Image Based EFIT Simulation for Nondestructive Ultrasonic Testing of Austenitic Steel*

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Abstract

The ultrasonic testing (UT) of an austenitic steel with welds is difficult due to the acoustic anisotropy and local heterogeneity. The ultrasonic wave in the austenitic steel is skewed along crystallographic directions and scattered by weld boundaries. For reliable UT, a straightforward simulation tool to predict the wave propagation is desired. Here a combined method of elastodynamic finite integration technique (EFIT) and digital image processing is developed as a wave simulation tool for UT. The EFIT is a grid-based explicit numerical method and easily treats different boundary conditions which are essential to model wave propagation in heterogeneous materials. In this study, the EFIT formulation in anisotropic and heterogeneous materials is briefly described and an example of a two dimensional simulation of a phased array UT in an austenitic steel bar is demonstrated. In our simulation, a picture of the surface of the steel bar with a V-groove weld is scanned and fed into the image based EFIT modeling.

Key words : Elastodynamic Finite Integration Technique (EFIT), Simulation of Wave Propagation, Anisotropic and Heterogeneous Material, Image Based Modeling, Nondestructive Ultrasonic Testing

1. Introduction

Austenitic steel is used in many components of nuclear power plants because it has high toughness and resistance to corrosion and heat. The weld in the austenitic steel is an acoustically anisotropic and locally heterogeneous material, that is, the ultrasonic wave is skewed along crystallographic directions in the weld and is attenuated due to scattering by metallic grain boundaries. Therefore it is difficult to predict the wave propagation in the austenitic weld without any computational tools^{(1),(2)}. Thus a straightforward simulation method is desired for the reliable nondestructive ultrasonic testing (UT). As a powerful simulation tool, the elastodynamic finite integration technique (EFIT) has been proposed by Langenberg et al.^{(3),(4)}. The EFIT is a grid-based numerical time domain technique and easily treats different boundary conditions which are essential to model ultrasonic wave propagation in heterogeneous materials. A combined method of EFIT and digital image processing is developed in this study. The geometry of an inspection area is determined by a scanned digital picture and then the processed RGB image is directly fed into the EFIT simulation. This simplified preprocessing is called the image based modeling⁽⁵⁾. To solve arbitrary initial boundary value problems, appropriate boundary conditions are implemented in our tool. Absorbing boundary conditions⁽⁶⁾ and internal damping effect⁽⁷⁾ are also introduced in our tool to model unbounded

regions and dissipative phenomena, respectively. Because of the simple structure of the EFIT equations, our model is well suitable for high-performance parallel computation⁽⁵⁾. In our 2D simulation, the wave propagation in austenitic steel with a single V-groove weld is demonstrated. This paper describes the brief theory and discretization of EFIT, then shows the results of the image based EFIT simulations.

2. The Elastodynamic Finite Integration Technique –EFIT–

2.1. The Governing Equations

The governing equations of elastic waves in general anisotropic media are the Cauchy equation of motion and the equation of deformation rate. These equations are given in integral form for a finite volume V with the surface S by

$$\frac{\partial}{\partial t} \int_V \rho v_i dV = \int_S T_{ij} n_j dS + \int_V f_i dV \quad (1)$$

$$\frac{\partial}{\partial t} \int_V s_{ijkl} T_{kl} dV = \int_S \frac{1}{2} (v_i n_j + v_j n_i) dS \quad (2)$$

where $\mathbf{v}$ is the particle velocity vector, $\mathbf{T}$ is the stress second rank tensor, ρ is the density, $\mathbf{n}$ is the outward normal vector on the surface S , and $\mathbf{f}$ is the body force vector. In Eq.(2), $\mathbf{s}$ is the compliance tensor of rank four. The inverse of $\mathbf{s}$ is the stiffness tensor $\mathbf{c}$, namely $\mathbf{s}^{-1} = \mathbf{c}$. We can express Eq.(2) with the stiffness tensor $\mathbf{c}$ of rank four:

$$\frac{\partial}{\partial t} \int_V T_{kl} dV = \int_S \frac{1}{2} c_{klij} (v_i n_j + v_j n_i) dS = \int_S c_{klij} v_i n_j dS \quad (3)$$

