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Simulation of Ultrasonic Beam Focusing on a Defect in Anisotropic, Inhomogeneous Media

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Abstract In ultrasonic testing of dissimilar metal welds, application of phased array technique in terms of incident beam focusing is not easy because of complicated material structures formed during the multi-pass welding process. Time reversal(TR) techniques can overcome some limitations of phased array since they are self-focusing that does not depend on the geometrical and physical properties of testing components. In this paper, we test the possibility of TR focusing on a defect within anisotropic, heterogeneous austenitic welds. A commercial simulation software is employed for TR focusing and imaging of a side-drilled hole. The performance of time reversed adaptive focal law is compared with those of calculated focal laws for both anisotropic and isotropic welds.

Keywords: Beam Focusing, Austenitic Weld, Anisotropy and Inhomogeneity, Phased Array, Time Reversal

1. Introduction

One of the most important things in ultrasonic NDT is the capability of focusing the incident beam on defect/damage locations. For this purpose, phased array focusing is widely used these days[1]. Some of the attractive features of phased arrays include electronic focusing and steering capabilities. To generate a focused beam at any specified angle and distance, time delays are calculated and applied electronically to each element. However, these techniques suffer important limitations. They are all based on a priori knowledge of geometry and acoustic properties of the sample and assume that the sound velocity is known and constant in each medium. Since most of real components are nonuniform in geometry, and inhomogeneous and anisotropic in properties, the phased array technique cannot provide accurate beam focusing at a desired position within components of unknown material properties [2,3].

Time reversal(TR) focusing technique can overcome some limitations of phased array since they are self-focusing that does not depend on those parameters. One of the fundamental features of TR techniques is the ability to focus the propagating ultrasonic beam on a defect position (source location) within the test material [4,5]. Compared to ultrasonic phased arrays, the TR focusing does not require a prior knowledge about the properties and structures of the media and the transducer. The TR focusing can be realized as follows: (a) One of the array elements is (or all array elements are) first excited as an unfocused array, (b) Backscattered signals are recorded by the elements of the array, time-reversed, and then re-emitted simultaneously, and (c) The wave back-propagates through the medium and focuses on the original source location.

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In this paper, we investigate the possibility of focusing the incident array beam on a specified defect located inside the dissimilar metal welds. The austenitic welds are one example of such welds frequently found in the components of nuclear power plants and represent typical inhomogeneous, anisotropic media, causing difficulty in ultrasonic beam focusing.

Modeling tools for ultrasonic testing(UT) simulation have been developed at CEA[6-8]. The CIVA software can deal with real testing configurations in terms of probes (single, phased arrays . . .), flaws, arbitrary component geometries (2D, 3D . . .) and material properties (isotropic, anisotropic inhomogeneous . . .). However, the capability of simulating the time reversal process with the full waveform is not available even in the latest version of the CIVA platform. Implementation of the TR focusing technique basically requires excitation of the time-reversed version of the received signal for each element of array transducer. In our previous work[9], it was shown that time reversal of received signal by each channel is equivalent to applying the necessary time delay to focus its beam at the source position. Therefore, in this study, instead of using time reversal of full waveform we employ the capability of inter-element firing and reception of the CIVA platform to apply appropriate time delays to each channel. In what follows, we employ the CIVA program to simulate time reversal focusing on a defect in anisotropic, inhomogeneous austenitic welds. The simulation results are compared with the phased array technique.

2. Simulation

2.1 Material and Array Transducer

In the case of multi-pass austenitic welds, anisotropy and heterogeneity result from the metal solidification and are correlated with the grain orientation. A precise description of the material is very difficult to describe due to its complicated microstructure.

