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Use of Time Reversal Techniques for Focusing of Ultrasonic Array Transducer Beams

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Abstract For enhancement of flaw detactability using array transducers, focusing of ultrasonic waves on a target in an inhomogeneous medium or through a complex geometry is important. But focusing can be strongly degraded by geometrical distortion of field radiated by the array transducers or by sound speed fluctuations in the propagating medium. In recent years, the time reversal technique has been proposed. Thus, in this paper, we describe the basic principal of the time reversal technique for focusing. Then, the implementation results of the time reversal technique for ultrasonic inspections using bulk waves and guided waves generated by array transducers are presented.

Keywords: Array Transducer, Time Reversal Technique, Focusing of Ultrasound

1. Introduction

To improve the probability of detection (POD) of flaws, ultrasonic inspections using array transducers have been paid a great attention in ultrasonic nondestructive evaluation since it can provide many benefits, especially of focusing and/or steering ultrasonic waves. Array transducer systems are increasingly being used to improve the detectability of small flaws or crack-like flaws in structures and/or components due to the ability of controlling the delays of individual elements.

However, focusing can be strongly degraded by geometrical distortion of the fields radiated by array transducers or by sound speed fluctuations in the propagating medium and the dispersive characteristics of ultrasonic guided waves. Unfortunately, array systems usually do not consider these variations when they calculate time delays. In recent years, several approaches have been extensively studied such as the Fermat surface transducer (Miette et al., 1996), multi-element array transducer (Rose, 1999; Wooh and Shi, 2000; Fink, 1992), adaptive focusing technique (Wooh and Shi, 2000) and phase tuning method (Fink, 1992). However, these techniques suffer from important limitations. For the phased array ultrasonic testing, a priori knowledge of geometry and acoustics properties of the specimen and highly precise positioning of the transducer are required. And for the ultrasonic guided wave inspection, the phase tuning method is to control the wave modes but not to focus waves on the defects. Therefore, it is strongly desired to have efficient focusing method which takes into account of geometrical distortion and sound speed fluctuation for focusing of array guided waves.

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To take care of such needs, in this study, we adopt a time reversal technique that is claimed to be very robust to focus ultrasonic waves on the defect. Up to now, two kinds of time reversal techniques have been proposed: 1) the time reversal mirror (TRM) technique (Fink, 1992; Fink et al., 2000) and 2) D.O.R.T. (French acronym for Decomposition of the Time Reversal Operator) method (Chakroun et al., 1995; Parada et al., 1995). These methods are motivated by claims that can provide robust solutions to determine the proper time delays on the flaw for the array transducer system. However, the TRM technique generally requires special hardware including programmable generators, storage memory on each channel, etc (Fink, 1992). Contrary to the TRM technique, the D.O.R.T. method does not require programmable generators, and it allows the simultaneous detection and separation of several defects based on a mathematical analysis of the iterative time reversal process (Parada, 1996). Thus, in this study, we implement the D.O.R.T method to calculate time delays for focusing ultrasonic bulk waves and guided waves generated by array transducer on the flaws.

In this paper, we describe the basic principles and focusing procedures of the D.O.R.T. method. Then, the performance of the D.O.R.T. method is considered based on experimental studies of focusing ultrasonic bulk waves on simple scatterers in anisotropic and inhomogeneous materials by using an ultrasonic phased array testing system and numerical studies of focusing ultrasonic guided waves on the notch in a thin plate by using simulation software. The results are compared to those obtained by conventional focusing methods.

2. Time Reversal Technique

If we consider the wave equation in a lossless fluid medium without body force, we have the wave equation of pressure, $p(\mathbf{x},t)$, as:

$$\nabla^2 p(\mathbf{x},t)-\frac{1}{c^2}\frac{\partial p(\mathbf{x},t)}{\partial t^2}=0 \qquad (1)$$

In Eq. (1), the wave equation contains a second-order time-derivative operator. Thus, if $p(\mathbf{x},t)$ is solution of Eq. (1), then $p(\mathbf{x},-t)$ also is another solution. Time reversal techniques rely on this property. So, if we have a received signal scattered from a flaw located in complex material, we have another wave theoretically that is time reversed one. Thus, using this property, we could precisely focus on a flaw.