2.2. Spatial Discretized Form of Two Dimensional EFIT (2D-EFIT)

We consider the Cartesian coordinate $\{x_1, x_2, x_3\}$ and ultrasonic wave which propagates in two dimensional x_1x_3 -plane. For this reason, it is assumed that all field variables are independent of x_2 . From the fact $\partial/\partial x_2 = 0$ and Eq.(1), we have three equations:

$$\frac{\partial}{\partial t} \int_V \rho v_1 dV = \int_S T_{11} n_1 + T_{13} n_3 dS \quad (4)$$

$$\frac{\partial}{\partial t} \int_V \rho v_2 dV = \int_S T_{21} n_1 + T_{23} n_3 dS \quad (5)$$

$$\frac{\partial}{\partial t} \int_V \rho v_3 dV = \int_S T_{13} n_1 + T_{33} n_3 dS \quad (6)$$

where we set $\mathbf{f}=\mathbf{0}$. If one of the two shear waves is a purely anti-plane mode, Eq.(5) is independent from Eqs.(4) and (6). For examples, transversely isotropic and cubic crystal structure, etc. correspond to this case. Austenitic steel is assumed to be a transversely isotropic material⁽⁸⁾, therefore we can omit the velocity term v_2 and treat only the coupled equations (4) and (6) in our formulation.

$$\begin{aligned} \frac{\partial}{\partial t} \int_V T_{11} dV &= \int_S c_{1111} v_1 n_1 + c_{1113} (v_1 n_3 + v_3 n_1) + c_{1133} v_3 n_3 dS \\ &= \int_S C_{11} v_1 n_1 + C_{15} (v_1 n_3 + v_3 n_1) + C_{13} v_3 n_3 dS \end{aligned} \quad (7)$$

$$\begin{aligned} \frac{\partial}{\partial t} \int_V T_{13} dV &= \int_S c_{1311} v_1 n_1 + c_{1313} (v_1 n_3 + v_3 n_1) + c_{1333} v_3 n_3 dS \\ &= \int_S C_{15} v_1 n_1 + C_{55} (v_1 n_3 + v_3 n_1) + C_{35} v_3 n_3 dS \end{aligned} \quad (8)$$

$$\begin{aligned} \frac{\partial}{\partial t} \int_V T_{33} dV &= \int_S c_{3311} v_1 n_1 + c_{3313} (v_1 n_3 + v_3 n_1) + c_{3333} v_3 n_3 dS \\ &= \int_S C_{13} v_1 n_1 + C_{35} (v_1 n_3 + v_3 n_1) + C_{33} v_3 n_3 dS \end{aligned} \quad (9)$$

where we abbreviate subscripts of $\mathbf{c}$, such as $C_{16}=c_{1112}$. For our calculation we have a set of five discrete equations (4), (6), (7)-(9). Using a square as the integral volume in Fig.1(left figure), we can discretize Eq.(4) to $\dot{v}_1$ the component.

$$\dot{v}_1 \cong \frac{1}{\rho \Delta x} [T_{11}^{(r)} - T_{11}^{(l)} + T_{13}^{(t)} - T_{13}^{(b)}] \quad (10)$$

Fig. 1 Grid arrangement of v_1 (left figure) and T_{11} (right figure) in 2D-EFIT. All material parameters are defined in the T_{11} -integration volume.

where Δx is the length of the integration volume, superscript $()$ expresses the position of the physical quantity and dot $\{\cdot\}$ means the time differentiation. Since the density parameter ρ is given at the T_{11} -integration volume, the average value $\bar{\rho} = (\rho^{(l)} + \rho^{(r)})/2$ is used for heterogeneous materials.

Next we consider the discretization of Eq.(7) using the integral volume in Fig.1(right figure):

$$\dot{T}_{11} \cong \frac{1}{\Delta x} \left[C_{11} (v_1^{(r)} - v_1^{(l)}) + C_{15} (\bar{v}_3^{(r)} - \bar{v}_3^{(l)} + \bar{v}_1^{(r)} - \bar{v}_1^{(l)}) + C_{13} (v_3^{(r)} - v_3^{(b)}) \right] \quad (11)$$

where we used an averaging technique to perform the integral concerning $\int_S C_{15} v_3 n_1 dS$, because the field component v_3 is not allocated to the right and left hand sides of the integral volume V . Here we take the average using adjacent grid point v_3 and reallocate fictitious grid points $\bar{v}_3^{(l)}$ and $\bar{v}_3^{(r)}$. The same idea is introduced to the integral $\int_S C_{15} v_1 n_3 dS$. Similar procedures are applied to the v_3 , T_{13} and T_{33} components.

