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Time Delay Focusing of Ultrasonic Array Transducers on a Defect Using the Concept of a Time Reversal Process

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Abstract In an application of a time reversal(TR) focusing of array transducer on a defect inside the test material, we employ a new time delay focusing technique based the TR process. In order to realize this idea, a multi-channel ultrasonic system is constructed capable of applying necessary time delays to each channel. The TR-based focusing procedure first measures the backscattered signals after firing one of the array elements. A phase slope method is then used to determine the time-of-flights of the backscattered signals received by all elements of the array. These time delays are used to adjust the time of excitation of the elements for transmission focusing on the defect. In addition to the TR focusing, the classical phased array focusing is also considered for comparison. Experimental results show that the TR-based time delay focusing produces much stronger backscattered signals than the phased array focusing, demonstrating the enhanced capability of the TR focusing.

Keywords: Time Reversal, Array Transducer, Time Delay, Beam Focusing

1. Introduction

The ability of array transducers of multiple elements to focus interrogating beams inside test materials provides benefits over conventional ultrasonic technology. Beam focusing provides enhanced spatial resolution for flaw detection and sizing. Focusing can also significantly improve signal-to-noise ratio in challenging applications. Ultrasonic phased array transducers are widely used in the area of nondestructive evaluation (NDE) and in many medical applications(R/D Tech Corp, 2004). 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.

Because of these limitations and in order to improve the flexibility of the focusing process, self-focusing techniques have been proposed (Deutsch et al., 1997). Time reversal acoustics (TRA) is one of the most interesting topics in this respect(Fink, 1992; Kim et al., 2006; Choi et al., 2008). One of the fundamental features of time reversal(TR) techniques is the ability to focus the propagating ultrasonic beam on a defect position(source location) within the test material. Compared to ultrasonic phased arrays, the TR

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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. Thus, implementation of the TR focusing technique requires a programmable generator to excite the time-reversed version of the received signal for each element of transducer. In our previous paper (Jeong et al., 2008), 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 a programmable generator we devised a multi-channel ultrasonic testing system capable of inter-element firing and reception, and applying appropriate time delays to each channel as well.

In this paper, we describe an experimental approach for the time delay focusing of ultrasonic array transducers on a defect using the concept of a TR process. An eight channel ultrasonic system is constructed for inter-element firings and time delay applications. The TR focusing procedure first measures the back-scattered signals after the first emission by one of the array elements. A phase slope method is used to determine the time-of-flight differences of the backscattered signals received by the elements of the array. These time delays are used to adjust the time of excitation of the elements for transmission focusing on the defect. Experimental results are presented and compared with conventional phased array focusing method.

2. Time Delay Focusing Based on the TR Process

The time delay focusing based on the TR process is illustrated in Fig. 1. An element in central part of the array transducer is excited first (Fig. 1(a)), and the defect scatters the incident wave. In general, any element of the array

