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Numerical simulations of ultrasonic array imaging of highly scattering materials

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ABSTRACT

A Finite Element modelling framework is outlined that enables the investigation of ultrasonic array imaging within highly scattering, polycrystalline materials. Its utility is demonstrated by investigating the performance of arrays, within both single and multiple scattering media. By comparison to well-established single scattering models, it is demonstrated that FE modelling can provide new insights to study the stronger scattering regimes. In contrast to established single scattering results, Signal-to-Noise Ratio (SNR) no longer increases monotonically with respect to increasing aperture, which suggests that maximum apertures are not necessarily optimal. Furthermore, by measuring the SNR of the individual transmit receive combinations of the array, it is found that through separating the emitter and receiving source, it is possible to reduce the received backscatter.

1. Introduction

Ultrasonic arrays have enabled exciting possibilities for NDE in recent years. Not only have they been adopted for their ease of use, the wealth of spatial information [1] which can be acquired has enabled imaging capabilities which were previously inconceivable using monolithic transducers (see e.g. [2,3]). Such advances have presented promising opportunities for progress but ultrasonic NDE still faces significant challenges: namely, it is fundamentally limited by the onset of scattering [4] once the probing wavelength becomes dimensionally similar to the microstructure of the propagation medium. For many materials, such as coarse grained polycrystalline metals [5], this occurs at typical inspection wavelengths. Consequent increases in attenuation, coherent noise, and possibly anisotropic effects, all contribute to a reduction in the Signal-to-(coherent)-Noise ratio (SNR), thereby limiting the range of materials which can be reliably inspected, ultrasonically.

Scattering within polycrystalline media has been studied in a great variety of contexts (see e.g. reviews [5,6]) where an initial distinction can be made between single and multiple scattering regimes. Single scattering is a 'weak' scattering condition, generally accepted to be valid within the long-wavelength regime, where the polycrystalline material can be approximated by a random distribution of discrete scatterers and the contribution of each scatterer can be considered independently. The Independent Scattering Model (ISM) [7] is a well-respected implementation of this and has enabled notable progress [8] for the ultrasonic inspection of scattering materials. Single scattering assumptions however are known to become invalid for stronger scattering media once multiple scattering arises [9].

Alternatively, numerical modelling currently presents opportunities to study these more challenging scattering regimes. Recent Finite Element (FE) models of elastodynamic wave propagation within polycrystalline materials [10–12] have been shown to capture the complex scattering physics [13], including multiple scattering [14], with high fidelity. These numerical methods can also be advantageous over experimental studies, as statistically significant studies are enabled by repeating multiple FE studies relatively inexpensively, and with complete knowledge and control of the parameters.

Such advantages present FE as an ideal tool to provide a quantitative understanding and answer the remaining questions (see e.g. [15]) to determine the optimal array parameters to for instance maximise imaging SNR and by association the possibility of a successful detection. The latter can involve a multitude of parameters to optimise, associated to either hardware (e.g. the aperture size) or software (e.g. the imaging algorithm). Here we pursue an initial interest in the array configuration, including its number of array elements, which defines the aperture angle and the element layout, and therefore we constrain software parameters such as the imaging algorithm.

Within the field of ultrasonic array imaging, there has been a recent surge of advanced imaging algorithms (see e.g. [2,3] and

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reviews [16,17]) which have shown impressive progress. Still, it has proven challenging to suppress coherent noise [16,17] and thereby increase imaging performance beyond that provided by standard sum-and-delay beamforming. Consequently, the currently most popular algorithm, the Total Focusing Method (TFM) [18], for the time being, remains the benchmark, offering both high performance as well as relative simplicity. Thus this article will rely on TFM for its investigations and illustrations; it is expected that the findings will be equally relevant for other imaging algorithms.

This article outlines a FE modelling framework, an extension to the basis reported in [10–14], that enables the investigation of ultrasonic array imaging of highly scattering, polycrystalline materials. It details modelling devices which allow the isolation of different physical phenomena (e.g. element directivity, beam spreading, attenuation, backscatter) and therefore enables new and useful insights into the effects of scattering, particularly without relying on a single scattering assumption. The methodology is applied to a relatively simple but also general case such that it both illustrates and investigates the fundamentals of array performance. The approach is now also ready for a wide variety of simulations where it can be useful in future evaluations of performance: for instance to determine the optimal configuration for a more practical inspection, quantify the smallest detectable defect, or assess new data processing algorithms such as new candidate array imaging algorithms.

