Ultrasonic focusing and scanning with multiple waves*

Zhang Bi-Xing(张碧星)[a)†], Liu Dong-Dong(刘冬冬)[a)], Shi Fang-Fang(师芳芳)[a)], and Hefeng Dong[b)]

[a)] *State Key Laboratory of Acoustics, Institute of Acoustics, Chinese Academy of Sciences, Beijing* 100190, *China*

[b)] *Department of Electronics and Telecommunications, Norwegian University of Science and Technology, NO*-7491, *Trondheim, Norway*

(Received 13 June 2012; revised manuscript received 15 July 2012)

This paper presents a new focusing and scanning method which focuses multiple waves on a target. The key of the method is to control excitation pulses for each element of the transducer array. The excitation pulse on each array element is obtained by time reversing the signal received by the same element, which is generated by an imaginary source at the target. The excitation pulses from all array elements are transmitted and arrive at the target simultaneously, and focusing is achieved. The performance of the two methods is compared in numerical examples, and it is demonstrated that the proposed method achieves a satisfactory focusing and a good signal-to-noise ratio no matter where the target location is.

Keywords: ultrasonic focusing and scanning, multiple waves, transducer array

PACS: 43.20.+g, 43.35.+d, 43.60.+d **DOI:** 10.1088/1674-1056/22/1/014302

1. Introduction

Propagation of the ultrasonic wave in media is very complicated.[1–3] Ultrasonic focusing and imaging have been become an important research topic. The acoustical time reversal and the ultrasonic phased array have been studied and applied in many fields as the effective focusing methods.

Time reversal is extended from the phase conjugation method of a monochromatic continuous wave in an optical field. Self-adaptive focusing can be achieved by using the time reversal technique without knowing the acoustic parameters of a medium, the transducer configuration, and other prior knowledge. Due to this characteristic, the time reversal method has been widely used in many fields, such as ultrasonic testing.[4–9]

The principle of ultrasonic time reversal focusing is to use a transducer array to receive an acoustic signal from a sound source or scattering from a scatter, which is then reversed and re-transmitted. This re-transmitted signal will be focused self-adaptively on the location of the source or the scatter. Self-adaptive focusing can be achieved by using the time-reversal technique in a medium without knowing the acoustic parameters of the medium, and it can also be achieved by using time-reversed waves generated from a source or scattered by a scatter. These two features of time-reversal focusing can well compensate for the shortages of the ultrasonic phased array technique which can only focus one type of waves.

The ultrasonic phased array utilizes an electronic technique to control the time delay, the pulse length, and the amplitude of the transmitted signal on each array element. Therefore the shape and the orientation of the focused acoustic beam can be controlled by electronic techniques.[10–15] Currently, the ultrasonic phased array method can only focus on one type of wave with a time delay calculated for this kind of wave on each array element for transmission and reception. However, this method encounters difficulties in the situation where compressional (P) and shear (S) waves and a variety of guided waves with different propagation velocities exist in a complex medium. The phased array can obtain good focusing in one direction for one type of wave, for instance, the S-wave by controlling the time delay based on the S-wave velocity, while in another direction, focusing will not be achieved using the same time delay. That is to say, the phased array method cannot give a good focus in the whole detected region when more than one types of wave exists in the detecting region.

In this paper, a new ultrasonic focusing and scanning method for focusing multiple waves is proposed. The new method utilizes time reversal self-adaptive focusing for multiple waves and compensates the shortage of the ultrasonic phased array scanning. The performance of the new method is compared with that of the ultrasonic phased array method by numerical examples in which different configurations of a transducer array and a target location are considered. The reminder of this paper is organized as follows. Section 2 introduces the new method. Section 3 presents the numerical examples, and Section 4 summarizes and discusses the work.

2. Ultrasonic focusing and scanning with the time reversal technique

Consider an elastic solid half-space with a free surface. A transducer array of N elements is placed on the free surface. Each element of the transducer array transmits an acoustic sig-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11174322 and 11074273) and the Research Council of Norway (Grant No. 186923/I30).

