COMPUTATIONALLY EFFICIENT RAY TRACING ALGORITHM FOR SIMULATION OF TRANSDUCER FIELDS IN ANISOTROPIC MATERIALS

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ABSTRACT

This contribution describes a computationally efficient ray tracing algorithm for evaluating transducer generated ultrasonic wave fields in anisotropic materials such as austenitic cladded and austenitic weld components. According to this algorithm, ray paths are traced during its propagation through various layers of the material and at each interface the problem of reflection and transmission is solved. The presented algorithm evaluates the transducer generated ultrasonic fields accurately by taking into account the directivity, divergence, density of rays, phase relations as well as transmission coefficients. The ray tracing algorithm is able to calculate the ultrasonic wave fields generated by a point source as well as a finite dimension transducer. The simulation results are compared quantitatively with the results obtained from Elastodynamic Finite Integration Technique (EFIT) on several configurations generally occurring in the ultrasonic non-destructive testing of anisotropic materials. The excellent agreement between both models confirms the validity of the presented ray tracing algorithm. Finally, the ray tracing model results are also validated by means of experiments.

Keywords: Ultrasonic sound field, Ray tracing, Directivity, Anisotropy, Austenitic weld

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INTRODUCTION

Ultrasonic non-destructive inspection of anisotropic materials such as austenitic welds and austenitic cladded components is complicated because of inhomogeneity and anisotropy of the materials and this leads to beam distortion, beam skewing and beam splitting.

In the early 90's, Johnson et al. [1] presented a ray tracing approach to calculate ultrasonic transducer sound fields in homogeneous isotropic solids. Ray tracing models are numerical in procedure, but the complete wave propagation phenomena are evaluated based on the analytical expressions resulting from elastic plane wave theory [2] and calculations are involved only at the interfaces between different layers. This drastically reduces computational time as compared to the finite element [3] and finite difference [4] techniques. A ray tracing method for austenitic steel welds and its application in optimizing ultrasonic inspection techniques was investigated by Ogilvy [5]. Based on the first order Bessel functions, the approximated spherical point source beam profiles in austenitic materials were also presented by the same author [6].

In the present paper the ray model calculations for ultrasonic sound fields generated by finite dimension transducers in anisotropic materials are performed by considering the finite size effects of the transducers and superposition phenomena. The aim of the present paper is threefold. First, we present the theoretical description of the ultrasonic sound field evaluation in anisotropic materials using a ray tracing model. Second, we validate the ultrasonic sound fields predicted on austenitic cladded and weld materials from the ray tracing model quantitatively with Elastodynamic Finite Integration Technique (EFIT) model [7,8] calculations. Third, we present the experimental validation of ray tracing results.

THEORY

According to the ray tracing model, a ray bundle is considered at the source point of the excitation. In case of finite dimension transducer, we model the finite dimension transducer by several point sources and at each point source a diverged ray bundle is considered. The excitation process may be normal beam or angle beam excitation. Depending on the nature of excitation, the directivity factor of the ray in an isotropic solid or general anisotropic solid is calculated based on Lamb’s reciprocity theorem [9,10], procedure briefly reviewed in the following section.
Stepping forward along the ray in the direction of energy velocity, the ray's new position is calculated. If the material properties vary during the ray propagation, the problem of reflection and transmission at the interface is solved and yields reflected and transmitted ray energy directions, amplitude coefficients as well as energy coefficients. At the end, the final ray amplitudes at the region of interest in the material are obtained by incorporating an exact inverse distance factors. The final ray amplitudes are expressed in terms of density of rays. In case of finite dimension transducer excitation, we incorporate the superposition of rays resulting in constructive or destructive interference phenomenon.

Ray Behavior at an Interface between Two Dissimilar Materials

The behavior of the reflected and transmitted rays at an interface between two dissimilar materials is obtained by solving the problem of reflection and transmission analytically based on the approach presented by Rokhlin et. al [11]. Let us consider a ray impinging at an interface between two columnar grained anisotropic austenitic weld materials. According to Snell's law, all the projections of the slowness vectors on the interface equal to one another and the only unknown parameters are the normal components of reflected and transmitted slowness vectors. The resulting six degree polynomial equations for the reflected and transmitted media are expressed as follows

$$A^2(S^{2^r}_r)^2 + B^2(S^{2^r}_r)^2 + C^2(S^{2^r}_r)^2 + D^2(S^{2^t}_t)^2 + E^2(S^{2^t}_t)^2 + F^2S^{2^t}_t + G^2 = 0$$ (1)

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Six solutions are found in each medium, three of which only correspond to physically real solutions. Energy flow directions for the reflected and transmitted waves are the criterion for the selection of valid roots [11].