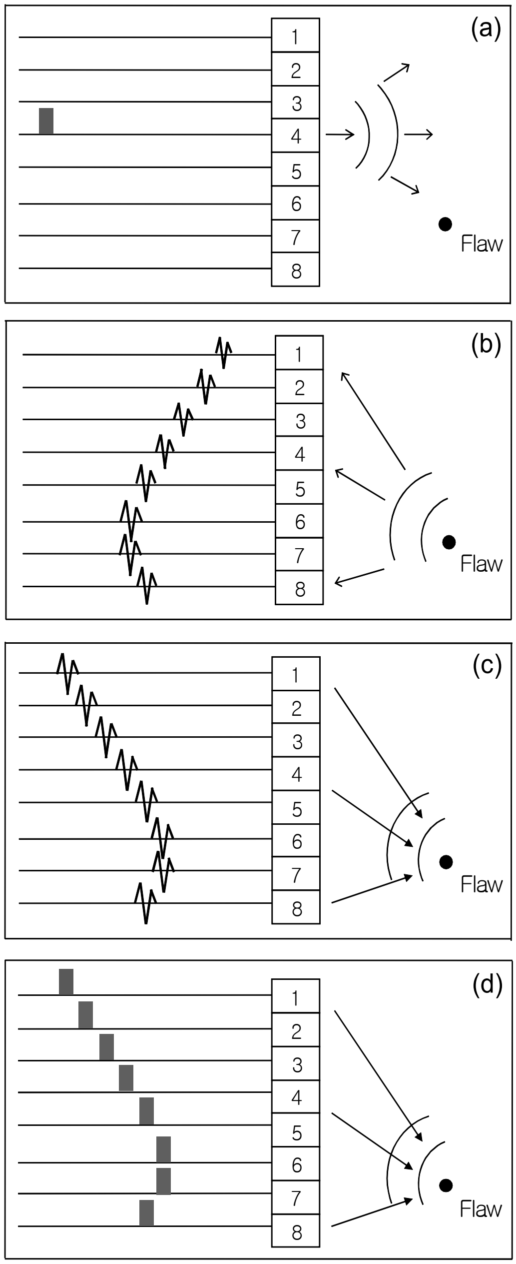

Fig. 1 Procedure of TR-based time delay focusing: (a) single element firing, (b) reception of backscattered signal by all elements, (c) time reversal and reemission for transmission focusing, and (d) excitation of pulses for each element with transmitting time delays obtained by reversing the receiving time delays

transducer could be used for this initial firing. The backscattered wave *pi*(**r**,*t*) is recorded by all transducer elements(Fig. 1(b)). For homogeneous, isotropic materials, the arrival time for each element depends on the path length between the defect and the individual element. 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 convenience, Fig.1 assumes a homogeneous case. According to Fig. 1b, the longest path traversed is by #4 firing and #1 reception, so the backscattered wave arrives last at element #1.

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(Fig. 1(c)). 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. A set of transmitting time delays is obtained by reversing the receiving time delays (Fig. 1(d)). The element #1 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 (Jang et al., 1999). 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.

3. Experiments

A schematic illustration of the 8 channel ultrasonic system with the time delay focusing capability is given in Fig. 2. An internal trigger source is employed as a master trigger that synchronizes the system. A pulse generator periodically generates the master pulse, which triggers the data acquisition and supplies the input signal for the delay electronics. The master pulse can be delayed by the delay electronics. It can generate a time delays from 0 to 1000 ns with 20 ns increment at present time. A controlling computer adjusts the delay electronics, so that the desired delay time is produced. Delayed trigger signals excite the eight pulser/receivers connected to the individual transducer element. The data from the receiver channels are acquired using a data acquisition (DAC) board in the controlling computer. It is also possible to acquire the data from a multi-channel digital oscilloscope. The data can be transferred to the computer via a GPIB(general purpose interface bus) for further processing.

Fig. 3 shows the specimen that was used in the TR focusing experiment. A side-drilled hole (SDH) of 4 mm diameter is located 20 mm from the top surface of the aluminum block. The properties of aluminum is characterized by the sound speeds c_p = 5900 m/s, c_s = 3200 m/s, and density ρ = 7900 kg/m^3. The linear array used in the ultrasonic system is a 5 MHz transducer. It consists of eight rectangular elements with sizes of 0.85 mm by 12 mm with 1 mm gap between elements. The experiments are performed in the contact, pulse-echo mode with a constant pressure applied during the entire course of measurements. For on-axis focusing, the center of the array transducer is positioned to be aligned with the line passing through the center of the SDH.

The TR focusing process is composed of two steps. In the first step of TR, one of the array elements is fired and the backscattered signals are collected with all eight elements. The time-of-flights or receiving time delays of the backscattered signals are obtained with the phase slope technique. For the second step, this set of receiving time delays are reversed and applied to each element of the linear array to achieve transmission focusing of insonified beam on the initial defect position.