†Corresponding author. E-mail: zhbx@hit.edu.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

nal induced by an electric excitation and receives the reflected signal or scattering from targets. For convenience, we consider the half-space to be a two-dimensional medium and use the Cartesian coordinates (x, z), where the x axis is along the free surface and the z axis points to the medium interior. The origin of the coordinate system is at the centre of the transducer array (Fig. 1).

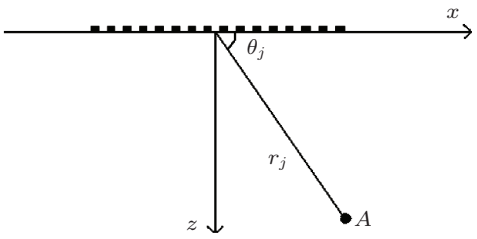


Fig. 1. Configuration of ultrasonic scanning using the time reversal method, where an N-element transducer array is placed on the free surface and the center of the transducer coincides with the origin of the coordinates. Target A is located at (r_j, θ_j).

The phased array uses an ultrasonic focusing and scanning method, and it generates a focused acoustic beam whose direction and shape can be controlled by time delays of the excitation signals on elements of the transducer array. By changing the time delays, the focused acoustic beam moves gradually and scans the whole detecting area. However, the phased array method can only focus and scan one type of wave. In an elastic medium, multiple types of waves with different propagation velocities usually exist. The phased array method cannot achieve focusing for all types of waves in the whole detecting area. For this reason, the time reversal method, a self-adaptive focusing method that focuses on all types of waves on a focal point, is considered and used for focusing and scanning by controlling the electric excitation signals (instead of time delays) on the array elements. The key of this method is to design an excitation signal on each array element so as to form an acoustic beam which focuses multiple types of waves on the focal point, and by moving the focal point gradually, the whole detecting area is scanned.

According to the above idea of multiplewave focusing and scanning we present a method for calculating the excitation signals to realize ultrasonic focusing and scanning with multiple waves by time reversal in the following steps.

(i) Assume a point source at point A (a target, see Fig. 1). It is straightforward to calculate the received signal on each array element with known acoustic parameters of the medium when the source transmits an acoustic pulse. Assume that the z- (or x-) component of the particle displacement received by the j-th array element is $U_j(t)$.

(ii) Reverse the received signal $U_j(t)$ to get $U_j(T-t)$, where T is the time duration of the received signal. It can be concluded according to the principle of time reversal that the acoustic beam will focus self-adaptively on the target, A, when the time reversed signal $U_j(T-t)$ is transmitted from the element. Therefore, the acoustic beams from all array elements will focus on target A for all kinds of waves when signal $U_j(T-t)$ is designed as the excitation signal for the corresponding array element.

(iii) Change the target position of A and repeat steps (i) and (ii).

The whole detecting area will be scanned and the acoustic field is always focused on target A self-adaptively no matter what position A is in. Scanning with the focused beam is realized for all types of waves. In steps (i) and (ii), an imaginary source at the target location is only a tool. The purpose is to get an excitation pulse on each array element. The excitation signal will make all types of waves focused on target A simultaneously.

3. Numerical simulation and analysis

The time reversal focusing method present above is compared with the phased array method by using numerical examples. In the simulation, the configuration of Fig. 1 is used, and the elastic medium is chosen to be steel in which the P- and S-wave velocities are 6000 m/s and 3000 m/s, respectively. For simplification, the effect of surface waves is ignored and only focusing effects of the P- and S-wave fields are analyzed. The ray approximation method[16] is used for calculating the P and S wave fields in the medium. The transducer consists of 16 elements with 1.7 mm spacing, and the width of each element is 1.32 mm. The center of the transducer array coincides with the coordinate origin. Each element of the transducer array vibrates along the z direction and radiates an acoustical field under the electric excitation.