The subsequent sections are organised as follows. Section 2 outlines the FE methodology starting with the description of a polycrystalline medium and later the ultrasonic array models. Before considering polycrystalline scattering media, Section 3 uses established theory to study array performance within a single scattering environment. These results enable comparisons with Section 4 which repeats the same procedure but considers stronger, multiple scattering by introducing polycrystalline material properties. Section 5 then compares the results obtained from both previous sections. Before setting out with these studies, we present the currently established theory for determining detection performance of an array imaging a noisy medium, under single scattering assumptions.

1.1. Established single scattering theory

In many circumstances of NDE, such as the inspection of acoustically transparent materials, detection performance is predominantly defined by random noise such as electrical noise. Once scattering occurs, coherent noise manifests and typically becomes the limiting factor. Assuming that random noise has been eliminated by, for example, temporal averaging, SNR will hereon refer to the Signal-to-(coherent)-Noise Ratio.

Single scattering models, such as the aforementioned ISM [19,20], determined that SNR is inversely proportional to the ultrasonic pulse volume for monolithic transducers. This led to the adoption of focused transducers to improve sensitivity of industrial inspections of scattering materials. More recently, Wilcox [4] (and others e.g. [21]) found similar results for arrays by showing SNR to depend on the Point-Spread Function (PSF) of an array (see Eq. (1)).

$$SNR(\boldsymbol{r}) = \frac{q}{\mu}\frac{|P(\boldsymbol{r},\boldsymbol{r})|}{\sqrt{\int |P(\boldsymbol{r},r')|^2 dr'}} \quad (1)$$

Here μ is the backscatter coefficient, derived for polycrystalline materials by Rose [22] and q is the scattering potential of the imaging target. Outside these two parameters, the remainder of Eq. (1) is defined by two Point Spread Functions, e.g. $P(\mathbf{r},\mathbf{r'})$ is the image response at $\mathbf{r}$ of an idealised single point scatterer located at $\boldsymbol{r'}$. Thus the remaining fraction is solely determined by the imaging system and is equivalent to the reciprocal of the square root of the normalised PSF area [4], σ. For our purposes of finding an optimum, only relative SNR is of interest, and hence in the studies presented here we can disregard the two parameters μ and q [21] and redefine a relative SNR, denoted by $\overline{\mathrm{SNR}}_p$, where pk denotes peak.

$$\overline{SNR_p}(\boldsymbol{r}) = \frac{|P(\boldsymbol{r},\boldsymbol{r})|_{pk}}{\sqrt{\int |P(\boldsymbol{r},r')|^2 dr'}} \quad (2)$$

The relation between SNR and the PSF has several interesting connotations. It firstly implies the monotonic increase of SNR which improves as the PSF is reduced. SNR is thus maximised when using the largest possible aperture [23]. The PSF area, σ, is a widely used metric and can be quantified in various ways (see e.g. [18]), the approach adopted here is to calculate the area of the PSF which encompasses half its peak, and subsequently normalise it against the centre-wavelength squared, denoted by $\bar{\sigma}$.

The PSF comprises the imaging system and can thus be controlled by optimising the array and the imaging algorithm; as previously mentioned, we will focus on the former using a specific choice of imaging algorithm.

2. Method: finite element simulation of highly scattering materials

Here we discuss how to incorporate polycrystalline material properties into an FE model, followed by its extension into our model of an ultrasonic array, which consists of a noise and a signal model.

2.1. Polycrystalline material model

Whereas time-domain explicit FE modelling of wave propagation within isotropic media is well established [24], incorporating a polycrystalline microstructure is a relatively new addition [10–12] which is becoming increasingly popular [13,14]. The methodology, as used here, relies on a Voronoi approach which is widely used in other fields of research such as that of material science (see e.g. [25]) to generate random tessellations which are representative of polycrystalline morphologies. The main obstacle to its adoption for the study of dynamic wave propagation has been its computational cost which is significantly higher than for conventional wave propagation modelling [24] due to a more demanding mesh sampling criterion, defined by the grain size. The simulation package used here is Pogo [26] and the mesh comprises a structured grid of triangular elements, sampled such that the length of the element edge is finer than at least one tenth of the average grain size d to meet the criteria for convergence.

Given the already large computational cost, the relatively large dimensions necessary for our studies, and the interest in performing multiple analyses in order to pursue a range of studies, the models discussed here are limited to a 2D domain. This simplification introduces certain model limitations (discussed in more detail in [13]): the scattering mechanism is reduced to a third order frequency dependence in the Rayleigh regime as shown in [13,27], and it is not obvious how to relate the spatially incoherent fields, namely the grain noise, perceived by a 2D transducer to that of a 3D one. It is expected that 2D models overestimate the absolute level of noise as there is less spatial averaging which occurs across the length of the transducer, as opposed to an equivalent area in 3D. Despite this lack of absolute accuracy, the relative accuracy is expected to be good, as the overall frequency dependent scattering behaviour has been shown to correlate well