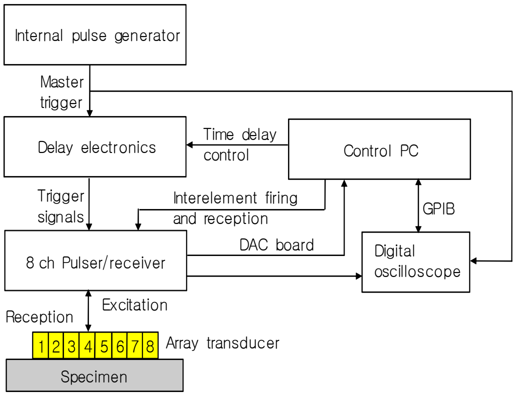

Fig. 2 Schematic of the time delay focusing system for the 8 channel linear array transducer

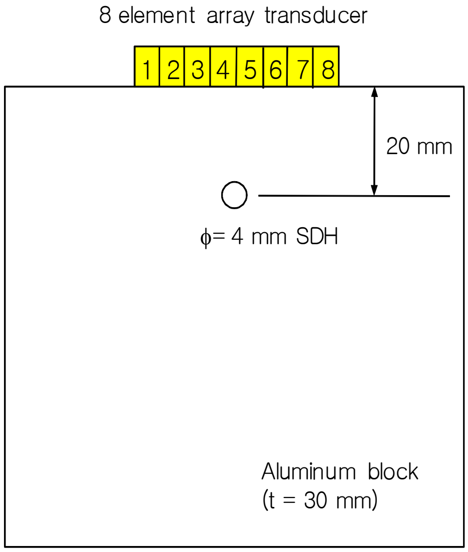

Fig. 3 Aluminum block specimen with a side-drilled hole(SDH)

4. Results and Discussion

Fig. 4 shows the backscattered signals "s11" and "s14" received by the element #1 and the element #4, respectively when the element #1 is fired. The waveform is mainly composed of the main bang, and reflections from the SDH. Only the first reflected signal from the hole is considered, and the main bang and other reflections are removed for calculations. Fig. 5 highlights these first reflections received by each transducer element. The top plot in the figure is the signal s11 from the element #1, the second plot is s12 from the element #2 and so on. Referring to Fig. 3, s11 and s18 have the longest path lengths, and they receive the signals last. On the other hand, s14 and s15 have the shortest path lengths, and they receive the signals first.

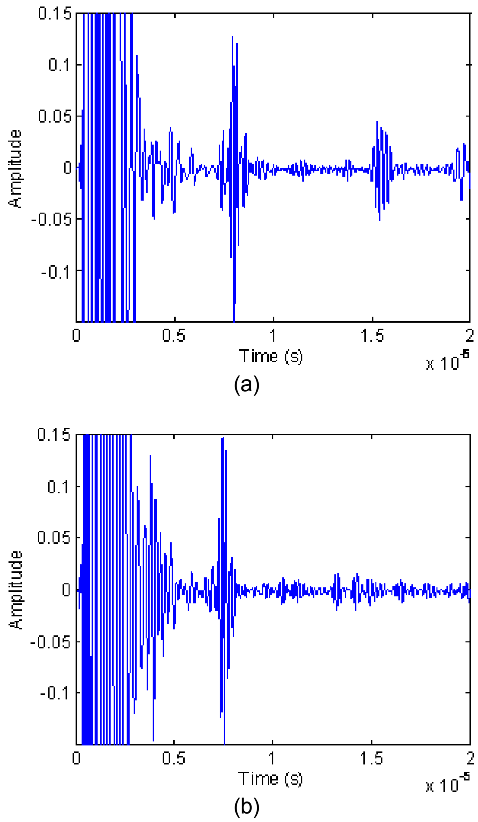

Fig. 4 Received backscattered signals: (a) s11- #1 firing and #1 reception, and (b) s14- #1 firing and #4 reception

The time-of-flight of the backscattered signal is obtained with the phase slope technique and they are used for transmission focusing. The unwrapped, continuous phase spectrum is first found for the gated SDH reflections. Fig. 6 shows these phase spectra for signals s11 and s14 from which the time-of-flights or the time delays are calculated by eqn. (1) using the phase data in the frequency range of 4 to 6 MHz.

