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Time Reversal Beam Focusing of Ultrasonic Array Transducer on a Defect in a Two Layer Medium

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Abstract The ability of time reversal techniques to focus ultrasonic beams on the source location is important in many aspects of ultrasonic nondestructive evaluation. In this paper, we investigate the time reversal beam focusing of ultrasonic array sensors on a defect in layered media. Numerical modeling is performed using the commercially available software which employs a time domain finite difference method. Two different time reversal approaches are considered – the through transmission and the pulse-echo. Linear array sensors composed of *N* elements of line sources are used for signal reception/excitation, time reversal, and reemission in time reversal processes associated with the scattering source of a side-drilled hole located in the second layer of two layer structure. The simulation results demonstrate the time reversal focusing even with multiple reflections from the interface of layered structure. We examine the focusing resolution that is related to the propagation distance, the size of array sensor and the wavelength.

Keywords: Time Reversal, Array Transducer, Beam Focusing, Layered Medium

1. Introduction

The ability of time reversal(TR) techniques to focus interrogating beams on the source location is important in many aspects of ultrasonic nondestructive evaluation. Narrowly focusing the beam can provide enhanced spatial resolution for flaw detection and sizing. Focusing can also significantly improve signal-to-noise ratio in challenging applications. Recent application areas include underwater acoustics, biomedical ultrasound imaging and therapy, nondestructive evaluation, and seismology. Applications of TR in nondestructive evaluation is found in the work by (Chakroun et al., 1995), who developed a TRM for focusing on small defects in titanium and duraluminum samples submerged in water tanks. TR has been also applied to the detection of flaws and delaminations in thin solid plates (Ing et al., 1996a and 1998). The presence of defects inside the plate changes the quality of the TR reconstruction of the source waveform(s). Defects can be detected by comparing the TR reconstruction of the source in the test sample with the TR reconstruction obtained from an intact sample. TR of surface acoustic waves (SAWs) has also been demonstrated in a very wide frequency range from infrasound and high seismic frequencies, to the high ultrasound (Ing et al., 1996b). TR using SAWs include applications in development for characterizing thin films and plates with microscale heterogeneity (Tournat et al., 2006).

Two different time reversal approaches can be considered – the through-transmission and the pulse-echo (Fig. 1). The through-transmission TR principle can be implemented as follows: (a) A

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scattering source or a defect emits an initial wave in the solid, and the scattered wave is transmitted into the structure and recorded by the array transducers. (b) Each transducer signal is time-reversed, and then re-emitted simultaneously. (c) The wave back-propagates into the medium and focuses on the original source position. In the pulse-echo approach, the TR focusing can be realized in the following way: (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 at the same time, (c) The wave back-propagates through the medium and focuses on the initial source location. Draeger et al., (1997) used an analytical approach to investigate the focusing quality of through-transmission TR process in a two-phase (water-solid) medium, followed by an experimental verification of their theoretical results (Draeger et al., 1998). Tsogka and Papanicolaou (2002) performed a numerical study for a through-transmission time reversal through a solid-liquid interface. The present study is extended to take into account the pulse-echo mode TR focusing and a solid-solid interface, which seems to be of more practical importance.

In this paper, we perform a numerical simulation for the analysis of TR beam focusing in a heterogeneous medium with a solid-solid interface. More specifically, a time domain finite difference method(FDM) is used to model the focusing behavior of pulse-echo mode TR process that includes a volumetric scattering source (side-drilled hole) in the second solid. We consider the case where the scatterer is located along the central axis of the array transducer. We also examine the focusing resolution that is related to the propagation distance, the size of array sensor and the wavelength.