In this work, the local structure of the austenitic weld is described by dividing it into several layers. Each layer has different elastic properties depending on the grain orientation. Fig. 1 shows a simplified material model of the weldment and their corresponding divisions into eight homogenous layers. The grains are assumed to be tilted in the vertical x–z-plane with no tilt out of the plane. The grain orientation of each division is measured clockwise with respect to the global x axis as follows: 140°, 130°, 110°, 95°, 85°, 70°, 50°, 40°. The elastic constants of these regions can be obtained by transforming those of single crystal 308 stainless steel whose [100]-axes are along the columnar grain direction:

$$C = \begin{bmatrix} 262.7 & 98.2 & 145 & 0 & 0 & 0 \\ 98.2 & 262.7 & 145 & 0 & 0 & 0 \\ 145 & 145 & 216 & 0 & 0 & 0 \\ 0 & 0 & 0 & 129 & 0 & 0 \\ 0 & 0 & 0 & 0 & 129 & 0 \\ 0 & 0 & 0 & 0 & 0 & 82.3 \end{bmatrix} \text{GPa},$$

$$\rho = 8120 \ \text{kg/m}^3$$

The microstructure of the austenitic weld described above was also used by Spies[10]. The elastic properties of the ferritic steel are C_{11}=283GPa, C_{12}=121GPa, and r=7850 kg/m^3.

The array geometry used for the simulation is that of a linear array transducer with equi-spaced elements. As an example the operation of a typical commercial 5 MHz array with 60 elements was modeled. The array has an element pitch of 1 mm and active aperture size of 60 mm. The size of rectangular element is (1, 10) mm in the x- and y-directions. The output signal of each element has a center frequency of 5 MHz and a -6 dB bandwidth of 50%.

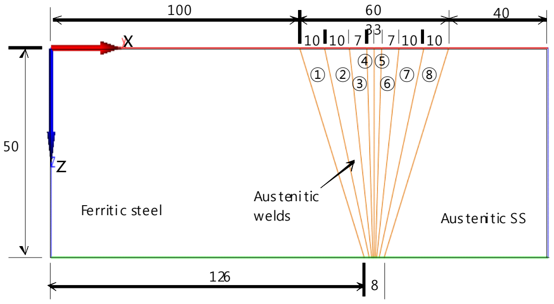

Fig. 1 Schematic of material model for anisotropic, inhomogeneous austenitic weld

2.2 Time Reversal Process

The simulated time reversal concept for generating adaptive focal laws using an array transducer and a side-drilled hole(SDH) inside the austenitic weld is illustrated here. The diameter of the SDH is 2 mm and its location is (x, z)=(140, 35) mm. A 5 MHz linear array with sixty elements at a pitch of 1 mm coupled to the wedge is mounted on the top surface of the ferritic zone. The wedge angle was chosen to generate 60° refracted L-wave into the steel.

The simulation shown in Fig. 2 is used to first illustrate the concept of generating the TR-based delay law through received signals from the target SDH. An element in the central part of the array transducer is excited first (Fig. 2(a)), and the defect will reflect the incident wave. In general, any element of the array transducer could be used for this initial firing. The backscattered wave pi(r,t) is recorded by all transducer elements(Fig. 2(b)). Since the TR focusing or the TR-based time delay focusing is adaptive, it does not require a prior knowledge about the properties and structures of the media and the transducer. For transmission focusing by the TR process, the time-reversed wave pi(r,T-t), where T is the duration of the time window, is reemitted by all elements simultaneously. Thus, the waves sent out by all of the elements arrive at the defect position at the same time.

An alternative way of realizing this TR focusing is to excite pulses for each element with transmitting time delays[9]. A set of transmitting time delays is obtained by reversing the receiving time delays. For instance, the element #60 that received the backscattered signal last is fired first with the shortest transmitting time delays. The receiving time delay is the time-of-flight of received signal by the individual element. A phase slope technique can be used to determine time delays of received signals for each element. There are several ways to find the time delay of a signal in time and frequency domains[11]. The phase slope technique makes use of the linear property of phase spectrum of nondispersive wave. The time delay or the time-of-flight of a signal is given by

$$t_d = \frac{1}{2\pi}\frac{d\phi}{df} \tag{1}$$

where ϕ is the unwrapped, continuous phase spectrum, and f is the frequency. $\frac{d\phi}{df}$ denotes the phase slope, and it is usually calculated within the bandwidth of the magnitude spectrum. Fig. 2(c) shows that the waves sent out by all of the elements with proper time delays arrive at the defect position at the same time. The solid bars above the array transducer associated with each element represent the delay applied to each element.