For phased array focusing by P-wave (or S-wave) time delay, a cosine envelope is chosen to excite each element. The cosine envelope can be represented as

$$f(t) = \begin{cases} \frac{1}{2}\left[1+\cos\frac{2\pi}{T}\left(t-\frac{T}{2}\right)\right]\cos 2\pi f_0\left(t-\frac{T}{2}\right), & 0 \le t \le T, \\ 0, & t \le 0, t \ge T, \end{cases} \tag{1}$$

where t is the time variable, f_0 is the central frequency, and T is the pulse length.

For multiple-wave focusing, the excited pulses of the array elements are obtained by assuming a point source on the target. In the numerical simulation, we suppose that the point source vibrates along the z direction and transmits a cosine envelope with $T = 10/f_0$ and $f_0 = 3.5$ MHz. The waveforms at the array elements are calculated using the ray approximation method.[13] First we assume that the z component of the displacement on the j-th array element is $U_j(t)$. Then, we reverse signal $U_j(t)$ to get $U_j(T-t)$ which is the excitation pulse on the j-th array element for multiple-wave focusing. In the numerical simulation, $U_j(T-t)$ is always normalized so that the maximum of the excitation signal on each element is the same.

To analyze the characteristics for only P-wave or S-wave focusing, and for both P-wave and S-wave focusing, we calculate the z-component (u_z) of the displacement at three target locations by the phased array method for the P-wave or S-wave field and by the proposed focusing method for both the P-wave and S-wave fields.

Figure 2 shows $u_z(t)$ at the target location (0.1 m, 0.01 m). The focused wave field is achieved by giving a time delay to each array element. The time delay is calculated with the P-wave (Fig. 2(a)) or S-wave (Fig. 2(b)) velocity based on the phased array method. Figure 2(a) indicates that the amplitude of the P-wave is very small, although the P-waves superpose in phase at the target location. The amplitude of the S-wave is relatively large compared with that of the P-wave. The reason for this is that the angle between the target location and the horizontal axis $\theta = \mathrm{tg}^{-1}(0.1)$ is very small and the transmitted signal from the transducer array has a much smaller component in the P-wave direction than that in the direction perpendicular to the P-wave direction, which contributes to the S-wave. The amplitude of the P-wave in Fig. 2(b) is almost invisible due to both the small projection of the transmitted signal and the out-of-phase superposition. The amplitude of the S-wave is large, which results from both the large projection of the transmitted signal contributing to the S-wave and the in-phase superposition. It shows that the focusing results are not good with the phased array method by the superposition of the signals from all of the transducer elements with the time delays calculated with the P-wave velocity when the angle θ is very small.

Figure 3(a) displays the excitation signals of transducer elements for the same target location (0.1 m, 0.01 m) when both the P-wave and S-wave are used for focusing. For convenience, the transducer elements are numbered 1, 2, ..., 16 from left to right in Fig. 1, and the waveforms from top to bottom in Fig. 3(a) correspond to the excitation signals of array elements 1, 2, ..., 16, respectively. The excitation signals of the transducer elements are obtained by the time reversed waveform generated by an imaginary point source vibrating in z-direction at the target location. Figure 3(b) displays the received wavefield at the target when all array elements transmit the excitation signals given in Fig. 3(a). It is clearly shown in Fig. 3(b) that both the P-wave and the S-wave arrive at the target simultaneously and superpose coherently so that a large peak is obtained. Compared with that in the phased array method, the excitation signal on each element (instead of the time delay) is controlled for the target. The focused wave field in Fig. 3(b) indicates that both the P-wave and the S-wave are focused with a narrow beam at the target location simultaneously. Good focusing is achieved.

Figure 4 presents the results when the target location is at (0.01 m, 0.1 m). In this case the angle between the target location and the horizontal axis $\theta = \mathrm{tg}^{-1}(10)$ is very large and the transmitted signal from each element has a larger projection to the P-wave and a very small projection contributing to the S-wave. Figure 4(a) shows that the amplitude of the P-wave is very large due to the large projection and the in-phase superposition, while the S-wave is invisible due to the small projection and the out-of-phase superposition. Figure 4(b) indicates that the amplitude of the P-wave is much larger than that of the S-wave even though S-waves superpose in phase. It is indicated that the focusing results are not good with the phased array method by superposition of the signals from all the transducer elements with time delays calculated based on the S-wave velocity when the angle θ is very large.