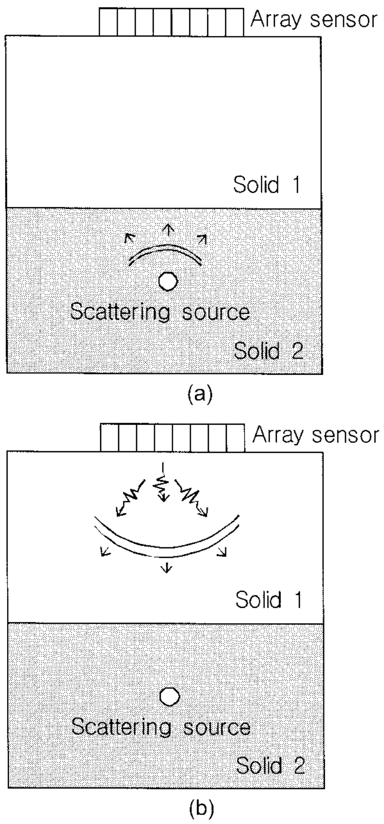


Fig. 1 Through-transmission and pulse echo time reversal principle

2. Numerical Simulation for Time Reversal Focusing

The geometry of the simulated structure is composed of two solid layers, as shown in Fig. 2. We have used absorbing boundary conditions on three faces. Consider a linear array consisting of large number of line sources arranged in the width direction. A total of 31 elements are used in this work. The center-to-center element spacing is p=2 mm. A line source of width a=1 mm, center frequency f_0=2 MHz and n=1 cycles is used to simulate an actual signal waveform in the time domain. The propagating medium is aluminum and steel. Table 1 lists the material data and the array transducer data, respectively. In this study, we assume that the geometry of the problem is invariant in the y direction, i.e. the one perpendicular to the (x, z) plane of the paper. The boundary conditions at the solid/solid interface are assumed to be an intimate contact, so that it satisfies continuity of all components of displacements and stresses.

We will use the pulse-echo mode to investigate the TR focusing on a single source placed in the second layer of the structure. As a scattering source, a side-drilled hole(SDH) is placed in the steel layer. The process which we simulate here is described as follows: The central element of the array transducer (No. 16) emits an initial wave, and the wave is partially transmitted through the interface and reflected by the scatterer. The reflected wave is recorded by the array transducer, time-reversed and re-emitted simultaneously to focus on the scattering source. Only the L-wave displacement is considered in the emission, propagation and reception.

Table 1 Material and array sensor data

Material data	Aluminum	Density	2700 kg/m^3
		Lame constant, λ	61380 MPa
		Lame constant, μ	24950 MPa
	Steel	Density	7900 kg/m^3
		Lame constant, λ	113200 kg/m^3
		Lame constant, μ	80900 kg/m^3
Array sensor data	Number of elements		31
	Element width		1 mm
	Pitch		2 mm

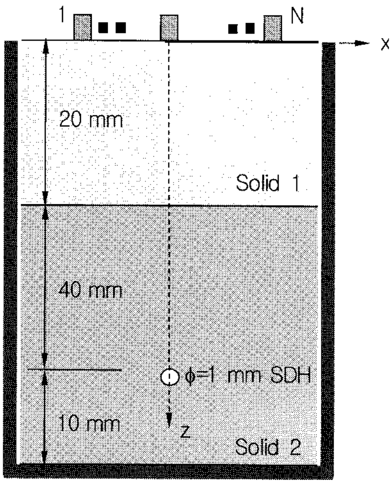


Fig. 2 Geometrical configuration of 2-D numerical simulation for the pulse-echo TR focusing: An illuminating pulse emits an initial wave, and the wave is partially transmitted and reflected by the scatterer. The reflected wave is recorded by the array transducer, time-reversed and re-emitted simultaneously to focus on the scattering source

3. Results and Discussion

Using the array transducer of 31 elements mounted on the top surface (configuration of Fig. 2), the received time domain signal typically contains several resolved echoes arising from different modes and flaw scattering. Fig. 3(a) shows the time domain signals so obtained when the 16th element fires and receives in the pulse-echo mode. Three successive echoes reflected from the interface are observed followed by the scattered wave of small amplitude from the side-drilled hole. The identity of each echo is given in the figure, where (L->L)^2 means the second bounce echo of the L-wave. When a pair of transducer is used in the pitch-catch mode, the received signals are more complicated. For example, Fig. 3(b) shows the received waveforms by the 1st element when the 16th

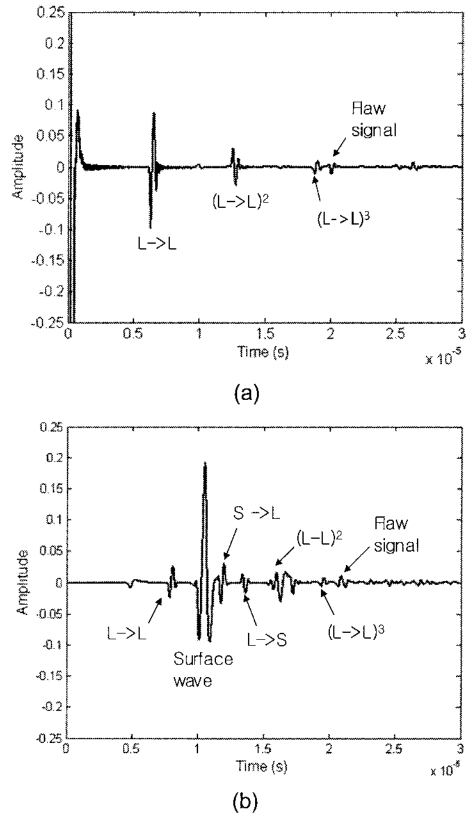
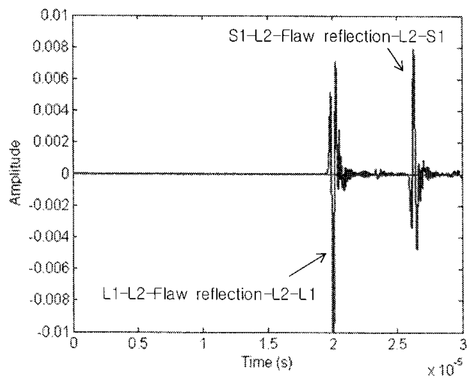


