Modelling II

Prediction of Phased Array Ultrasonic Beams in Austenitic Metal Welds
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ABSTRACT

Phased array ultrasound testing is widely used for flaw inspection for it produces a steerable, tightly focused and high-resolution beam. However, description of the behaviour of phased array ultrasonic beams in austenitic metal welds is not an easy task, since an ultrasonic beam is skewed and distorted severely in austenitic metal welds, which also makes the inspection of austenitic metal welds using ultrasonic phased array a difficult task.

In an effort to address such a need, firstly we used a modified Ogilvy’s model to describe austenitic metal welds. Then, a normalized linear phasing multi-Gaussian array beam model is applied to predict the beam field in multi-layered anisotropic structure.

Beam fields are simulated and the off axis behaviour of different beam models shows that linear phasing multi-Gaussian array beam model increases the accuracy compared to multi-Gaussian array beam model.

INTRODUCTION

Phased arrays ultrasonic testing (PAUT) has been widely used in non-destructive evaluation (NDE) over the last decades, especially in nuclear industry for its high versatility. Accurate positioning and sizing of defects are a strong requirement for NDE, however, in the inspection of austenite welds, anisotropy and inhomogeneity of the material results in the scattering and attenuation of the beam from PAUT. Thus, predicting the signal for PAUT in austenite welds is one of the most difficult tasks. However, to predict the flaw signals and extract it from experimental signals, we need a correct model to describe the PAUT beam field austenite weld. To meet this need, beam models for PAUT should be developed to simulate the beam field in such inhomogeneous anisotropic material.

There are numbers of beam models describing ultrasonic wave propagation and transmission/reflection. One of the most efficient models available to date is the multi-Gaussian beam model which represents the transducer beam in terms of a superposition of coaxial Gaussian beams[1]. It can be used to simulate the wave fields of planar/focused transducers radiating into either isotropic or anisotropic media. In addition, there is no requirement that the orientation of the plane of incidence be aligned with a principle curvature plane of the interface when using a multi-Gaussian beam model to transmit/reflect at curved interfaces. Although the multi-Gaussian beam model was originally developed for a circular piston transducer, it can also be extended to model the wave fields of an elliptical or rectangular piston transducer [2].

In this paper, we first introduce the ingredients of beam inspection for austenitic metal welds, including modelling the grain orientation of the weld, calculating the ray path, determining the focal law. Then we focus on developing a single Gaussian beam model into linear phasing multi-Gaussian beam (LPMGB) model for phased array to inspect flaws in austenitic metal welds. Examples of simulation using the LPGMB model are given and compared with beam fields simulated using conventional multi-Gaussian beam models.
GRAIN ORIENTATION AND FOCAL LAW

Fig. 1 - Schematic diagram of a phased array ultrasonic testing and the specimen

Fig. 1 shows the size and grain orientation of austenite welds and the ray tracing method to obtain the time delay for phased array in such material.

Here, we chose modified Ogilvy’s model and its optimal values of parameters to describe the grain orientation. This model describes the asymmetrical nature of the austenite weld and it is easy to apply after careful observation on the macrograph [3].

To steer a beam to be refracted along the desired position in austenitic steel weldments, correct time-delay law should be applied. However, due to the influence of inhomogeneity, time of flight of each element is not proportional to the distance that each ray passes from element to the desired position, which makes the anisotropic focal laws different from isotropic focal laws for linear phased array.

The inhomogeneous weld could be regarded as a smoothly inhomogeneous medium. The most popular method of studying waves propagating in smoothly inhomogeneous media is the ray series method. This medium is modelled by using a system of thin homogeneous layers, where a surface along which the velocity is constant. We shall replace them locally by tangent planes at the point of intersection with the ray. Moreover, if we choose sufficiently thin layers, the velocity contrast across the individual fictitious interfaces will be small, so that ray trajectory in each layer can be calculated [4]. Once the group velocity and distance the ray travels in each layer is obtained, the proper time delay is obtained, too [3].

Linear phasing Multi-Gaussian beams for linear phased array

The Multi-Gaussian beam model, one of the most efficient models available to describe the transducer beam, is in terms of a superposition of coaxial Gaussian beams [5,2].