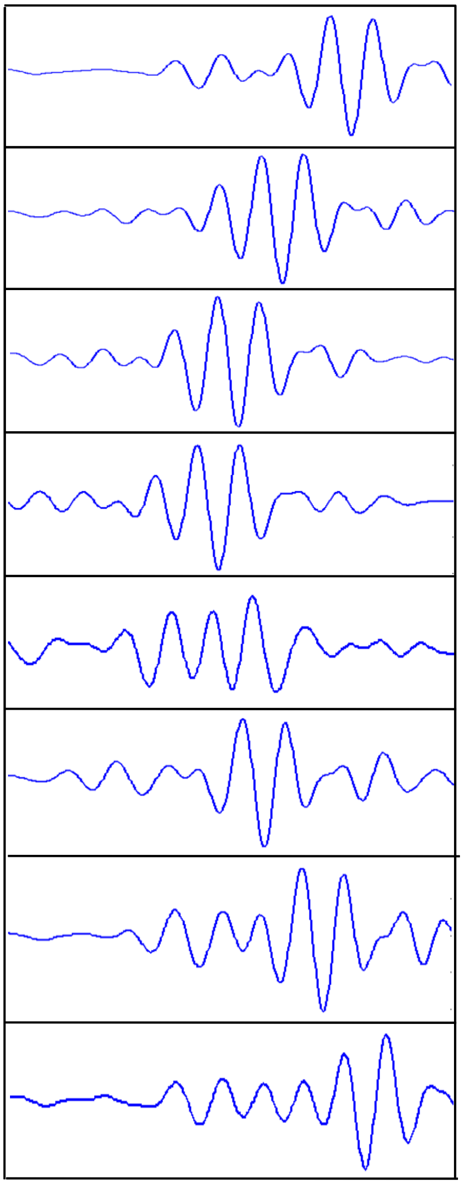

Fig. 5 First reflected signals from the side-drilled hole received by element #1 through element #8

These are the receiving time delays that correspond to the time-of-flight of received signal by the individual element. For transmission focusing, a set of time delays is obtained by reversing the receiving time delays, as shown in Fig. 7. The element #1 that received the backscattered signal last is fired first