In this paper, we describe a focusing process by the D.O.R.T method briefly. As mentioned before, the D.O.R.T. method is a detection technique that is derived from the theoretical analysis of TRM. As shown in Fig. 1, the signal received by the l^{th} element of the array transducer, which has N elements, is defined as

$$r_l(t)=\sum_{m=1}^{N}k_{lm}(t)\otimes e_m(t) \qquad (2)$$

where $e_m(t)$ is the input signal applied to the m^{th} element, $k_{lm}(t)$ is the impulse response from the l^{th} element to the m^{th} element and $\otimes$ is the convolution in the time domain.

If we take the Fourier transform of Eq. (1) and use matrix notation, we have

$$\mathbf{R}(\omega)=\mathbf{K}(\omega)\mathbf{E}(\omega) \qquad (3)$$

where $\mathbf{K}(\omega)$ the transfer $N \times N$ matrix, is an matrix (Parada et al., 1996). Since we consider the linear-time-invariant system, the new input signal at the i^{th} iteration, $\mathbf{E}^i(\omega)$, can be defined by

$$\mathbf{E}^i(\omega)=\mathbf{K}^*(\omega)\mathbf{E}^{i-1*}(\omega) \qquad (4)$$

where * denotes complex conjugation corresponding to a time reversal. Thus, the received signal at the i^{th} iteration, $\mathbf{R}^i(\omega)$, can be written as

$$\mathbf{R}^i(\omega)=\left[\left\lfloor \mathbf{K}(\omega)^*\mathbf{K}(\omega)\right\rfloor \mathbf{E}^{i-1}(\omega)\right] \qquad (5)$$

where $\mathbf{K}(\omega)^*\mathbf{K}(\omega)$ is called the time reversal operator (Parada et al., 1996).

Based on the assumptions, a linear time-invariant system and lossless medium, the transfer matrix is symmetrical. Thus, the time reversal operator is Hermitian positive. Also, the number of significant eigenvalues of the time reversal operator is equal to the number of well resolved scatterers (Parada et al., 1996). From the eigenvector corresponding to significant eigenvalues, we can obtain the time delays required to focus on the scatterer using Eq. (6).

$$\Delta t_i = \frac{\Delta \phi_i}{\omega} \tag{6}$$

where ϕ_i is the phase of the eigenvector.

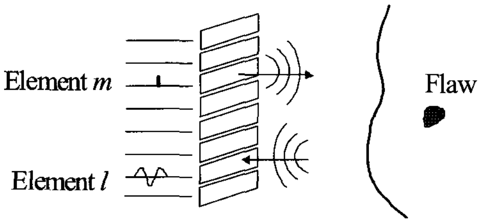


Fig. 1 Schematic diagram of inter-element impulse response

3. Experimental Results for a Phased Array Transducer

To investigate the D.O.R.T method for a phased ultrasonic testing system, we have used a linear array transducer, which has 32 elements with 1 mm element spacing and 5 MHz center frequency, and the TomoscanFocus (made by R/DTech) electronics for transmitting/receiving signals. Also, TomoView (made by R/DTech) software was used to control the phased array system as well as to calculate the time delay based on the conventional ray-acoustic method. To calculate the time delay by the D.O.R.T. method, we have developed software using MATLAB 6.0.

3.1 FBH in Powder Titanium Specimen

Figure 2 shows measured inter-element firing signals from a #1 FBH (1/64 inch diameter, metal depth of 25.4 mm), placed in a powder titanium specimen having a very fine grain size, without time delay using a 32 element linear array

