Three-Dimensional Elastic Wave Modeling in Austenitic Steel Welds using Elastodynamic Finite Integration Technique

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Abstract
Austenitic steel weld structures are heavily used in nuclear power industries. Ultrasonic Nondestructive Testing (NDT) is the prominent way to ensure the quality of welded structures as they occur e.g. in pressure vessels. The detection of two-dimensional planar defects in the weld region is a challenging task and the geometrical conditions require three-dimensional modeling to understand and predict the scattering properties. A specialised implementation of the three-dimensional elastodynamic finite integration technique (3D-EFIT) was developed to handle such complex geometries. Because of the orientation of crystals of the welding material, the path of the reflected waves is strongly distorted and the optimum position of the sending and the receiving transducers is determined using 3D-EFIT. The modeling results are compared against measurements. In addition to the modeling for understanding the wave phenomena, the reflected elastic wave field obtained at the measurement surface can be utilized for imaging of the defects.

Keywords: NDT, 3D-EFIT, austenitic welds, modeling and simulation, anisotropy, elastic wave scattering

1. Introduction

The investigation with elastic waves for nondestructive evaluation of solid materials has proved to be efficient. The scattering of elastic waves in the material gives us the information about the irregularities present in the material. In anisotropic media, the elastic wave propagation and scattering due to defects is very complex because of the directional dependency of elastic wave propagation on the material elastic stiffness tensor and the crystals orientation. The austenitic steel weld structures are increasingly in use in nuclear power industries where the quality assurance of the materials involved has the utmost priority. Detection of flaws in the austenitic steel weld structures requires a very effective numerical modelling method. Finite integration technique is an efficient way to model the elastic waves enclosed in the intricate geometries. Application of the finite integration technique to the fundamental elastic wave equations in integral form, lead us to the development of the tool called Elastodynamic Finite Integration Technique (EFIT) [1]. It has been proved that real life NDT problems can be effectively modeled using EFIT [2, 3, 4 and 5]. Here in this paper we present results of 3D-EFIT simulations. The objectives of these simulations are to investigate the influence of the material crystals orientation on the detection of a two-dimensional planar defect and the study of wave scattering [6] due to the defect.

2. Governing Equations of 3D-EFIT

The governing equations of 3D-EFIT comprises of Newton-Cauchy’s equation of motion (Eq. 1) and deformation rate equation (Eq. 2) in integral form [7]. 3D-EFIT uses the dual orthogonal grid system and marching on in time algorithm [1, 7] where the velocity vector \( \mathbf{v}(\mathbf{R}, t) \) components and the elastic stress tensor \( \mathbf{T}(\mathbf{R}, t) \) components are determined simultaneously using the leapfrog technique. For the simulations, the spatial and temporal
discretization is performed sustaining the stability condition of EFIT. Material parameters volumetric mass density ($\rho$) and compliance tensor ($s(R)$) constitute for the determination of different elastic wave mode velocities in the material. In Eq. (1) and Eq. (2) the force density vector ($f(R, t)$) and the induced deformation rate tensor ($h(R, t)$) respectively are the source terms.

\[
\iint_V \rho \frac{\partial}{\partial t} v(R, t) \, dV = \oint_{S=\partial V} n \cdot T(R, t) \, dS + \iint_V f(R, t) \, dV \\
\iint_V s(R) : \frac{\partial}{\partial t} T(R, t) \, dV = \oint_{S=\partial V} \text{Sym} \{ n \cdot v(R, t) \} \, dS + \iint_V h(R, t) \, dV
\]

3D-EFIT has the capability to run on multi processors for faster computation as it is developed using Message Passing Interface (MPI) functions in “C” programming.

3. Influence of the Crystal Orientation

Numerical modeling of elastic waves in inhomogeneous transversely isotropic media is presented in this section using 3D-EFIT. The optimal transducer location and the incident angle of the pressure wave beam are determined to obtain the focusing of the field at the back wall of the geometry where there is a possibility of existence of a crack. The C-scan obtained at the back wall is compared against the measurement.

3.1 Geometry

The geometry used for the simulations is depicted in Fig. (1). The geometry consists of two isotropic steel blocks, with material constants $c_{11} = 276.87$ GPa, $c_{44} = 83.44$ GPa and $\rho = 7900$ kg/m$^3$, conjoined by a welding process. The welding material austenitic steel has transversely isotropic behaviour.

The welding has a herringbone structure ("V" shaped butt weld). The elastic material parameters of the austenitic steel material, with crystal axis orientation $a = e_i$ are $c_{11} = 216.0$
GPa, $c_{22} = 262.75$ GPa, $c_{44} = 82.5$ GPa, $c_{55} = 129.0$ GPa, $c_{23} = 98.25$ GPa, $c_{12} = 145.0$ GPa, and $\rho = 7860$ m/kg. The grains at the left side of the center of the weld, shown with dot-dashed line, have the orientation of $\theta = (180^\circ - 55^\circ) = 125^\circ$ whereas on the right side $\theta = 55^\circ$. The orientation vector of the crystal is expressed as $\mathbf{a} = (\cos(\theta) \mathbf{e}_1 + \sin(\theta) \mathbf{e}_3)$. The stiffness parameters of the material with these rotated crystals are determined using Bond transformation [8].