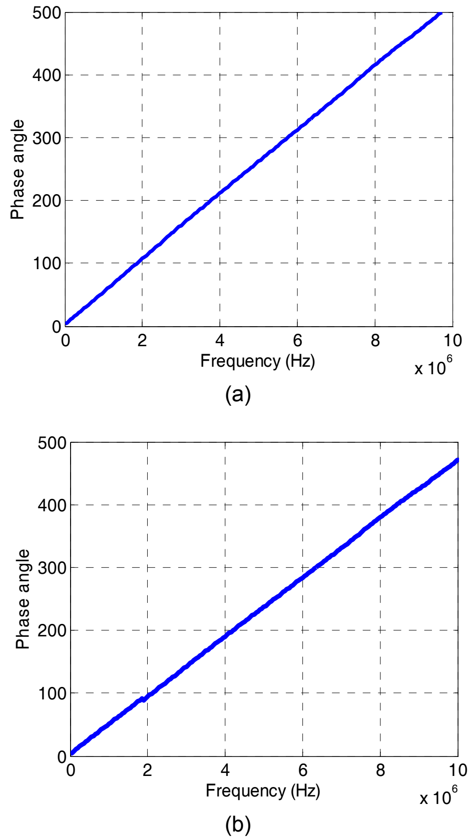

Fig. 6 Phase spectrum: (a) signal s11, and (b) signal s14

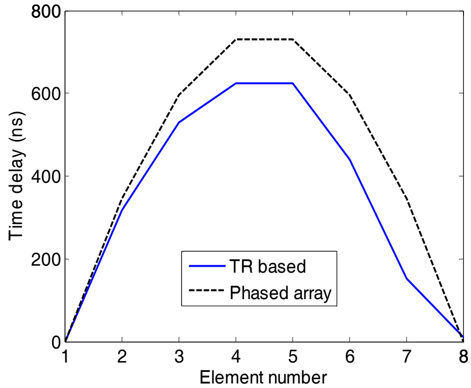

Fig. 7 Time delays for transmission focusing

with the shortest transmitting time delays. Also shown in Fig. 7 are the time delays necessary for phased array focusing. These time delays are calculated from the known geometries of the array transducer and the specimen, and the acoustic properties of the aluminum specimen (Azar et al., 2000).

A set of time delays of Fig. 7 were then applied to each element of the array transducer for transmission focusing on the initial source position(i.e., at the leading edge of the SDH). Fig. 8 shows the received signals at element #1 after transmission focusing by element #1 through #8 and reflection from the SDH, respectively. It is noticed that the signals radiated by different elements arrive synchronously in phase. Thus, they will be enhanced by each other if superposed.

The superposition of backscattered signals after transmission focusing is shown in Fig. 9 together with phased array focusing results. Compared to the phased array focusing, transmission focusing based on the TR process produces much larger amplitudes. In TR focusing, the signals that travelled actually inside the test material are used for TR process or time

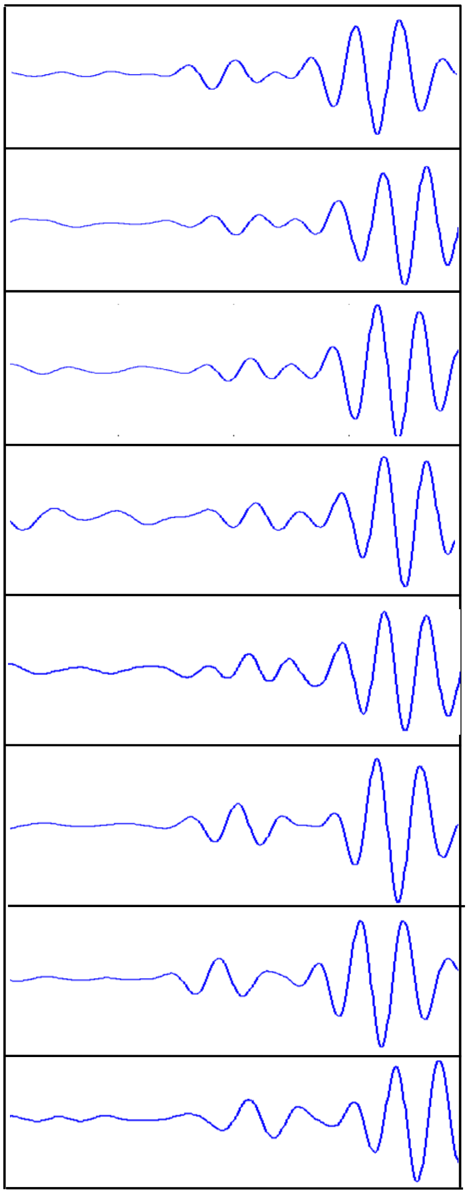

Fig. 8 Received signals at element #1 after transmission focusing by element #1 through #8 and reflection from the SDH