2.3. Time Discretization

In the time domain, stress components T are allocated at half-time steps, while the velocities v are at full-time steps. The following time discretization yields an explicit leap-frog scheme:

$$\{v\}^z \cong \{v\}^{z-1} + \Delta t \{\dot{v}\}^{z-\frac{1}{2}} \quad (12)$$

$$\{T\}^{z+\frac{1}{2}} \cong \{T\}^{z-\frac{1}{2}} + \Delta t \{\dot{T}\}^z \quad (13)$$

where Δt is the time interval and the superscript z denotes multiple integers of time step of Δt . Therefore the EFIT repeats the operations of Eqs.(12) and (13) from the time step number $z=1$ to N by means of adequate initial and boundary conditions. A specific stability condition and adequate spatial resolution must be fulfilled to calculate the EFIT accurately^{(9),(10)}.

2.4. Verification of EFIT Calculation

Figure 2 shows the group velocity curves of quartz and snap shots of ultrasonic wave propagation calculated by the EFIT. The material constants of quartz in the original coordinate system are as follows: $C_{11}=C_{22}=8.674$, $C_{12}=0.699$, $C_{13}=C_{23}=1.191$, $C_{33}=10.72$, $C_{14}=-C_{24}=C_{56}=-1.791$, $C_{44}=C_{55}=5.794$, $C_{66}=3.9875$, others=0 in 10^{10}N/m^2 and $\rho=2651\text{ kg/m}^3$. Here the stiffness constants are transformed by clockwise rotation of coordinates over an angle of 90° about x_3 axis⁽¹¹⁾. The calculation is performed in x_1x_3 -plane. The ultrasonic wave is excited by a force in x_3 direction with a 1.5-cycles pulse and 1.5MHz center frequency. Because of the 2D-EFIT modeling only wave fronts of the quasi-pressure (qP) and the quasi-shear (qS) modes are shown. The snap-shots of the wave fronts by means of the EFIT are explicitly related to the group velocity curve.

Fig. 2 Group velocity curve (upper figure) and snap-shots of EFIT calculation (lower figures).

Fig. 3 Picture of austenitic V-groove weld and its image based modeling.

3. EFIT Modeling for Ultrasonic NDT of an Austenitic V-groove Weld

Figure 3 shows the geometry of the austenitic V-groove weld surrounded by isotropic stainless steel. The crystalline orientation was implemented using previous data obtained by Köhler et al.⁽⁸⁾. In this model, the anisotropy is seen at both the weld and buttering. The weld is divided into three different crystalline orientations (blue, yellow and pink colors) and light blue color shows the buttering part. The material parameters of the welding and the buttering are $C_{11}=C_{22}=26.275$, $C_{12}=9.825$, $C_{13}=C_{23}=14.5$, $C_{33}=21.6$, $C_{44}=C_{55}=12.9$, $C_{66}=8.225$, others=0 in 10^{10}N/m^2 and $\rho=7800\text{kg/m}^3$. The material parameters of the isotropic stainless

Fig. 4 Snap-shots of ultrasonic wave propagation in austenitic steel bar with V-groove weld.

steel are $C_{11}=C_{22}=C_{33}=25.9685$, $C_{12}=C_{13}=C_{23}=10.3909$, $C_{44}=C_{55}=C_{66}=7.7888$, others=0 in 10^{10}N/m^2 and $\rho=7800\text{kg/m}^3$. The curves of the group velocity in different crystalline orientations are shown at the bottom of Fig.3.

In this simulation, it is assumed that the ultrasonic wave is transmitted into the steel from the top surface by a phased array transducer as shown in Fig.4. The element number of the array transducer is 24, the center frequency of incident pulse is 1.5MHz, and the pitch (distance between two elements) is 2mm. The excitation timing (delay time) of the phased array transducer is set to focus the qP-wave into the crack tip. In Fig.4, the qP-wave generated by the array transducer is shown at $9.6\mu\text{s}$. At $24.96\mu\text{s}$, the qP-wave arrives at the crack tip, then the diffracted wave from the tip is generated. Finally the diffracted wave is received at the array transducer.

4. Summary

The image based EFIT modeling was developed to predict the ultrasonic wave propagation in austenitic steel with weld. The advantage of our model is that we can model highly heterogeneous anisotropic material configuration because of the stable and accurate EFIT and the image based modeling.

As future works, we will compare our simulation result with experimentally measured signals by utilizing a laser vibrometric detector.

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