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# Ultrasonic array imaging through an anisotropic austenitic steel weld using an efficient ray-tracing algorithm

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ABSTRACT

Ultrasonic inspection of austenitic welds is challenging due to their highly anisotropic and heterogeneous microstructure. The weld anisotropy causes a steering of the ultrasonic beam leading to a number of adverse effects upon ultrasonic array imagery, including defect mislocation and aberration of the defect response. A semi-analytical model to simulate degraded ultrasonic images due to propagation through an anisotropic austenitic weld is developed. Ray-tracing is performed using the A* path-finding algorithm and integrated into a semi-analytical beam-simulation and imaging routine to observe the impact of weld anisotropy on ultrasonic imaging. Representative anisotropy weld-maps are supplied by the MINA model of the welding process. A number of parametric studies are considered, including the magnitude and behaviour of defect mislocation and amplitude as the position of a fusion-face defect and the anisotropy distribution of a weld is varied, respectively. Furthermore, the use of the model to efficiently simulate and evaluate ultrasonic image degradation due to anisotropic austenitic welds during an inspection development process is discussed.

## 1. Introduction

Within the nuclear power generation industry, ultrasonic Non-Destructive Evaluation (NDE) is employed as a means to verify the structural integrity of a given component at a manufacturing stage and at various points throughout its operational life. Due to the safety-critical nature of the industry, the ability to accurately detect, characterize and size defects is of paramount importance. Ultrasonic NDE of austenitic welds is particularly challenging due to their highly anisotropic and heterogeneous microstructures [1]. One of the principal anisotropic effects occurs when ultrasound passing through a weld is 'bent' in a process known as 'beam-steering' [2]. Since it is common practise to assume material isotropy during ultrasonic inspections, this can lead to a variety of problems during ultrasonic array inspection of anisotropic and heterogeneous materials, including the mislocation of defects, and aberration of the defect response. In turn, this can lead to a reduced Probability of Detection and an increased Probability of a False Alarm, influencing both the quality of the inspection and the confidence placed in its results. The degree of defect mislocation and degradation may be a function of inspection parameters such as the probe position, the beam angle, the number and distribution of array elements, the weld anisotropy, the defect location and many more. As such, the ability to model beam-steering and its impact upon ultrasonic imaging allows a qualitative and quantitative assessment of the impact of anisotropy of a particular weld upon a given ultrasonic inspection, and more importantly, the potential to optimise the inspection through parametric analysis or an optimisation framework e.g. simulated annealing or genetic algorithms [3–6].

A key aspect to the modelling of defect aberration due to wave propagation in an anisotropic weld is the calculation of the ray-path and its deviations as it progresses through the anisotropic weld metal. Two modelling strategies commonly applied to the modelling of anisotropic wave propagation include use of the Finite Element Method (FEM) and also a semi-analytical method that draws upon a ray-tracing tool. The FEM is a robust and well-established tool for the simulation of wave propagation and defect interaction in materials, and has seen widespread use in the modelling of wave propagation in austenitic welds. Fellinger et al. [7] first adapted the Elastodynamic Finite Integration Technique (EFIT) from electromagnetics to ultrasonics for anisotropic heterogeneous media in 3D. The EFIT technique relies upon the discretisation of the underlying elastodynamic equations for ultrasonic propagation and Fellinger et al. considered various two-dimensional NDE problems with snapshots of the wave propagation at various time intervals. Halkjaer et al. [8] used the EFIT in tandem with the Ogilvy weld model [9] for an austenitic weld, assuming a transversely isotropic material, demonstrating good agreement between experimental and

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simulated A-scans, while Hannemann et al. [10] applied the EFIT to the inspection of an idealised V-butt weld with good qualitative agreement between experimental and simulated B-scans. Langenberg et al. [11] also used the EFIT with validation against a weld transmission experiment using a simplified symmetrical weld structure. Chassignole et al. [12] developed the 2D finite element code, ULTSON, to predict ultrasonic wave propagation in anisotropic and heterogeneous media. Chassignole discretised an austenitic weld into twelve homogeneous domains and determined the columnar grain direction from X-ray Diffraction analysis and Electron Back-scattered Diffraction analysis. Apfel et al. [13] used a 2D finite element propagation code, ATHENA, using a fictitious domain method such that a regular mesh of the calculation domain could be combined with an irregular mesh of the defect domain, allowing a superior computation speed. This work was further developed to analyse attenuation of the beam [14], comparison to the pulse-echo amplitude of Side-Drilled-Holes in a mock-up weld [15], and structural noise in a multiple-scattering environment [16]. More recently, the ATHENA code has been extended to 3D [17] showing good agreement with the modelling tool CIVA [18] in isotropic and heterogeneous media. However, FEM approaches suffer from extended computation times and physical memory limitations, especially if a large simulation domain is required, for example a large 3-D weld inspection scenario. Furthermore, accurate simulation of various inspection setups is non-trivial, for instance, the modelling of an immersion inspection where accurate simulation of the fluid/solid interface would be required.