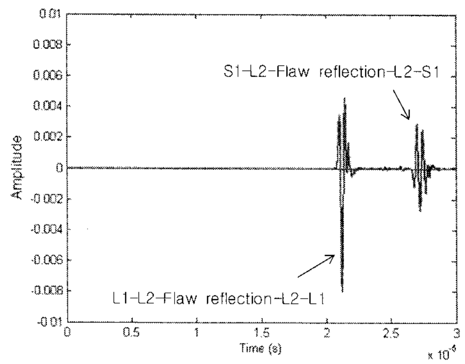
Fig. 3 Received signals: (a) 16th element firing and 16th element reception; (b) 16th element firing and 1st element reception

element fires. Surface waves and mode converted echoes at the interface (L->S, S->L and S->S) as well as the successive regular interface echoes (L->L) appear before the SDH-reflection arrives.

The focusing behavior due to time reversal is examined in two ways, and their results will be compared. First, only reflected waves from the side-drilled hole are time reversed and reemitted. These purely reflected waves are easily available by subtracting the received signals obtained with the side-drilled hole from those without the side-drilled hole The reference signal obtained without the side-drilled hole will be referred to as the baseline signal. Although this subtraction is hard to practice in real situation, it can be easily done in numerical simulation. The purpose of using the flaw-related signals only is to simplify the TR process and to better understand the TR focusing behavior. Fig. 4 shows pure SDH-reflections for two cases corresponding to Fig. 3. In Figs. 4(a) and 4(b), the first flaw signal is due to the L-wave propagations in both media, reflection from the SDH, and then L-wave propagations again in both media (L1->L2->Flaw reflection->L2->L1). On the other hand, the second flaw signal is due to the S- and L-wave propagations in both media, reflection from the SDH, and then L- and S-wave propagations again in both media (S1->L2->Flaw reflection->L2->S1). Next, the whole received signals obtained with the side-drilled hole are used in the TR process.

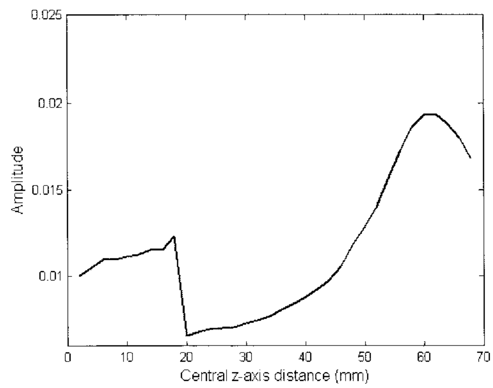


(a)

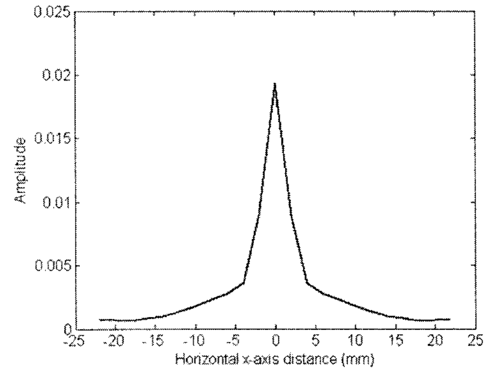


(b)

Fig. 4 Pure reflections from the SDH obtained by subtracting the received signals of reference configuration: (a) 16th element firing and 16th element reception; (b) 16th element firing and 1st element reception



(a)



(b)

