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A numerical database for ultrasonic defect characterisation using array data: Robustness and accuracy

Robert Malkin*, Mihai Caleap, Bruce W. Drinkwater

Department of Mechanical Engineering, University of Bristol, Bristol BS8 1TR, UK

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ABSTRACT

Elastodynamic scattering matrices are known to contain geometrical information about a given scatterer, such as its size and shape. Here, the extent to which this scattered information can be retrieved using an ultrasonic array and used to characterise defects for Non-Destructive Evaluation is explored. Experimentally measured defect scattering matrices are compared to a database of possible scatterers and the nearest neighbour used to characterise the defect's geometry in terms of crack length and orientation. As an example, a database of scattering matrices for small (lengths 0.2–2.0 mm) cracks at a range of frequencies (2–20 MHz) is formed. The short range similarity (i.e. that between close neighbours) and the long range similarity (i.e. uniqueness) are used to understand the uncertainties inherent in this approach. In addition, the effect of spatially coherent noise, such as grain scattering in a polycrystalline metal, on the scattered information content is quantified. It is shown that as the noise level or frequency increases, so the information retrievable from a given crack is reduced, setting bounds on the accuracy of characterisation possible from a given ultrasonic dataset.

1. Introduction

In order to assess the safety of a structure it is important to be able to detect, locate and characterise various types of defects. Ultrasonic array-based Non-Destructive Testing (NDT) techniques have allowed for this to become a regular aspect of structural inspections. Of particular interest is the ability of an inspection to fully characterise the nature of the defect and to decide if it is a critical defect which may lead to failure, or if the defect is sub-critical and may safely be ignored or monitored.

Using ultrasonic array imaging methods such as the: total focusing method [1], synthetic aperture focusing technique [2,3], inverse field wave extrapolation [4] or wavenumber algorithms [5], a range of defects can be detected and accurately located. If the defects are large, i.e. greater than a few wavelengths, these methods also offer the possibility to determine the defect shape and/or orientation of the defect directly from the image [6]. Sizing of large defects is also possible using mathematical models of scattered signal data [7], corner trap the tip diffracted echoes [8] and superimposed echo modelling [9,10]. If the defect is small, it has been shown that characterisation may be possible by utilising information contained within the defect scattering matrix, which describes the angular scattering behaviour of a given scatterer [11].

The scattering matrix, or S-matrix, describes the amplitude and phase of the scattered field of a defect in the far field, and has been shown to encode the far-field information arising from all wave-scatterer interactions [12]. Let $\boldsymbol{r}$ be the position vector of a point in the x-z plane which in polar coordinates is given by, $\boldsymbol{r} = (r, \theta)$; here $r=|\boldsymbol{r}|$ and θ is measured from the positive z-axis. For 2-D problems, the far-field scattering amplitude is defined by, [13].

$$u^{\mathrm{sc}}(\boldsymbol{r}) \simeq \sqrt{\frac{2}{\pi}} e^{-i\pi/4} \frac{e^{ikr}}{\sqrt{kr}} S(\theta) \text{ as } r \to \infty, \tag{1}$$

where $i=\sqrt{-1}$, $k = \omega/c_L$ and c_L is the longitudinal wave velocity. For a given angular frequency, ω, $S(\theta, \omega)$ gives the field scattered in the direction θ. If the incident field is a plane wave propagating in the direction θ_{in}, we write $S(\theta,\theta_{in},\omega)$ – this angular shape function is what we call in our paper the S-matrix. Note that here we approximate the far-field array element output in the vicinity of a small defect as a plane wave.

The S-matrix, or more strictly, portions of it, may be extracted from array data using, for example, back-propagation imaging as shown in [14]. As S-matrices are extracted from a known point within an array image all the propagation paths/distances are known, therefore propagation, directivity and frequency

* Corresponding author.
E-mail addresses: r.e.malkin@gmail.com (R. Malkin), mihai.caleap@bristol.ac.uk (M. Caleap), b.drinkwater@bristol.ac.uk (B.W. Drinkwater).

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dependent damping effects may be accounted for. Zhang et al. [6] demonstrated that if the extracted S-matrix contains a specular reflection, accurate sizing of a 1-D crack (for crack lengths ≈ 0.5-1.5λ) is possible. A recent study by the authors used a database of pre-calculated S-matrices against which an experimentally extracted S-matrix was compared [11]. Using this approach, the length and orientation of cracks could be accurately measured, even if the specular reflections were not captured. This work showed that even relatively small regions of the S-matrix (i.e. in terms of range on incidence and scattered angles) potentially contain sufficient information for defect characterisation. It should be noted that realistic defects will likely feature surface roughness, for which a database of pre-calculated S-matrices would be unmanageably large. Recent work has demonstrated that defects roughness can be thought of as adding noise to the defect classification process, i.e. classification is unaffected by low levels of surface roughness and, as the roughness increases, so does classification uncertainty [15]. We build on this work by exploring the information contained within an S-matrix and the measurement confidence of the characterisation result. In particular, we examine the effect of spatially coherent scattering noise on S-matrix information content and hence on defect characterisation accuracy.

