NDT and E International 95 (2018) 45–56

Contents lists available at ScienceDirect

NDT and E International

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

A combined marching and minimizing ray-tracing algorithm developed for ultrasonic array imaging of austenitic welds

Haipeng Zhou [a,b], Zandong Han [a,b,*], Dong Du [a,b], Yifang Chen [a,b]

[a] Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China
[b] State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Keywords:
Ray-tracing
Anisotropic material
Ultrasonic array imaging
Austenitic weld

ABSTRACT

In order to improve the performance of defect sizing and locating in the ultrasonic inspection of austenitic welds, it is important to predict ultrasonic propagation paths using ray-tracing algorithms considering the anisotropy and inhomogeneity of the weld. An effective ray-tracing algorithm is proposed in this paper, which predicts rays in a P2M mode (from a point to a target matrix). The algorithm combines the marching ray-tracing strategy and the minimizing ray-tracing strategy to improve the computing efficiency and accuracy. The performances of both two ray-tracing strategies were analyzed, based on which the parameters of the proposed algorithm were optimized. The propagation times of all the target points were acquired by the algorithm and applied for ultrasonic array imaging. Images generated using inspection experimental signals can prove that the proposed algorithm can achieve P2M ray-tracing efficiently and realize good imaging performance.

1. Introduction

Austenitic stainless steel is the most commonly used material for pressurized components in nuclear reactors. To assure the structural integrity of the reactor, non-destructive testing (NDT) techniques should be applied for accurate inspection and location of defects inside the structures and welds. Due to the complex process of crystal growing with phase transformations, coarse-grained microstructures usually exist in the austenitic welds with anisotropy and inhomogeneity [1]. Ultrasonic testing (UT) technique is one of the most commonly used NDT technique for weld inspection, but does not always perform well for austenitic welds, as ultrasonic waves get distorted when propagating into the coarse-grained welds, together with severe scattering and attenuation [2].

In order to improve the performance of ultrasonic inspection and defect location in austenitic welds, it is necessary to predict the ultrasonic propagation paths through the welds. The prediction of paths, often referred to as the ray-tracing problem, includes three modes of finding paths, as illustrated in Fig. 1. The basic mode is to find the path from a point along a certain direction, while the P2P mode requires ray-tracing from a starting point to a target point. Both two modes find single rays according to given requirements. For the ultrasonic array imaging problem, the paths to all the points in the imaging zone should be acquired in the P2M ray-tracing mode (from a point to a target matrix of points). It is important to improve the computing efficiency of the P2M ray-tracing together with the accuracy, as a large number of rays are required to be predicted. The target of this paper is to develop a P2M ray-tracing algorithm for ultrasonic array imaging, which can be achieved efficiently with high accuracy.

Many techniques are available for the prediction of ultrasonic propagation paths, among which Finite Element Method (FEM) is robust and well-established. Fellinger et al. [3] first proposed the Elastodynamic Finite Integration Technique (EFIT) to calculate the ultrasonic propagation for anisotropic inhomogeneous media. Afterwards Halkjær et al. [4] and Langenberg et al. [5] successively adopted EFIT to simulate the ultrasonic propagation of austenitic welds with validation against experimental results. However, these FEM methods are time-consuming with considerable computing costs. For the efficient ray-tracing problem discussed in this paper, rapid algorithms are needed. There are mainly two strategies to achieve the rapid ray-tracing algorithm, including the marching strategy and the minimizing strategy. In the marching strategy, the rays are generated point by point and the reflection and refraction of the rays are calculated based on Snell's Law. Ogilvy proposed the code called RAYTRAIM (Ray-tracing in Anisotropic Inhomogeneous Media) [6], in which assumed boundaries between points are applied when the calculated ray is marched in anisotropic inhomogeneous media. Afterwards, Schmitz et al. [7] generalized Ogilvy's RAYTRAIM into 3D situations. Ye et al. [8] combined RAYTRAIM with multi-Gaussian beam

* Corresponding author. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China.
E-mail address: hanzd@tsinghua.edu.cn (Z. Han).

https://doi.org/10.1016/j.ndteint.2018.01.008
Received 9 September 2017; Received in revised form 29 December 2017; Accepted 29 January 2018
Available online 31 January 2018

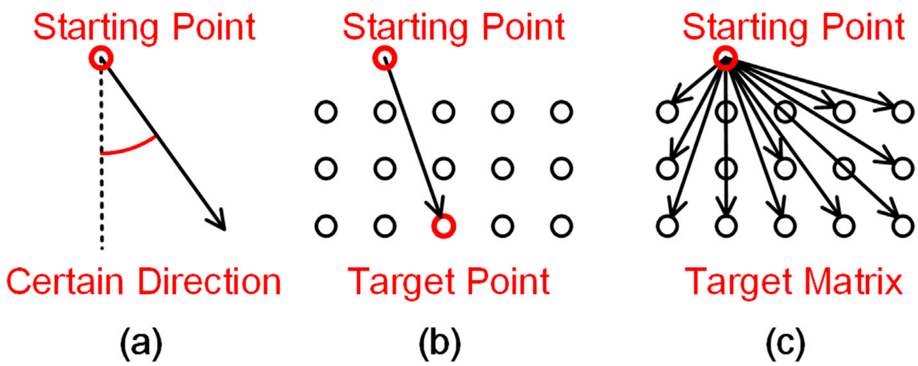

Fig. 1. Illustration of path finding modes, including (a) basic mode, (b) P2P mode and (c) P2M mode.