Gaussian beam, originating from Optics, is a very important type of propagating wave since it is an elementary wave that can be used as an efficient building block for constructing the more complex wave fields. When reflected/refracted, a Gaussian beam is transformed into another Gaussian beam (characterized by a different set of parameters), which explains why it is a convenient, widespread model [1].

An explicit expression for a single propagating Gaussian beam in an anisotropic material in local slowness coordinates \((y_1, y_2, y_3)\) (given in terms of its starting amplitude, \(U(0)\), and phase, \(\mathbf{M}(0)\), namely

\[
\mathbf{u}_r = U(0) \mathbf{d}_r \frac{\sqrt{\text{det}[\mathbf{M}(r)]}}{\sqrt{\text{det}[\mathbf{M}(0)]}} \exp\left[i\alpha(r/c_0 + \frac{1}{2} \mathbf{y}^T \mathbf{M}(r) \mathbf{y} - t)\right]
\]

(1)

Where the solution for \(\mathbf{M}(r)\) can be expressed in ABCD matrix form [1]:

\[
\mathbf{M}(r) = [\mathbf{D}^r \mathbf{M}(0) + \mathbf{C}^r] [\mathbf{B}^r \mathbf{M}(0) + \mathbf{A}^r]^{-1}
\]

(2)

In an anisotropic component, the energy direction differs from the wave vector direction. The slowness surface, related to a type of wave, gives the evolution of the phase velocity as a function of the direction. Let \(s_2 = S(s_1, s_3)\) be the function defining this surface. For a given wave vector on the slowness surface, the corresponding energy direction (group velocity direction) is given normally to this surface.
The axial ray of a Gaussian beam is located along the geometrical acoustics path, which is defined by the energy direction in an anisotropic medium. The evolution of the Gaussian beam is given by the evolution of the normal to the slowness surface. The propagation of a Gaussian beam of type $\alpha (\alpha = qP, qS1, qS2)$ travelling a distance $r$ can be described by the ABCD matrices

$$A^p = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad B^p = \begin{bmatrix} -rS_{20} & -rS_{11} \\ -rS_{11} & -rS_{02} \end{bmatrix},$$

$$C^p = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad D^p = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (3)$$

With $S$ being defined $s = S(s_1, s_3)$ in a basis so that $s_1 = s_3 = 0$ corresponds to the wave vector of the axial ray, so $[6]$

$$s = S(s_1, s_3)$$

$$S(0, 0) + \frac{\partial S}{\partial s_1} s_1 + \frac{\partial S}{\partial s_3} s_3 + \frac{1}{2} \frac{\partial^2 S}{\partial s_1^2} s_1^2$$

$$+ \frac{1}{2} \frac{\partial^2 S}{\partial s_1 \partial s_3} s_1 s_3 + \frac{1}{2} \frac{\partial^2 S}{\partial s_3^2} s_3^2$$

$$= s_0 + \bar{\kappa}_0 s_1 + \bar{\kappa}_1 s_3 + \bar{\kappa}_1^2 s_1^2 + \bar{\kappa}_2 s_1 s_3 + \bar{\kappa}_2 s_3^2$$

$$s_m = \frac{\partial n^m}{\partial s_5^m}$$

(4)

(5)

The inhomogeneous austenitic weld is described by a set of continuously changing inhomogeneous layers. Refraction and reflection occurs at the interface of two layers. Suppose a Gaussian beam incident from $j^{th}$ to $(j+1)^{th}$ layer, like the propagation law, the transmission/reflection law can be written, in the ABCD matrix form

$$M_j = [D_j]^T [M_j] [C_j]^T [B_j] [M_j] [A_j]^T - 1 \quad (6)$$

On the interface, if we define a rotation matrix $G_j$ and $G_{j+1}$, that projects the Gaussian beam in the slowness coordinate to the interface coordinate (one principal axis coincides with the interface) before and after interaction with the interface, then

$$A_j' = [G_{j+1}]^T [G_j] A_j, \quad B_j' = 0$$


$$D_j' = [G_{j+1}]^T G_j$$

where

$$G_j = \begin{bmatrix} \cos \theta_j^\alpha + \bar{\kappa}_0^\alpha \sin \theta_j^\alpha & \bar{\kappa}_2^\alpha \sin \theta_j^\alpha \\ 0 & 1 \end{bmatrix}$$