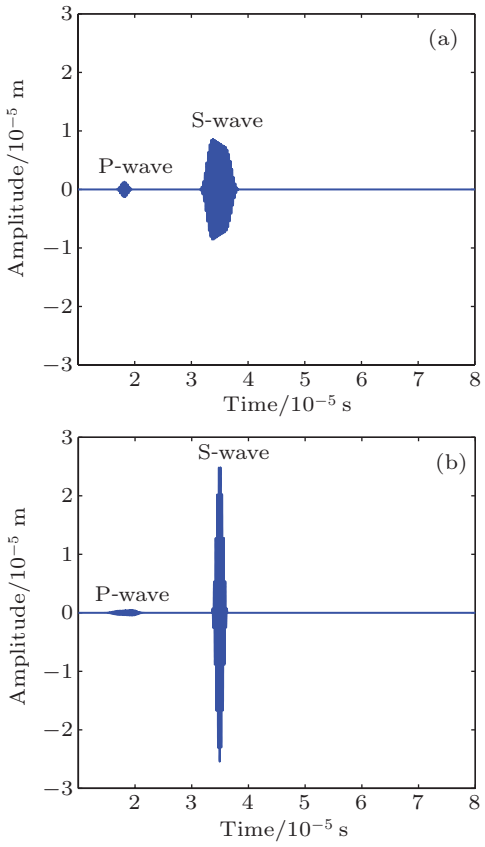


Fig. 2. (color online) Waveform of the vertical component of the displacement $u_z(t)$ at target location (0.1 m, 0.01 m) in the phased array method with the time delay calculated based on (a) the P-wave velocity or (b) the S-wave velocity.

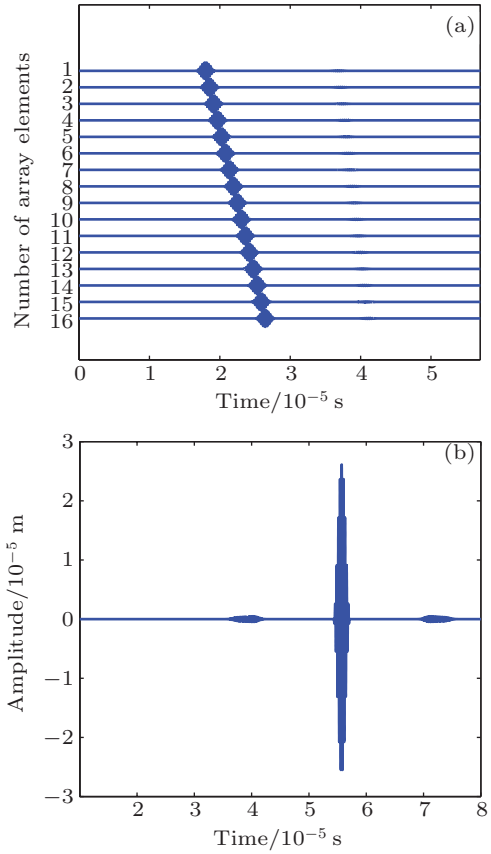


Fig. 3. (color online) (a) Excitation signals of the transducer elements and (b) waveform at the target location of (0.1 m, 0.01 m) when both the P-wave and The S-wave are used for focusing.