model to calculate the ultrasonic field in austenitic welds. Harker et al. [9] verified the results of RAYTRAIM by comparing with the simulated results of Finite Difference Method. Kolkoori [10] developed an adapted 2D ray tracing model with validation against the results of EFIT. All of these methods are influenced by Ogilvy's RAYTRAIM more or less, and are suitable for the basic ray-tracing mode as illustrated in Fig. 1(a). The marching strategy can also be applied to achieve P2P ray-tracing of Fig. 1(b) when combined with the binary searching algorithm [11,12]. In comparison, the minimizing strategy is completely different. Nowers et al. [13,14] first proposed this strategy for the ray-tracing problem, which finds the propagation rays within the defined nodal networks. The rays are calculated according to Fermat's Principle, which reveals that the ultrasonic waves will propagate along the path with the minimal propagation time [15,16]. Nowers et al. introduced two path-finding algorithms for this strategy, including Dijkstra algorithm [17] and A* algorithm [18]. Dijkstra algorithm achieves P2M ray-tracing of Fig. 1(c), while A* algorithm performs P2P ray-tracing by adding a heuristic cost to the original cost in Dijkstra algorithm. The strategies for route planning problems are adopted in these algorithms, which are suitable to find the paths along given nodes.

In the above ray-tracing algorithms, appropriate weld maps should be applied to obtain reasonable results. A weld map is about the distribution of crystal orientations inside the weld that indicates the anisotropy and inhomogeneity of the media. The weld map can be estimated by destructive experimental methods, including Electron Back-Scattered Diffraction (EBSD) [19,20], Spatially Resolved Acoustic Spectroscopy (SRAS) [21] and some other methods. Some researchers also tried to use non-destructive methods for this estimation, in which assumed weld models were applied to calculate simulated results and then minimized the errors between simulated and experimental results. Two of the most popular weld models are Ogilvy's weld model [6] and MINA model (Modelling anisotropy from Notebook of Arc welding) [22,23]. Ogilvy's model describes the crystal orientations in the weld by single functions whose values change continuously within the welding region, while MINA model is suitable for multi-pass welds and estimates the crystal orientations considering the solidification of multi-pass welding based on the manufacturing information. The minimization progress to estimate the weld maps has been achieved by probabilistic approaches like Monte Carlo Inversion [24] or by the genetic algorithms [25–27].

For the P2M ray-tracing algorithm applied for array imaging, it is suitable to adopt the minimizing strategy. However, the rays are limited to propagate through fixed points as defined by the preset nodal network, which will certainly affect the calculating accuracy. In addition, as the rays are predicted according to the minimum of propagation times, no reflection and refraction conditions are considered. On the contrary, the marching strategy can acquire more precise results with more considerations and no limitation of network, but it is difficult to be performed in the P2M mode and usually results in low computing efficiency. To solve this problem, an effective P2M ray-tracing algorithm is proposed in this paper, combining both the marching strategy and the minimizing strategy. The application of minimizing strategy can improve the computing efficiency a lot, while adopting necessary steps of marching strategy can ensure the computing accuracy. In the following sections, the principles of the algorithm are described, and the algorithm has been further optimized to achieve better computing accuracy and efficiency. Images were generated using inspection experimental signals to verify the algorithm, and results indicate that the proposed algorithm can achieve P2M ray-tracing efficiently with good imaging performance.

2. Principles

2.1. Bulk wave propagation in anisotropic media

The ultrasonic bulk waves show three quasi-modes of propagation in anisotropic media, including a quasi-longitudinal mode (qL) and two quasi-shear modes (qS_1 and qS_2). The wave propagation can be described by the information of velocities, including the magnitude of the phase velocity (v^P) and the group velocity (v^G), together with their directions. Based on the wave equation and relative deduction [28], we can get the Christoffel equation to describe the behavior of wave propagation, written as

$$\left[C_{ijkl}n_k n_l - \rho (v^P)^2 \delta_{ij}\right]\left[u_j\right] = 0 \tag{1}$$

The above equation is written in the notation of Einstein summation, in which the subscripts i, j, k, l change their values within 1, 2, 3 (representing x, y and z-axis). C_{ijkl} is the component of the elastic stiffness tensor, ρ is the density of the material, n_i is the directional cosine of direction i, and u_i is the particle displacement in direction i. δ_{ij} is Kronecker delta, whose value is 1 only if $i=j$ otherwise it equals to 0. Here C_{ijkl} represents a four-order symmetric tensor, which can be reduced to a two-order symmetric tensor by adopting Voigt notation. Voigt notation can relate the four indices of C_{ijkl} to the two indices of C_{IJ}, described by the following equation.

$$\begin{aligned} &[C_{ijkl}] \Rightarrow [C_{IJ}]; i,j,k,l = 1,2,3; I,J = 1,2,3,4,5,6 \\ &I = \begin{cases} i, i=j \\ 9-(i+j), i \neq j \end{cases}; J = \begin{cases} k, k=l \\ 9-(k+l), k \neq l \end{cases} \end{aligned} \tag{2}$$

For each given direction described by (n_1,n_2,n_3), the Christoffel equation can be solved as an eigenvalue problem and yields three eigenvalues λ_M and corresponding eigenvectors x_M, which are associated with the three propagation modes. According to the Christoffel equation, we have the relationship $\lambda = \rho (v^P)^2$ and $x = u$, so the phase velocity of each mode can be calculated as

$$(v^P)_M = \sqrt{\frac{\lambda_M}{\rho}}; M = qL, qS_1, qS_2 \tag{3}$$

Based on the relationship between phase velocity and group velocity, the group velocity's component in direction i can be calculated as