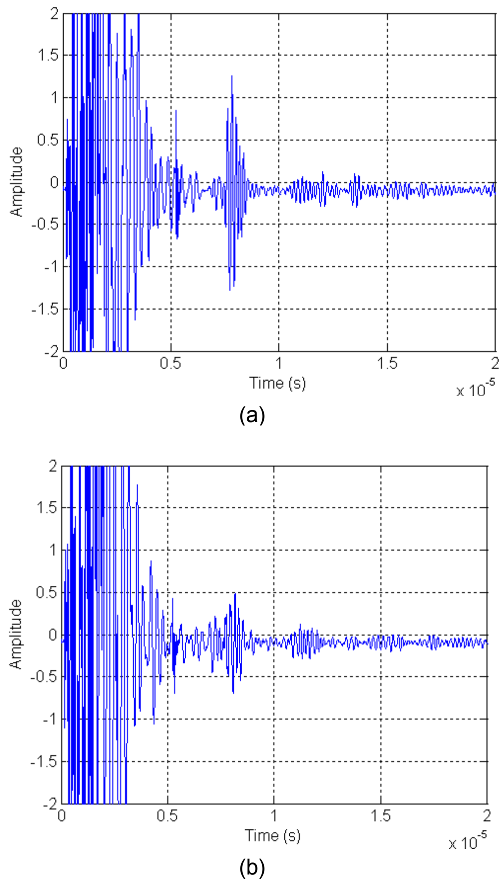

Fig. 9 Superposition of backscattered signals after transmission focusing: (a) TR focusing and (b) phased array focusing

delay calculation. Thus, TR focusing does not require a prior knowledge about the properties and structures of the media and the transducer, producing better focusing capability than the phased array technique.

5. Conclusion

We presented an experimental approach for the time delay focusing of ultrasonic array transducer on a defect using the concept of TR process. An eight channel ultrasonic system was constructed for inter-element firings/receptions, and transmission focusing with application of time delays based on the TR procedure. The TR-based time delay focusing involves measurements of backscattered signals, time-of-flight calculations by the phase-slope method, and reemission of delayed pulses. The phased array focusing was also considered, and the results were compared. The TR focusing produced significantly larger amplitude of reflected signal because it uses the actual signal for time delay calculation, not using a prior knowledge about the properties and structures of the sample and the transducer.

Acknowledgements

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References

Azar, L., Shi, Y. And Wooh, S. C. (2000) Beam Focusing Behavior of Linear Phased Arrays, *NDT&E International*, Vol. 33, pp. 189–198

Choi, B. K., Kim, B.-C., Sutin, A. and Sarvazyan, A. (2008) Ultrasonic Focused Waveform Generation Using Time Reversal Acoustic Focusing System, *Journal of Mechanical Science and Technology*, Vol. 22, pp. 699~707

Deutsch, W. A. K., Cheng , A. and Achenbach, J. D. (1997) Self-Focusing of Rayleigh and Lamb Waves with a Linear-Phased Array, *Research in Nondestructive Evaluation*, Vol. 9, pp. 81-95

Fink, M. (1992), Time Reversal of Ultrasonic Fields. I. Basic Principles, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, Vol. 39, pp. 555-566

Jang, Y.-S., Kim, J.-H., Jeong, H. and Nam, Y.-H. (1999) Measurements of Ultrasonic Velocity and Attenuation by Signal Processing Technique in Time and Frequency Domains, *Journal of The Korean Society for Nondestructive Testing*, Vol. 19, pp. 118-128

Jeong, H., Lee, J.-S., Jeong, Y.-H. and Bae, S.-M. (2008) On the Beam Focusing Behavior of Time Reversed Ultrasonic Arrays Using a Multi-Gaussian Beam Model, *Journal of The Korean Society for Nondestructive Testing*, Vol. 28, pp. 531-537

Kim, H.-J., Song, S.-J., Thompson, R. B. and Kim, J.-H. (2006) Use of Time Reversal Techniques for Focusing of Ultrasonic Array Transducer Beams, *Journal of The Korean Society for Nondestructive Testing*, Vol. 26, pp. 190-197

R/D Tech Corp. (2004), Introduction to Phased Array Ultrasonic Technology Applications, *R/D Tech Inc.*