The anisotropic delay law was also calculated by ensuring that the sound energy from all sixty elements arrives at the target point at the same time and in phase to constructively interfere for maximum sound pressure; the algorithm used was called ‘single point focusing’ in the CIVA platform. The performance of adaptive focal law based on the TR process will be compared with that of the calculated law in the next section.

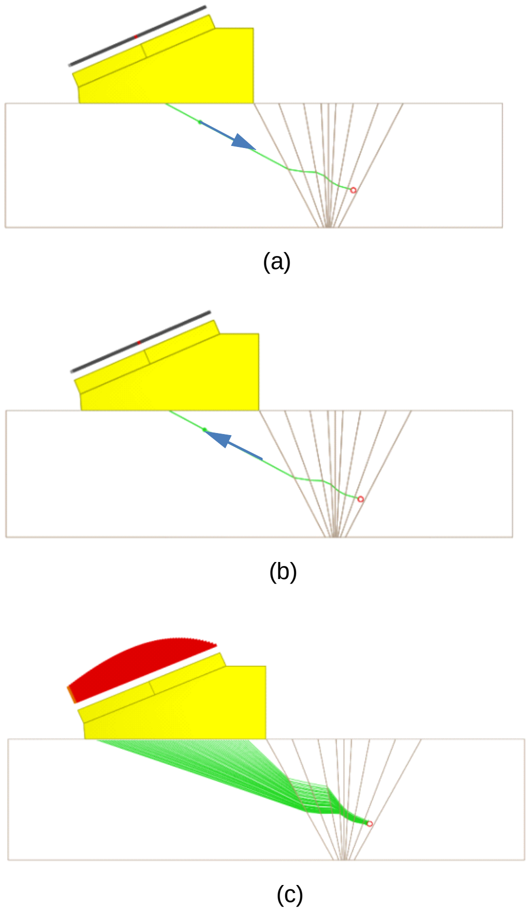

Fig. 2 Time reversal concept for generating adaptive focal laws using an array transducer and a side-drilled hole(SDH) inside the austenitic weld: (a) Single element firing, (b) Reception of backscattered signal by all elements, and (c) Excitation of pulses for each element with transmitting time delays obtained by reversing the receiving time delays

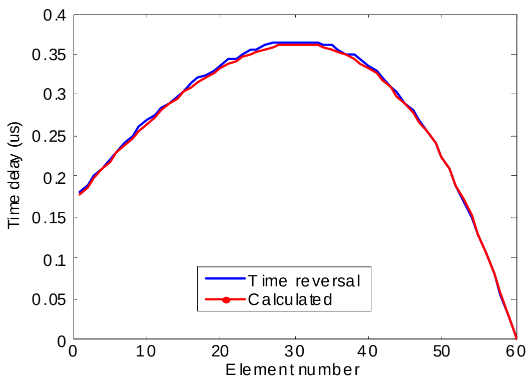

Fig. 3 Comparison of time delays for focusing on a defect inside the anisotropic weld material

3. Results and Discussion

Fig. 3 compares the TR-based adapted and calculated time delays that should be applied to the sixty elements for transmission focusing on the required target(SDH) position. These time delays are found to be almost the same for different two cases, proving the validity of the TR focusing in anisotropic, inhomogeneous medium. The simulated arrival times to and from the SDH were used to generate the calculated and adapted focal laws, respectively. Therefore, it can be said that the time delays necessary for both transmission and reception focusingare almost the same since the time delays for these two cases are almost the same.