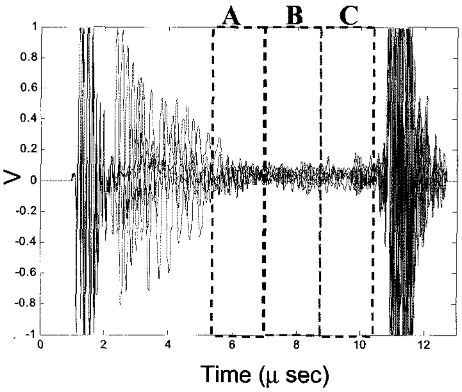
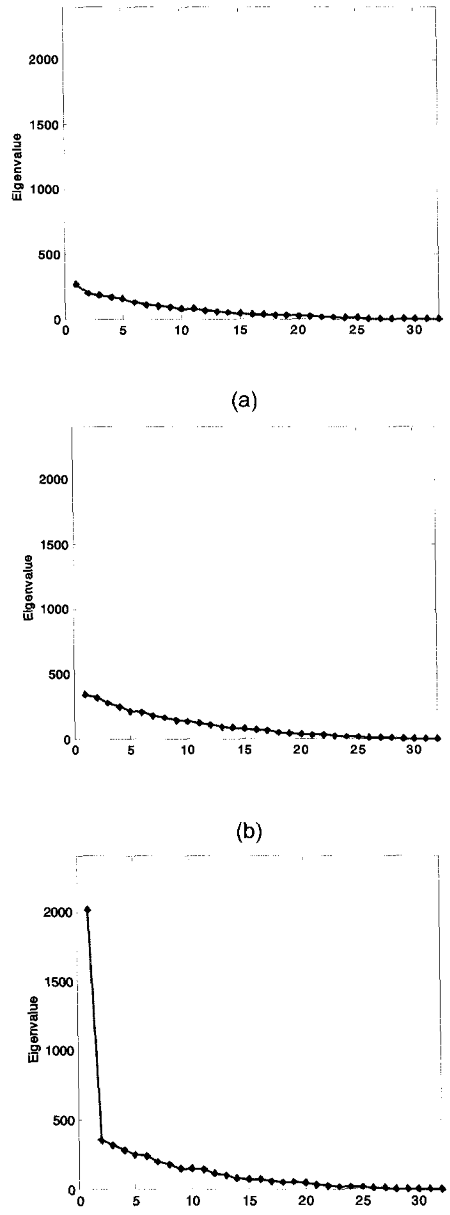


Fig. 2 Measured inter-element firing signals from a #1 FBH examined by a 32 elements linear array transducer of 5 MHz center frequency

transducer in an immersion setup. As shown in Fig. 2, we set three temporal windows since it is not easy to distinguish flaw signals from the acquired signals. Using the windowed signals, we have computed the time reversal operator, $\mathbf{K}(\omega)^* \mathbf{K}(\omega)$, by taking Fourier transform. Then, we calculate eigenvalues and eigenvectors of the time reversal operator by the singular value decomposition method. As mentioned in the previous section, the number of significant eigenvalues is equal to the number of well resolved flaws. Each column of the eigenvector corresponding to a significant eigenvalue contains information defining the phase and amplitude required to focus on each scatterer. As shown in Fig.3, the eigenvalues of the signals gated by window “A” and window “B” do not contain any significant eigenvalues, implying that true flaw signals are not contained in these windows. However, the window “C”, a significant eigenvalue is found which represents the signal form the FBH. Based on the eigenvector corresponding to this significant eigenvalue, we have calculated time delay to focus on the flaw by equation (5). Fig. 4 (a) shows two time delays calculated by the conventional ray-acoustic method (TomoView Software, RdTech) and the DORT method. As shown in Fig. 4 (a), a small difference between the time delay calculated by the conventional ray-acoustic method and the DORT method was observed. However, the peak-to-peak value of the signal acquired by using the DORT method is about 1.7 times greater than method as shown in Fig. 4 (b). Thus, small differences in time delay can make a big difference in the amplitude of flaw signals when we use the time delays to focus on the FBH. Since the FBH has a significant angular dependence of its reflectivity, a part of the improvement by DORT may be due to correcting for misalignment errors.

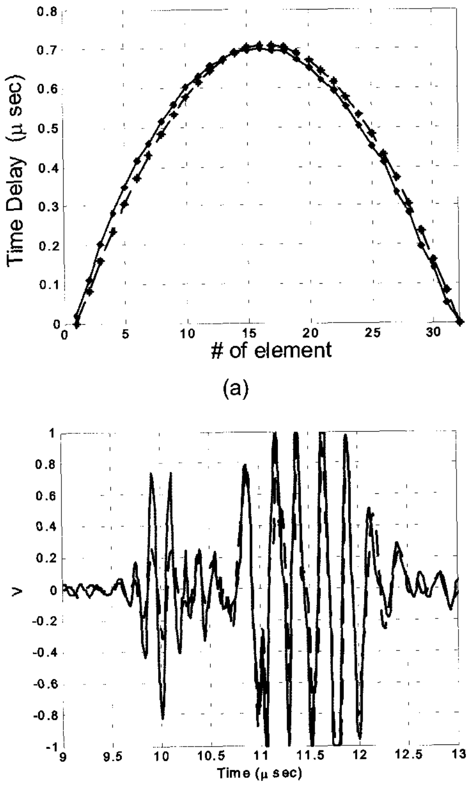


(a)