The geometry is applied with stress free boundaries at the front, back, top and bottom surfaces. At the left and right side of the geometry, the absorbing Convolutional Perfectly Matched Layer (CPML) [9, 10] of thickness of 3 mm is introduced. The scanned area of the measurement at the back wall is shown in grey color.

A synthetic transducer has been modeled using 2D-Tukey apodization and a time retardation that injects an angular pressures wave beam with an inclination of $32^\circ$ with respect to the normal. The position and the geometrical dimensions of the transducer shoe are also shown in Fig. (1).

### 3.2 3D-EFIT Simulation Results

The geometry is discretized into $N_1 \times N_2 \times N_3 = 580 \times 400 \times 320$ grid cells with a cubic grid cell edge length of $\Delta x = 100$ µm in the $x_1$, $x_2$, $x_3$ directions respectively. For the simulation the marching on in time is performed with a time step of $\Delta t = 8.0496$ ns.

![Figure 2. Time domain snapshots of the elastic wavefronts in $x_1x_3$-plane at $x_2 = 20$ mm. The wave fronts in terms of magnitude of the particle velocity vector on an absolute linear scale are depicted.](image-url)
The pressure wave is injected from the finite rectangular aperture into the steel material with an angle of 32° with respect to the normal. The time domain elastic wave snapshots in the $x_1$, $x_2x_3$-plane at $x_2 = 20$ mm, passing through the center of the transducer are presented in Fig. (2). The incident pressure waves (P) and shear vertical waves (SV) are transmitted into the welding region. The reflected pressure wave (M_1) and mode converted shear wave (M_2) from the incident pressure waves at the left interface of the welding with the steel block are also observed. The propagation of a transmitted quasi pressure wave (qP) and a mode converted quasi shear waves (qS) is visible. The efficient absorption of body waves as well as surface waves is recognized.

Figure 3. Comparison between 3D-EFIT and measurement results. The C-scans at the backwall corresponding to 3D-EFIT and measurement are shown in (a) and (b). The amplitude signals extracted from the respective C-scans at $x_2 = 0.023$ m are shown in (c) and (d). The amplitude signals are normalized to the maximum of the respective signals.

The $e_3$ component of the pressure wave field at the back wall is recorded in a specific time window in which the pressure waves reach the back wall. The data is recorded for a time sampling of $50\Delta t$. The C-scan is obtained by determining the maximum of the field at the back wall from all time samples. In the 3D-EFIT simulation the transducer is positioned on the left side of the welding structure. Whereas the measurement at the back wall are performed for a setup with the transducer positioned on the right side of the welding region at a same distance from the center of the welding as in the 3D-EFIT simulation. Since the geometry with respect to the center of weld, indicated with dot-dashed line in the Fig. (1), is symmetric one can compare the measurement and 3D-EFIT results by flipping the C-scan.
obtained by 3D-EFIT from left to right. The C-scan comparison between 3D-EFIT result and the measurement are shown in Figs. (3a) and (3b) respectively. The envelopes of the signals extracted along \( x_1 \) at \( x_2 = 0.023 \) m, from their respective C-scans are shown in the Figs. (3c) and (3d). These signals are normalized to their respective maxima. From the comparison it is clear that a very good agreement is reached between 3D-EFIT and measurement. In C-scans of 3D-EFIT the fringes in the \( x_2 \)-direction can be explained from the modeling of the synthetic transducer. The Tukey amplitude window function does not suppress the wave front edge effects appearing in the \( x_2 \)-direction as a result we see the fringes in the \( x_2 \)-direction.

4. Detection of Two-dimensional Planar Defects

In the anisotropic case it is difficult to predict the path of the wave propagation because of the directional dependence of the particle motion on the stiffness tensor and crystal orientation of the material. Apart from the observation of elastic wave propagation, the main objective of these 3D-EFIT simulations is to determine the optimal position of the receiving transducer to obtain the echo due to the two-dimensional rectangular crack.

4.1 Geometry

The geometry used for the 3D-EFIT simulations is shown in Fig. (4). Two isotropic steel blocks, with different material parameters are welded using austenitic steel. The material parameters of these isotropic steel blocks are given in Fig. (4).

The axes of the hexagonal s of austenitic steel material are oriented vertically i.e. in \( x_3 \) direction. The volumetric mass density of the austenitic steel is \( \rho = 7800.0 \) kg/m\(^3\). The elastic stiffness parameters in Voigt notation are \( c_{11} = 262.75 \) GPa, \( c_{33} = 216.0 \) GPa, \( c_{44} = 129.0 \) GPa, \( c_{66} = 82.5 \) GPa, \( c_{23} = 145.0 \) GPa, \( c_{12} = 98.25 \) GPa.