Semi-analytical methods require the modelling of each aspect of the ultrasonic test, including transducer simulation, beam propagation and beam-defect interaction. Beam propagation is modelled through use of a ray-tracing algorithm, which, as applied to ultrasonic NDE, is able to predict the path of a wave during propagation through an arbitrary medium. As such, ray-tracing algorithms are particularly useful for the prediction of wave propagation in heterogeneous and anisotropic materials, where the wave path is non-trivial and subject to deviations. Typically, the wave is 'traced' in the direction of maximum group velocity i.e. the energy flow. Ray-tracing models are inherently high frequency approximations and assume local plane wave propagation. A number of ray-tracing algorithms exist for a wide variety of applications [9,19,20] and principally differ in their treatment of ray properties. In general, ray-tracing algorithms that consider many ray properties during propagation e.g. velocity, amplitude, and polarisation may be computationally slower than those that consider only basic ray properties e.g. velocity. For this reason, the choice of ray-tracing algorithm is an important consideration and is dependent upon the exact requirements of the situation in which the ray-tracing algorithm will be used.

Historically, ray-tracing algorithms as applied to austenitic weld inspection have fulfilled a number of applications, including the modelling of wave paths to determine weld coverage [20–23], analysis of reflection properties of defects within welds [9], and the correction of degraded images due to wave propagation through austenitic welds [20,5]. This paper, however, concerns the novel use of the A* 'path-finding' ray-tracing algorithm to simulate degraded ultrasonic array images due to propagation through austenitic weld material. The paper also presents analysis of the characteristics of the degradation when key inspection parameters are varied through parametric analysis. Due to its improved computation speed as compared to the FEM, and ability to model a diverse range of inspection requirements (e.g. varying transducer types), a semi-analytical methodology is desirable as it is potentially necessary to conduct many thousands of ray-traces during a parametric study.

## 2. Ray-tracing algorithms

There are generally two types of ray-tracing algorithm as applied to ultrasonic NDE: 'marching' methods and 'minimisation' methods. Marching methods rely upon the principle of 'marching' a ray through a fixed time or distance interval coupled with iterative solution of the wave properties at each increment, while minimisation methods operate through the minimisation of the time-of-flight between two arbitrary points.

One of the first marching methods as applied to the prediction of beam-steering effects in anisotropic and heterogeneous materials was developed by Silk [24]. A source position is chosen and a ray is propagated at a given angle and velocity until a material interface is reached. At each step, the ray properties are then calculated dependent upon the local material properties either side of the boundary, and the procedure repeated until a ray-trace is formed. Ogilvy [21] developed the software RAYTRAIM, where a ray is moved in discrete distance intervals along its trajectory. At each step, an imaginary interface is created and the local material properties analysed to solve for the on-going ray. Both the wave amplitude and direction are predicted, however this can lead to lengthy computation times should a ray be required to propagate a long distance or to a specific termination point. Schmitz et al. [25] adapted Ogilvy's work to step a ray along discrete time intervals and developed a 3D ray-tracing tool for austenitic materials with good agreement between simulation and experiment when considering the modified beam-spread effect through an austenitic electron-beam weld. Connolly et al. addressed the difficulty of tracing to a desired termination point through adaptation of Ogilvy's work and implementation of a procedure to iteratively adjust the 'launch' angle of a ray until the ray terminates at the desired point in a trial-and-error approach [20]. This is particularly useful for array imaging where a specific ray creation and ray termination point are required e.g. transmitting array element to a receiving array element via a defect or back-wall. However, the algorithm can suffer from extended computation times due to the potential need for many trial launch angles before the correct termination point is achieved.

Minimisation methods operate based upon Fermat's principle of minimum time stating that a wave will propagate between two arbitrary points in space such that the time of propagation between the two is a minimum. A common example is the beam-bending method [19], which relies upon the iterative 'bending' of a spline curve between two points such that the total time-of-flight along the spline is minimised. Since the algorithm does not explicitly involve the calculation of wave properties (e.g. amplitude and polarisation) the algorithm benefits from a dramatically reduced computation time as compared to typical marching methods. Path-finding algorithms are a subset of minimisation methods, predominantly used within computer science applications but which have seen increased uptake into the field of NDE [5,26]. The A* algorithm is a computationally rapid path-finding algorithm and enables ray-tracing between two specified points through the connection of a number of nodes whose position is defined by the user. Unique to its operation is the use of 'heuristics', whereby knowledge of the termination point is used to inform the progression of the algorithm. This may be exploited to yield a solution for a given ray-trace in a very short amount of time, making the algorithm ideal for the model described in this paper, where many thousands of ray-traces may be required for a parametric study.

The beam-steering model described in this paper consists of four major parts: (1) weld simulation, (2) ray-tracing, (3) defect simulation and (4) beam-simulation and imaging. As detailed in Section 3.1, the weld simulation step concerns the specification of the weld anisotropy, and its material parameters such that the