(b)

(c)

Fig. 3 Calculated eigenvalues from the windowed measured signals acquired from a #1 FBH using (a) the window "A", (b) the window "B" and (c) the window "C"



(a)

(b)

Fig. 4 (a) Calculated time delay by the DORT method (solid line with diamond maker) and the conventional ray-acoustic method (dotted line with cross maker) and (c) acquired signals focusing on the FBH by the DORT method (solid line) and the conventional ray-acoustic (dotted line).

3.2 SDH in Cast Titanium Specimen

The efficiency of the DORT method was then examined by focusing through inhomogeneous and anisotropic media. For that purpose, we made two different sizes of SDHs (6 mm and 0.45 mm in diameters, metal depth of 23 mm) in a cast titanium specimen which is an anisotropic inhomogeneous material. And then we acquired inter-element firing signals from the SDH specimens immersed in water using the phased array transducer without time delay. Using the acquired signals, we have calculated a time delay from the calculated eigenvalues and eigenvectors. Figs. 5 (a) and (b) show the calculated time delays using the DORT method and the conventional ray-acoustic method for the large SDH and the small SDH, respectively. We believe that these differences in time delay might be come from the fluctuation of sound speed in the specimen or misalignment of the transducer and flaw. In the case of the small SDH, we found not only a time difference but also misalignment as shown in Fig. 5 (b), indicated by a slight offset in the two time delay curves.

Figs. 6 (a) and (b) show the measured signals from the 6 mm and the 0.45 mm diameter SDHs, respectively, obtained by focusing on the target flaws using the two different sets of time delays. In the case of the large SDH, the relative peak-to-peak amplitude ratio produced by the DORT method and the conventional ray-acoustic method differ by 16.8%. In the case of the small SDH, the peak-to-peak amplitude of the flaw signal acquired by focusing using the DORT method is of 72.5 % bigger amplitude than the conventional ray-acoustic one. The above results suggest that the DORT method can correct for the misalignment of transducer and flaw and the sound speed fluctuation of the inhomogeneous medium.

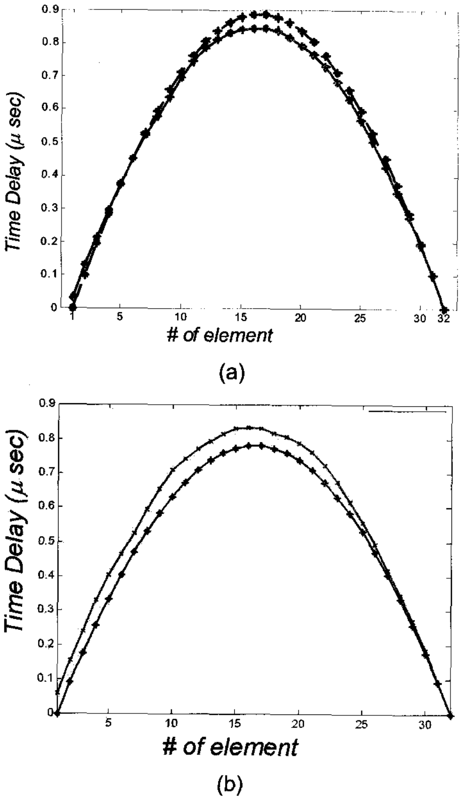


Fig. 5 Calculated time delays for focusing on (a) 6 mm diameter SDH and (b) 0.45 mm diameter SDH. Solid line with diamond maker: DORT method and dashed line with cross maker: conventional ray-acoustic method.