The simulations are performed with and without a defect in the weld. A two-dimensional rectangular planar defect at the right side interface of the welding is introduced as an inhomogeneity. The defect dimensions and the position are also shown in Fig. (4). The inhomogeneity is modeled with the material air. Very strong elastic wave reflections are anticipated from the air defect because of the very low velocity (\( C_p = 400.0 \) m/s) of the longitudinal waves in the air when compared against the steel.

The top, bottom, front and back boundaries of the geometry are applied with stress-free boundary condition. The Convolutional Perfectly Matched Layer (CPML) [8, 9], with a width of 3 mm, is introduced at the left and right boundaries (both the ends of the geometry in the \( x_1 \)-direction) of the geometry, in order to absorb the elastic waves.

A synthetic MWK45-2 shear wave angular probe is modeled by applying 2D amplitude weighting function (see Fig. 4c) and time retardation (see right Fig. (4d) needed to yield 45° inclined shear vertical wave. To suppress the edge effects the Tukey window function with a tapering of 50% on either side (left and right edges from the center of the transducer) in the \( x_1 \) direction is used as illustrated in Fig. (4c). An RC\(_2\) pulse with center frequency \( f_0 = 2 \) MHz is used for the excitation. The dimensions of the transducer shoe are shown in Fig. (4a).
4.2 3D-EFIT Simulation Results

The geometry is discretized into $N_1 \times N_2 \times N_3 = 900 \times 250 \times 320$ grid cells with a cubic grid cell edge length of $\Delta x = 100 \, \mu m$ in the $x_1, x_2, x_3$ directions respectively. For the simulation the marching on in time is performed with a time step of $\Delta t = 8.0496 \, ns$.

The comparisons of the time domain elastic wavefronts of the slice of $x_1, x_3$-plane at $x_2 = 12.5 \, mm$, for the geometries with and without defect are presented in Fig. 5. The snapshots are displayed on a logarithmic scale in the range [-40, 0] dB. Several elastic wave modes [11] are indicated. When the incident shear vertical (SV) impinges on the interface of the weld, it generates the reflected shear vertical ($M_1$) and the transmitted quasi shear vertical (qSV) wave. The transmitted qSV wave mode hits the defect resulting in a mode transformed quasi pressure wave ($M_2$). The $M_2$ wave mode is then reflected from the back wall generating mode transformed pressure wave ($M_3$), shear wave ($M_4$) and a quasi shear vertical wave ($M_5$). Hence $M_3, M_4, M_5$ are the echoes generated due to the defect which are not seen in the simulation result corresponding to the geometry without defect. The wave modes $M_3$ and $M_4$ ravel towards the transmitting transducer whereas the wave mode $M_5$ which carries more energy than $M_3$ and $M_4$ travels across the welding region reaching the measurement surface at approximately $x_1 = 0.06 \, m$. Hence the main defect echo ($M_5$) cannot be seen by the
transmitting transducer. The receiving transducer has to be placed at $x_1 = 0.06$ m in order to see the defect echo.

![Figure 5. Comparison of time domain elastic wavefronts corresponding to the geometries with (right column) and without (left column) air defect. The snapshots are displayed on a logarithmic scale in the range [-40 0] dB. The $x_1x_3$-slice at $x_1 = 0.0125$ m are displayed.](image)

### 4.2.1 A-Scans Along a $x_1$-line Over the Measurement Surface

The scattered field is recorded along the line shown with green color in the geometry of Fig. (4a). The B-scans obtained are illustrated in Fig. (6). The main echo from the defect is indicated with $M_5$. Both figures (Fig. (6a) and Fig. (6b)) look similar except in Fig. (6a) the echo $M_5$ is missing. The echo is received approximately at $x_1 = 0.06$ m. Hence it is clear from this simulation that a monostatic experiment where sending and receiving transducer coincide, the defect cannot be detected. With a bistatic experiment, where sending and receiving transducers are different, with receiver at $x_1 = 0.06$ m on the measurement surface one can detect the defect.
Figure 6. B-scans on the linear scale, captures along the $x_1$-line shown with green color in the Fig. (4). a) B-scan corresponding to the geometry without defect. b) B-scan corresponding to the geometry with defect.

5. Conclusions

Because of the very good agreement of the 3D-EFIT with measurements (see Fig. (3)) the approximate crystal orientation in the welding region is determined which is $\theta = 125^\circ$ and $\theta = 55^\circ$ at left and right side of the weld respectively. From the results presented in the section (4) it can be concluded that the 3D-EFIT is useful for detection of the two-dimensional defects and optimal transducer positions to obtain the echoes due to the defects.

Acknowledgements

The work presented in the section (3) of this paper is part of a project work funded by Federal Institute for Materials Research and Testing, Berlin, Germany. The authors would like to thank Mehbub–ur Rahman, the person in charge for the measurements at Materials Research and Testing, Berlin, Germany.

References