Fig. 4 shows the beam propagation patterns when the time delays of Fig. 3 were applied. The adapted and calculated focal laws to the sixty-element array are illustrated in Figs. 4(a) and 4(b), respectively. Additionally, the calculat-

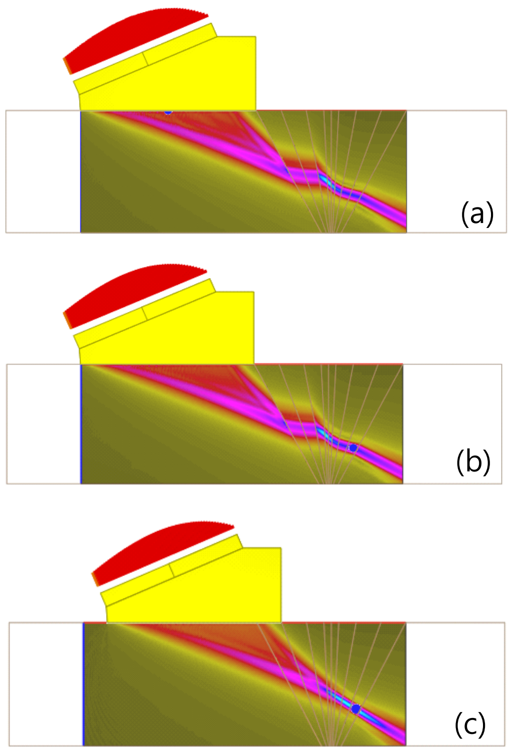

Fig. 4 Comparisons of beam propagation after time delays applied; (a) Adapted focal law, (b) Calculated focal law, and (c) Calculated focal law for isotropic (ferritic) weld material

ed focal law for isotropic(ferritic) weld material is presented in Fig. 4(c). The solid bars above the array transducer associated with each element represent the delay applied to each element. The delay laws applied in Fig. 4(a)-(c) dictate that the last element fires first followed by successive firing of the adjacent element up to element number 60. Hence, the delay of elements 1 to 59 are relative to element 60, which fires at time equals zero. The adapted law (Fig. 4(a)) shows similar performance to the calculated law (Fig. 4(b)) since the time delays for these two cases are almost the same. It is also noted that the actual focal points (the point of maximum sound pressure) does not occur at the original SDH position. This focusing behavior is well compared with that of isotropic weld case of Fig. 4(c), where the retrofocusing occurs near or close to the center of SDH . Further study will be necessary for the TR focusing behavior in anisotropic materials.

In order to obtain the defect image, the probe and wedge were moved a distance of 40 mm (with 1 mm resolution) on the surface such that the beams traversed the area of the SDH. The resultant B-scan from the simulated scanning is presented for three cases in Figs. 5(a)-(c). In these figures, the maximum signal strength is found near the flaw center.

Additionally, the signal amplitudes and arrival times of the echoes generated by the SDH target in the anisotropic and isotropic welds are also found and presented in Fig. 6. These A-scan signals were calculated by applying the receiving time delays that can be found similarly to the transmitting time delays. For the anisotropic weld, the received signal using the adapted delay law (Fig. 6(a)) shows similar performance to the calculated delay law (Fig. 6(b)) both in amplitude and time. Fig. 6(c) shows the received signal from the SDH for the isotropic weld case. The maximum signal strength of the anisotropic weld case is nearly 5 dB lower in comparison to that of the isotropic weld case. When the sound beam from different elements on the array are propagating through the anisotropic weld with appropriate time delays, more sound beams will deviate from the desired target SDH due to the distortion induced by the microstructures. This is the primary reason of having lower signal strength in the amplitude of A-scan.