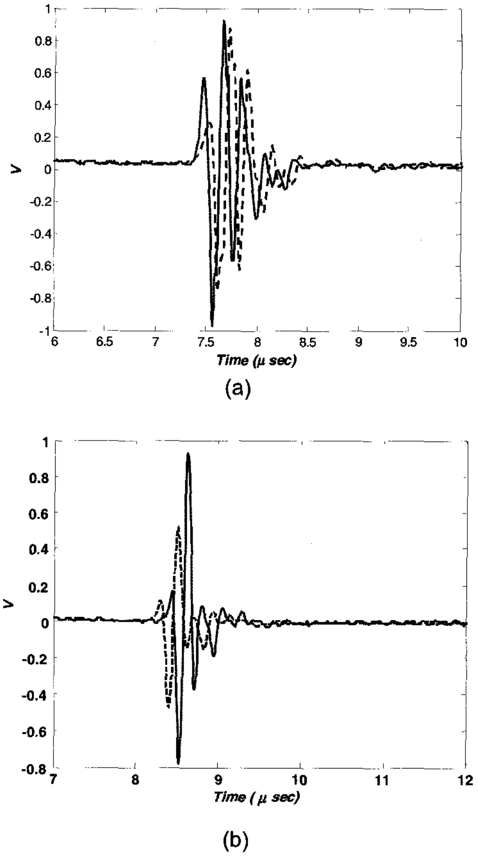


Fig. 6 Acquired signals focusing on the (a) 6 mm diameter SDH and (b) 0.45 mm diameter SDH by the DORT method (solid line) and the conventional ray-acoustic (dotted line)

4. Experimental Results for an Array Guided Waves

To investigate the D.O.R.T method for array ultrasonic guided waves, we have used the numerical simulation software (Wave2000Pro developed by CyberLogic Co. Ltd). Fig. 7 shows the numerical setup for array ultrasonic guided wave inspection applied in this study. As shown in Fig. 7, we set the five transducer (0.5 MHz of center frequency, 2 mm of width) with 3 mm inter-element space on the 2-D plate specimen (75 mm of length, 5 mm of thickness) with a notch (3 mm of depth).

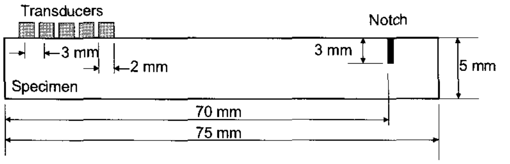
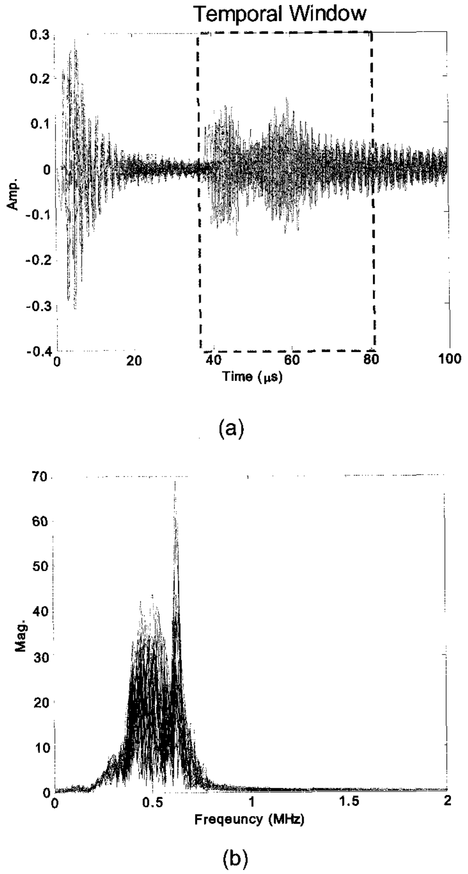


Fig. 7 A schematic diagram of the numerical simulation setup for an array ultrasonic guided wave inspection

As mentioned in previous section, to determine the proper time delay by the D.O.R.T method for the given numerical setup, we need inter-element responses acquired by the linear array transducer. Fig. 8 (a) shows the superposition of the acquired inter-element firing signals without time delay using the linear array transducer. A temporal window was placed as shown in Fig. 8 (a) to isolate these signals from the initial signals. And Fig. 8 (b) shows the frequency spectrum of the windowed inter-element signals.