Energy reflection and transmission coefficients are obtained by solving the boundary conditions for traction force components and particle velocity components at the interface. The elastic constants of transversely isotropic austenitic weld material and isotropic steel material for the numerical calculations are taken from reference [12].

Point Source Directivity Evaluation in Columnar Grained Austenitic Stainless Steel Material

Point source directivities in the columnar grained austenitic stainless steel material are calculated based on the Lamb's reciprocity theorem [11,13]. A generalized form to represent the directivity factor for the quasi longitudinal and quasi shear vertical waves under the excitation of normal or tangential forces is given as

$$D_{\alpha}^I(\theta) = R_{\alpha\beta_1}^1 u_{\alpha\beta_1} + R_{\alpha\beta_2}^2 u_{\alpha\beta_2} + R_{\alpha\beta_3}^3 u_{\alpha\beta_3}$$ (3)

where $\alpha$ represents the normal or tangential components (x, y, z), I = qP, qSV, SH representing the type of incident wave, $\beta_1$, $\beta_2$, $\beta_3$ represent the waves reflected from the stress free surface boundary of an anisotropic medium and $u_{\alpha\beta_1}$, $u_{\alpha\beta_2}$, $u_{\alpha\beta_3}$ are the particle polarization components for incident and reflected waves, respectively. As an example, Figure 1 shows the directivity patterns for the quasi longitudinal and quasi shear vertical waves for normal or tangential force excitation on an austenitic stainless steel material exhibiting unidirectional columnar grain orientation of 60°. It is clearly noticeable from Figure 1 thus the directivity patterns are
strongly influenced by the anisotropy. This results in non symmetrical patterns and distinct maxima and minima with respect to the surface normal of the columnar grained austenitic steel material.

**COMPARISON RESULTS AND DISCUSSION**

**Validation of Ray Tracing Model Results with EFIT Model Calculations**

In view of ultrasonic non destructive testing applications the ultrasonic sound field patterns are evaluated for two different configurations and two types of excitation. First, we compare the presented ray tracing model results with EFIT calculations [7,8] for normal point force excitation on 32 mm thick austenitic weld material with vertical grain orientation. A diverged ray bundle is considered at the excitation source. The transmitted quasi longitudinal wave (TqP) displacements are evaluated at a depth 16 mm from the excitation surface. The evaluated displacement profiles along the horizontal plane from the ray model show good agreement with EFIT calculations (see Figure2(c)). Minor deviations are present because monochromatic nature of the excitation source in ray model and also currently displacement contributions from mode converted waves are not considered in the ray model. Figure 3 shows a comparison of quasi longitudinal wave displacement profiles in 32 mm thick austenitic cladded material with normal point force excitation. The interface is assumed parallel and it is situated at 16mm depth. As can be seen from Figure 3, the predicted quasi longitudinal wave amplitude profiles from ray model agree quantitatively well with EFIT calculations.

Second, the calculations are performed for the finite dimension normal beam longitudinal wave transducer of 2.25 MHz center frequency and 12 mm diameter, insonifying into a homogeneous isotropic steel material (Figure 4(a)) and an interface between the isotropic ferritic steel and homogenous austenitic weld material (Figure 4(b)).
is located at 50mm depth from the isotropic (base) ferritic steel. The comparison shows good satisfactory agreement between simulated and experimental beam profiles.

CONCLUSIONS

A ray tracing algorithm for evaluating the ultrasonic transducer fields in anisotropic materials such as austenitic weld and austenitic cladded materials are presented. Ultrasonic sound fields are modeled accurately by taking into account the ray directivity, divergence, phase relations and transmission coefficients. The displacement amplitude profiles for both point force excitation and finite dimension transducer have been compared with Elastodynamic Finite Integration Technique (EFIT) calculations as well as experiments and a good quantitative agreement is achieved. The extension of present ray tracing algorithm in three dimension and 3D ultrasonic sound field evaluation in inhomogeneous anisotropic materials are planned for the future work.

Validation of Ray Tracing Model Results with Experiments

Experiments have been conducted on 32 mm thick austenitic weld sample as well as 62mm thick austenitic cladded material. For the experiments, we have used a piezoelectric normal beam transducer of 2.25 MHz center frequency and 12 mm diameter as a transmitting probe and amplitudes along the back surface are scanned using electrodynamic probes. Figure 5(a) shows a comparison of the simulated longitudinal wave field profile distribution along the back wall of the base material of the austenitic weld component with the experimental amplitudes. Figure 5(b) shows comparison of transmitted quasi longitudinal waves along the back wall of a 62mm thick austenitic cladded material. The assumed columnar grain orientation in the austenitic cladded region is 45°. The interface is located at 50mm depth from the isotropic (base) ferritic steel. The comparison shows good satisfactory agreement between simulated and experimental beam profiles.

Again, the ray model predictions show an excellent agreement with EFIT model calculations.

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