(7)

(8)

$$h_j = k_j^\alpha \cos \theta_j^\alpha - k_j^\beta \cos \theta_j^\beta,$$

with $\theta_j^\alpha$ and $\theta_j^\beta$ the incident and refracted angles of the $j^{th}$ interface.

For a complex propagation including multiple reflections or refractions into anisotropic media, the behaviour of the Gaussian beam can be described by the product of the all propagation and transmission matrix[7]. Consider $J+1$ is the final medium, then the global matrices is

$$[\begin{array}{c} A^G \\ B^G \\ C^G \\ D^G \end{array}] = [\begin{array}{c} A_{j+1}^G \\ B_{j+1}^G \\ C_{j+1}^G \\ D_{j+1}^G \end{array}] [\begin{array}{c} A_j^G \\ B_j^G \\ C_j^G \\ D_j^G \end{array}] \cdots [\begin{array}{c} A_1^G \\ B_1^G \\ C_1^G \\ D_1^G \end{array}]$$

(9)

By superposition 10 Gaussian beams twice using the same expansion coefficients obtained by Wen and Breazeale, one can simulate the wave fields of rectangular transducers [2]. Therefore, the velocity
wave field in the J+1th medium of a piston transducer whose dimensions are $a_1 \times a_2$, radiating into a multi-layered anisotropic material is given by

$$v_{J+1}(x, t) = v_{j}^{y(0)} \cdot \mathbf{d}_a \sum_{n=1}^{10} \sum_{m=1}^{10} A_n A_m \sqrt{\text{det}(J_{J+1}^{(y,y+1)}(r_{J+1}^{y(0)}))} \frac{\text{det}(M_{J+1}^{y,y+1}(0))}{\text{det}(M_{J+1}^{y,y+1}(0))} \mathbf{d}_{J+1} \prod_{m=1}^{M} y_{J+1}^{y,y+1} \cdot \exp[i \omega \sum_{m=1}^{M} \alpha_j r_{J+1}^{y(0)} + \frac{1}{2} \mathbf{y}^T [\mathbf{M}_{J+1}^{y,y+1}(r_{J+1}^{y(0)})]_{mn} \mathbf{y} - r] \tag{10}$$

where $\gamma_j$ indicates the type of the Gaussian beam travelling in the jth medium, $r_{J+1}^{y(0)}$ is the distance travelled along the ray path in the jth medium, $v_{j}^{y(0)}$ is the velocity amplitude of the starting Gaussian in the first medium, and

$$[\mathbf{M}_{J+1}^{y,y+1}(r_{J+1}^{y(0)})]_{mn} = [\mathbf{D}^G[J_{J+1}^{y}(0)]_{mn} + \mathbf{C}^G][\mathbf{B}^G[M_{J+1}^{y}(0)]_{mn} + \mathbf{A}^G]^{-1} \tag{11}$$

where the initial $\mathbf{M}$ matrix for model Eqn. (7) is

$$[M_1^{y(0)}]_{mn} = \begin{bmatrix} \frac{iB_n}{c_a D_{r_1}} & 0 \\ 0 & \frac{iB_n}{c_a D_{r_2}} \end{bmatrix} \tag{12}$$

Eq. (10) is written in slowness coordinates moving along the group velocity direction in the final medium. And in the conventional Multi-Gaussian beam model, the Rayleigh distance $D_{r_1} = k_a a_1^2 / 2$ and $D_{r_2} = k_a a_2^2 / 2$ are calculated in the direction normal to the face of the transducer.

MGB model approach was applied to simulate phased array transducers in isotropic material. However, the application found the MGB model of the array lost accuracy when the steering angles exceed about 20 degrees, due to the reliance on the paraxial approximation[8]. For a phased array in inhomogeneous and anisotropic material, which has a number of rectangular transducers, the possibility of breaking the paraxial approximation of modelling the sound field is larger than a single transducer.