Using the frequency values of windowed signal, we have performed singular value decomposition to get eigenvalues and eigenvectors. From the eigenvector corresponding to the significant eigenvalue, we have calculated the time delays by using Eq. (6). Fig. 9 shows the time delays calculated by the D.O.R.T. method and the conventional method (Rose 1999). As shown in Fig. 7, difference between conventional method and the D.O.R.T method were exists.



(a)

(b)

Fig. 8 Measured inter-element firing signals from a 3 mm depth notch in an steel specimen acquired by a 5 element linear array transducer of 0.5 MHz center frequency, (b) those frequency spectrums.

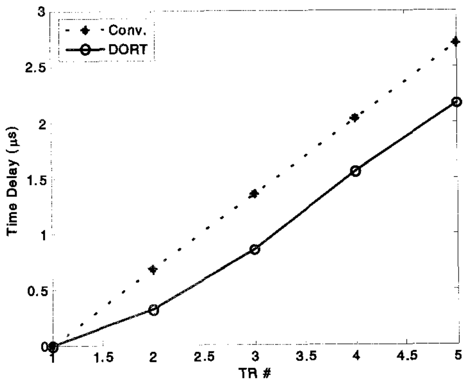
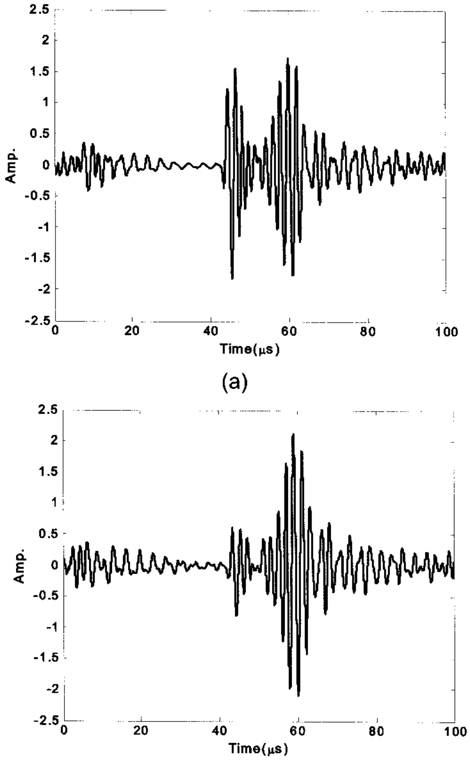


Fig. 9 Calculated time delay by the D.O.R.T. method (solid line with circles) and the conventional method (dotted line with cross marks)

Figs. 10 (a) and (b) show the received ultrasonic guided wave signals for the notch using the array transducer with the two different time delays. Fig. 10 (a) shows the received ultrasonic guided wave signals by adopting the time delay obtained from the conventional method. As shown in Fig. 10 (a), the received signal using the conventional method, we have two wave groups which have similar peak-to-peak amplitude between two wave groups. However, received signals using the D.O.R.T method, two wave groups have different peak-to-peak amplitudes: the second group is bigger than the first group as shown in Fig. 10 (b). From this observation, we found that the time delay obtained by D.O.R.T is emphasizing the second group of ultrasonic guided. Furthermore, received wave by adopting the time delay using D.O.R.T is of 18% greater amplitude than the conventional one.



(a)

(b)

Fig. 10 Calculated ultrasonic guided wave signal for the notch using the array transducer with three different time delay: (a) the conventional method and (b) the D.O.R.T.

5. Summary

In this paper, we have implemented the time reversal technique (the D.O.R.T method) for an ultrasonic phased array inspection and an ultrasonic guided wave inspection. From the experimental results of the ultrasonic phased array inspection, we have found that the D.O.R.T. method may be used to determine the number of flaws in the inspected area and also to find the proper time delay for focusing through inhomogeneous materials. It can also correct for misalignment of the transducer and the flaw. From the numerical simulation results of the array ultrasonic guided wave inspection, the received signal focused by the D.O.R.T method is of greater received signal amplitude than the conventional one. Thus, the D.O.R.T method can be used for improving the detectability of both ultrasonic phased array inspection and ultrasonic guided wave inspection by using an array transducer.

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