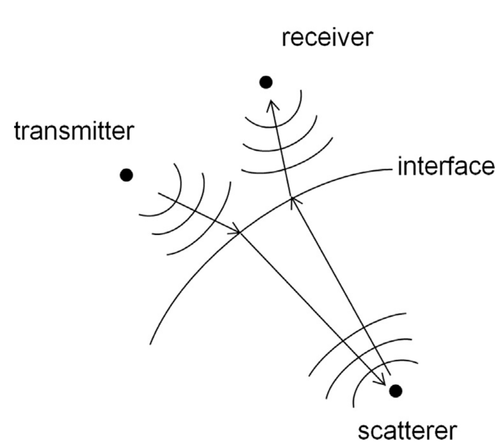

Fig. 2. Schematic diagram of the generalised forward model.