Huang et.al introduced a linear phasing term that by shifting an angle the $\theta_s$, from the normal to the face of the transducer to the real propagation direction of the ultrasonic beam of each element[9]. Thus, the expression of $D_{r_1}$ is replaced by $D_{r_1} = k_a a_1^2 \cos \theta_s^2 / 2 \tag{13}$

where $\theta_s$ is the tilting angle measured from the ray to the normal to the face of the transducer as shown in Fig.2. So the beam propagation direction follows the ray direction rather than the normal to the layer in this method. For a linear phased array, $\theta_s$ is the tilting angle of each element of the array, and the velocity field radiated from each element can be described by Eq.(10) by using proper propagation direction $\mathbf{d}$, with the proper time delay applied to every element, and sum the beam field, a phased array beam field in austenite weld can be obtained.
SIMULATION RESULTS

Fig.3 represents the simulated beam field using a LPMGB model in austenite weld and MGB model in austenite weld, respectively. An immersed linear array elements (dimension: 10mm×0.8mm, pitch: 1mm; central frequency: 5MHz) mounted on a wedge (wedge angle: 16 degree, thickness of the centre of the leftmost element: 14.9mm). The computation area displayed on this figure is oriented relatively to this desired beam orientation (3.1mm, 4.4mm), while the incident position is (14.2mm, 30.3mm). It shows that the beam focuses despite the strong distortion in the weld using a LPMGB model, while the beam field calculated using MGB model will lead to strong dispersion and deviation from the desired position.

<table>
<thead>
<tr>
<th>example</th>
<th>material character</th>
<th>incident position</th>
<th>desired position</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>from wedge to carbon steel</td>
<td>(-47.3 30.3)mm</td>
<td>(-27.1 4.4)mm</td>
</tr>
<tr>
<td>B</td>
<td>from wedge to austenite</td>
<td>(14.2 30.3)mm</td>
<td>(3.1 4.4) mm</td>
</tr>
<tr>
<td>C</td>
<td>from wedge to stainless</td>
<td>(40.3 30.3)mm</td>
<td>(23.1 3.4)mm</td>
</tr>
</tbody>
</table>

Table 1 - specifications of beam simulation of case A, B and C
Fig. 4 illustrates the tilting angle calculated in example A, B and C. In conventional MGB model, the tilting angle always remains zero and Fig. 5 shows the off-axis beam profile of another three examples of beam computation over the austenite weld specimen. The specifications of simulations are listed in Table 1.

![Figure 4 - Tilting angle of example A, B and C](image)

![Figure 5 - Predicted off-axis beam profile in austenite welds at (a) z=4.4mm of example A, (b) z=4.4mm of example B, (c) z=3.4mm of example C](image)

In example A, the beam is incident from Lucite to carbon steel, the performance of LPMGB and MGB is similar, all the simulated beams focus on the desired position. But in example B, when the beam is incident from Lucite to austenite weld, the advantage of LPMGB is obvious; only the beam using LPMGB in austenite weld focuses at the desired position with its amplitude bigger than the other one. Because of the impractical tilting angle, the MGB in austenite weld scatters around and can’t focus at...
In example C where the beam is incident from Lucite anisotropic stainless weld, the beam simulated using LPMGB in austenite steel focuses at the desired position (y=23mm), while the calculated focusing position using MGB deviates from the desired position to y=30mm. From the simulation above, we find that the LPMGB improves efficiency and accuracy of beam focusing and steering.

CONCLUSIONS

A theoretical model based on a single Gaussian beam model is developed into a linear phasing multi-Gaussian beam (LPMGB) model for phased array to inspect flaws in austenitic metal welds. Using this model, we can steer/focus a beam to a desired position in the austenitic metal welds despite its inhomogeneity and anisotropy. Simulation results using this model for phased array compared with beam fields simulated using conventional multi-Gaussian beam model show that it increases the accuracy to steer/focus a beam to a desired position.

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REFERENCES