The Structural SIMilarity (SSIM) index was originally developed as a method of objective evaluation of the similarity between two optical images, a reference and modified/degraded image. SSIM compares two images (X, Y) based on three parameters; mean, $m(X, Y)$, variance, $v(X, Y)$ and cross-correlation, $q(X, Y)$. The SSIM between the two images X and Y is given by

$$SSIM(X, Y) = m(X, Y)^{\beta} \bullet v(X, Y)^{\gamma} \bullet q(X, Y)^{\delta} = \left(\frac{2\mu_X\mu_Y + C_1}{\mu_X^2 + \mu_Y^2 + C_1}\right)^{\beta} \bullet \left(\frac{2\sigma_X\sigma_Y + C_2}{\sigma_X^2 + \sigma_Y^2 + C_2}\right)^{\gamma} \bullet \left(\frac{\sigma_{XY} + C_3}{\sigma_X\sigma_Y + C_3}\right)^{\delta}, \quad (2)$$

where μ is the mean, σ is the standard deviation, σ_{xy} is the cross-correlation (inner product) and $C_{1,2,3}$ are small constants used to avoid numerical instabilities when $\left(\mu_X^2 + \mu_Y^2\right)$ and/or $\left(\sigma_X^2 + \sigma_Y^2\right)$ and/or $(\sigma_X\sigma_Y)$ are close to zero. An SSIM of 1 results from two identical images. The exponents β, γ, δ allow the contributions of each of the three major terms to be modulated, we let $\beta = \gamma = \delta = 1$ as per the original published work [16].

2. S-Matrix database

As the number of possible defects, and thus corresponding S-matrices, is infinite we restrict our analysis to that of planar cracks of negligible thickness. Not only does this restriction have the potential to increase the chance of successful characterisation, but it also represents arguably the most important type of defect found in engineering materials. Future work will address the challenge of exploring the implications of further extending the range of defect types. The S-matrix database was created using the efficient finite element method developed in [17]. The method uses an integral representation of the wave field where the scattered field from an arbitrary shaped scatterer is decomposed into the far field scattering amplitudes, allowing the S-matrix to be calculated. The S-matrix calculation is performed at a single frequency yet typically it will be compared it to an experimental S-matrix measured using a transducer array with some bandwidth about its central frequency. This is reasonable as it has been shown that calculated single frequency S-matrices correlate extremely well with experimental S-matrices measured from time-domain data. It is also worth noting that techniques are available for extracting the S-matrices as a function of frequency and work is ongoing to understand this additional dimension to the information [14]. As shown in Fig. 1, our database is created from planar crack-like defects in a two-dimensional isotropic elastic material (aluminium, with properties from [18]). The $360^{\circ}_{incident} : 360^{\circ}_{scattered}$ angle S-matrices were computed with 1° angle increments. An experimentally acquired S-matrix however, will likely be significantly smaller in angular range than this due to the measured inspection angles which are possible. In order to study the effect of this reduced S-matrix each S_D was truncated into ten sub-matrix sizes ($[36^{\circ}_{inc.} : 36^{\circ}_{sca.}]$, $[72^{\circ}_{inc.} : 72^{\circ}_{sca.}]$,…., $[360^{\circ}_{inc.} : 360^{\circ}_{sca.}]$). As we keep the incident and scattered angular ranges equal we refer to each sub-matrix size simply by its angular range, i.e. a sub-matrix size of $36° = [36^{\circ}_{inc.} : 36^{\circ}_{sca.}]$. A database was then constructed with crack length, a, ranging from 0.2 mm to 2.0 mm in 0.03 mm increments, the rotation angle, α, ranging from 0° to 178° in 2° increments (the S-matrices are identical for cracks with $\pm 180°$ rotation thus we only compute half the rotational range), with all studies performed from 2 MHz to 20 MHz in 1 MHz increments. In total, per frequency, the database contains 5400 S-matrices, individually referred to as database elements, S_D. Each S-matrix had a data size of 790 Kb, stored as a 360×360 32 bit number matrix of the amplitude of the complex S-matrix. The database in effect acts as a 'look-up' reference against which experimentally extracted S-matrices may be compared and the nearest neighbour found. The assumption which is explored in this paper is that, as the SSIM increases, so the nearest neighbour in the database approaches the true experimental result in terms of the characteristics of the

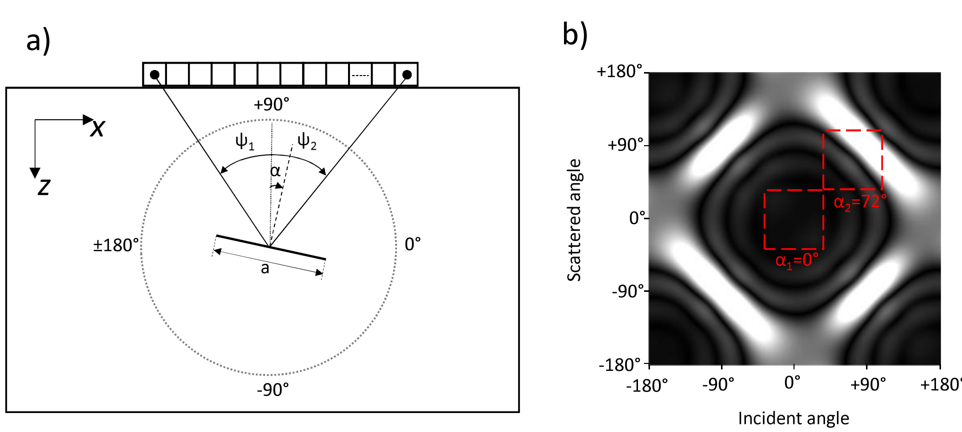

Fig. 1. Defect geometry and example S-matrix. (a) Geometry of crack-like defect, of length a, from which S-matrices are generated. Where ψ_1 and ψ_2 define the range of possible incident/scattered angles when using a fixed array, α is the rotation angle of the crack and x and z are the spatial coordinates. (b) Example S-matrix showing the full incident: scattered angular range $\pm 180°$ for a defect of $a = 1.00$ mm and $\alpha = 0°$ at 10 MHz. The red dashed boxes show 2 sub-matrices (both 72° in size) of the full S-matrix as may be acquired experimentally given limited inspection angles (ψ_1 and ψ_2 in a). The two sub-matrices represent the same defect shape with different rotations, α_1 and α_2.