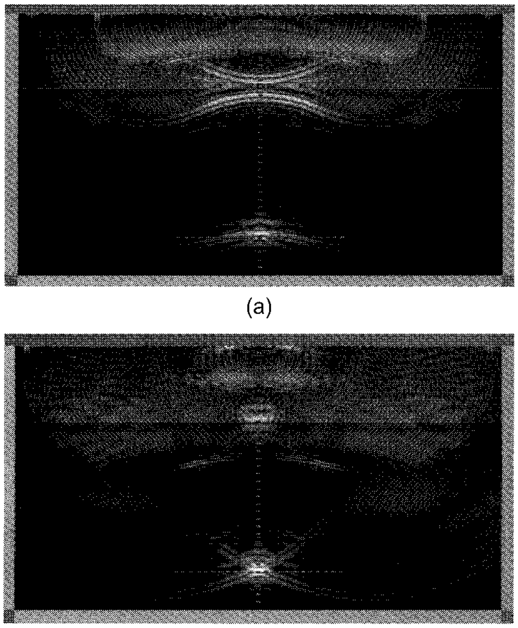
Fig. 5 Simulation results for time-reversal focusing : (a) displacement distribution along the central z-axis; (b) displacement distribution along the horizontal axis passing through the maximum amplitude of the displacement profile

The signals detected by the receiving transducers are then time reversed and rebroadcast from the same transducers. Fig. 5(a) shows the displacement distribution along the central z-axis, while Fig. 5(b) shows the displacement distribution along the horizontal axis passing through the maximum amplitude of the displacement profile. In Fig. 5(a), abrupt change of the displacement distribution near z=20 mm is mainly due to the transmission loss at the solid-solid interface. The spatial focusing due to the time reversal operation is seen to be very clear.

Fig. 6 displays the snapshots of the time reversed displacement field at two different time instants: relatively close to the source location and right on the source location. The traveling wavefield becomes tighter and brighter as the time reversed wavefront progressively moves toward the focal point. The amplitude reaches its maximum at the original source position, the leading edge of the side-drilled hole.

When the whole received signals are used in the TR process without the baseline signal subtracted, the horizontal axis distribution is compared with those of the pure SDH-reflected signals used and are shown in Fig. 7. When the pure SDH-reflected signals are used with the baseline signal subtracted, the distribution has a narrower lateral resolution with less side lobes. Because the SDH-reflected waves only are used, most of the energy radiated in the back-ropagation step retraces the paths traversed in the forward propagation. When all the received signals are used including the SDH-reflections, some of the energy goes elsewhere into the medium. This energy does not go back to the focal location, but it is present at other locations at the time of focus, diminishing focal quality.

The spatial focusing property of the TR array is important in various applications including nondestructive testing, so we need to examine the resolution limit of the TR focused signal. In a homogeneous medium it is known that the time-reversed and backpropagated signal due to a point source will focus in a region around the original focal point with spatial width (or the focal spot size) of order (Tsogka and Papanicolaou, 2002)



(a)

(b)

Fig. 6 Snapshots of time-reversed back-propagated wavefield at different time instants: (a) close to the source location; (b) focusing at the leading edge of the side-drilled hole, the original source location

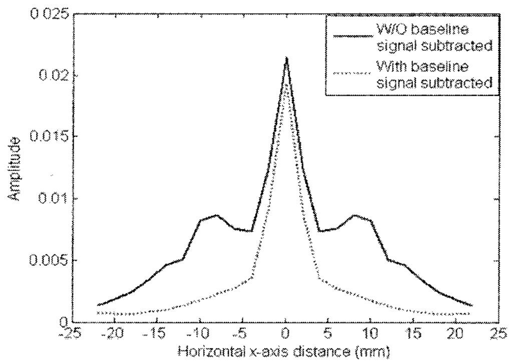


Fig. 7 Comparison of displacement distributions along the horizontal axis when the whole received signals and the pure SDH-reflected signals are respectively used in the TR process

$$d = \frac{\lambda_1 L_1 + \lambda_2 L_2}{D} \quad (1)$$

where λ_1 and λ_2 are the wavelengths in medium 1 and 2, L_1 and L_2 are the wave propagation distances in medium 1 and 2, and D is the aperture size of linear transducer array. For current simulation, λ_1=3.21, λ_2=2.95 mm, L_1=20, L_2=40 mm, and D=61 mm. The estimated focal size by eqn. (1) is 3 mm. Referring to Fig. 5(b), the measured spot sizes at 3 dB and 6 dB drops from the maximum amplitude are about 2.2 mm and 3.7 mm, respectively.

4. Conclusion

A finite difference method was used to study the time reversal beam focusing of ultrasonic transducer array on a side-drilled hole located in a two-layer structure. A pulse-echo mode of TR process was employed and the simulation results showed the spatial focusing on the original source location, the leading edge of the SDH. The estimated focal spot size was found to fall between the beam widths of 3 dB and 6 dB drops from the maximum displacement of simulated results.

Acknowledgments

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