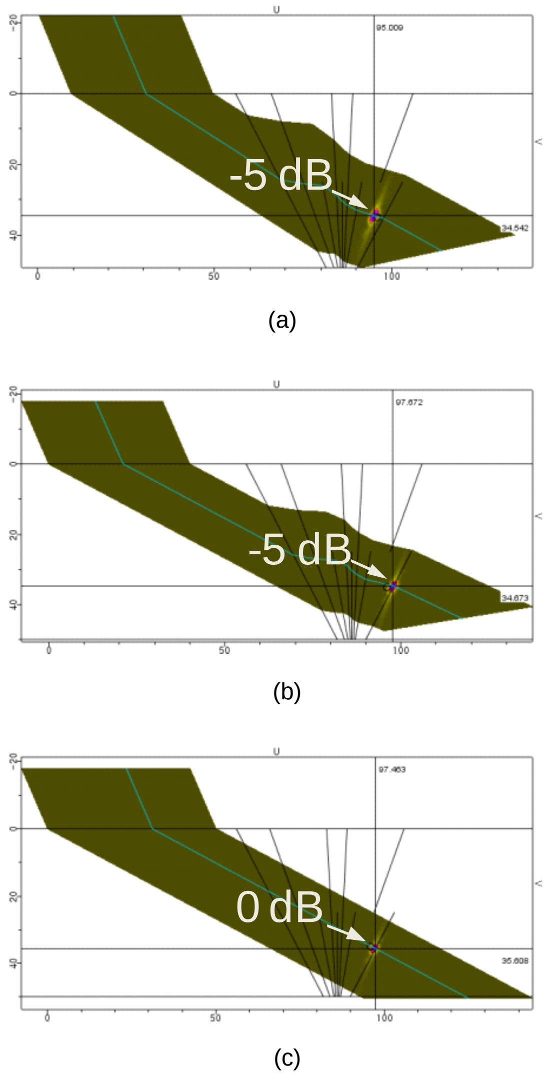

Fig. 5 The resultant B-scan images from the simulated scanning for three cases: (a) Adapted focal law for the anisotropic weld, (b) Calculated focal law for the anisotropic weld, and (c) Calculated focal law for the isotropic (ferritic) weld. The maximum signal strength for the anisotropic weld case is nearly 5 dB lower than for the isotropic weld case

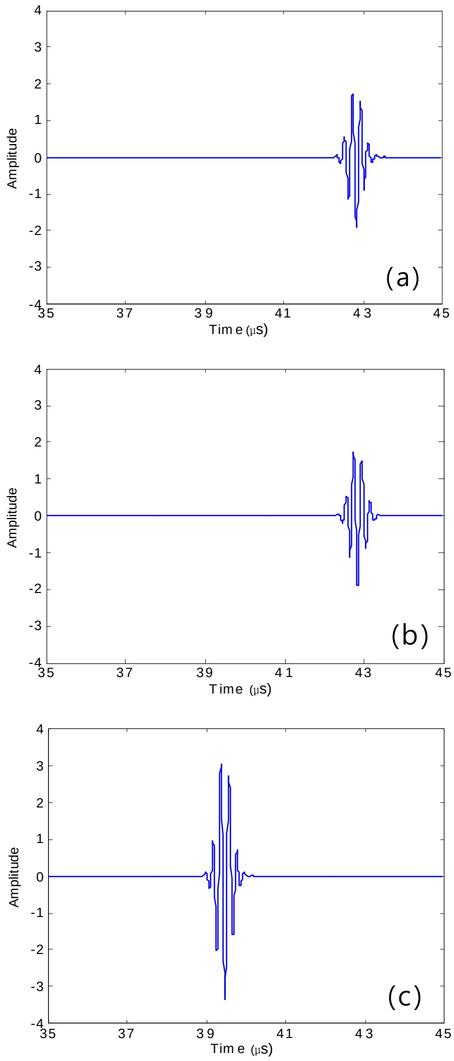

Fig. 6 Received signal amplitudes and arrival times of the echoes generated by the SDH target: (a) Adapted focal law for the anisotropic weld, (b) Calculated focal law for the anisotropic weld, and (c) Calculated focal law for the isotropic (ferritic) weld

4. Conclusions

We investigated the possibility of TR focusing on a defect within anisotropic, heterogeneous austenitic welds. The CIVA simulation platform developed at CEA was employed for TR focusing and imaging of a side-drilled hole(SDH). The TR-based adapted and calculated time delays necessary for transmission focusing on the required SDH position was compared and found to be almost the same, proving the validity of the TR focusing in anisotropic, heterogeneous medium. The B-scan image of the SDH was also acquired from the simulated scanning. The maximum signal was found near the flaw center, and its strength was almost the same for two cases studied. The amplitude of A-scan signal over the flaw was compared and the signal strength was nearly 5 dB lower in comparison to that of the isotropic weld case. Further issues of interest in TR beam focusing to be addressed are, for example, the consideration of grain boundary noise and attenuation, and the interaction of elastic waves with defects.

Acknowledgement

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