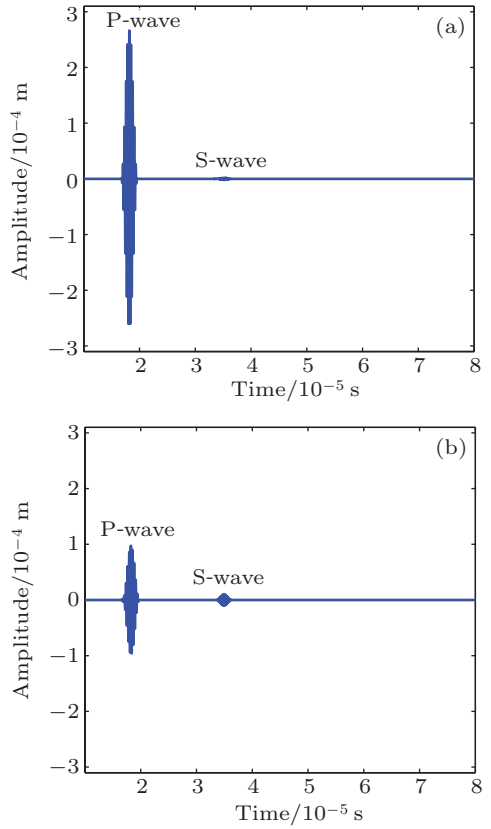


Fig. 4. (color online) Waveform of the vertical component of the displacement $u_z(t)$ at target location (0.01 m, 0.1 m) in the phased array method with a time delay calculated based on (a) the P-wave velocity or (b) the S-wave velocity.

Figure 5(a) displays the excitation signals of the transducer elements for the target location of (0.01 m, 0.1 m) when both the P-wave and S-wave are used for focusing. Figure 5(b) shows the focused wave field at the target location. The result is the same as that shown in Fig. 3(b). It shows that both the P-wave and the S-wave arrive at the target simultaneously. Good focusing with multiple waves is achieved.

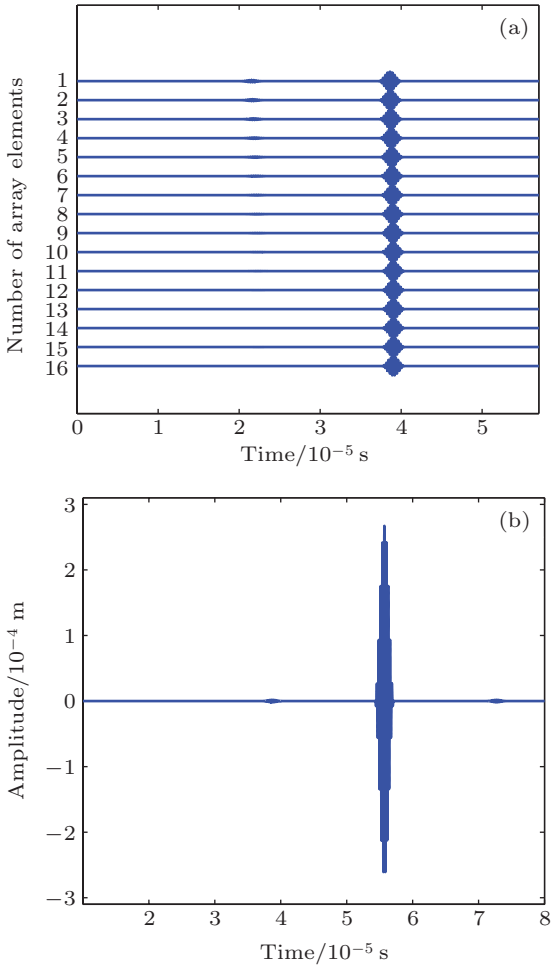


Fig. 5. (color online) (a) Excitation signals of the transducer elements and (b) waveform at the target location of (0.01 m, 0.1 m) when both the P-wave and the S-wave are used for focusing.

Figure 6 presents the results when the target location is at (0.09 m, 0.045 m). The angle between the target location and the horizontal axis $\theta = \mathrm{tg}^{-1}(0.5)$ is moderate and the projections of the transmitted signals from the transducer elements to the P-wave and the S-wave are not so different. However, it can be seen in Fig. 6(a) that the amplitude of the P-wave is much larger than that of the S-wave when using the time delay based on the P-wave velocity, while the amplitude of the S-wave is much larger than that of the P-wave when using the time delay based on the S-wave velocity, as shown in Fig. 6(b).

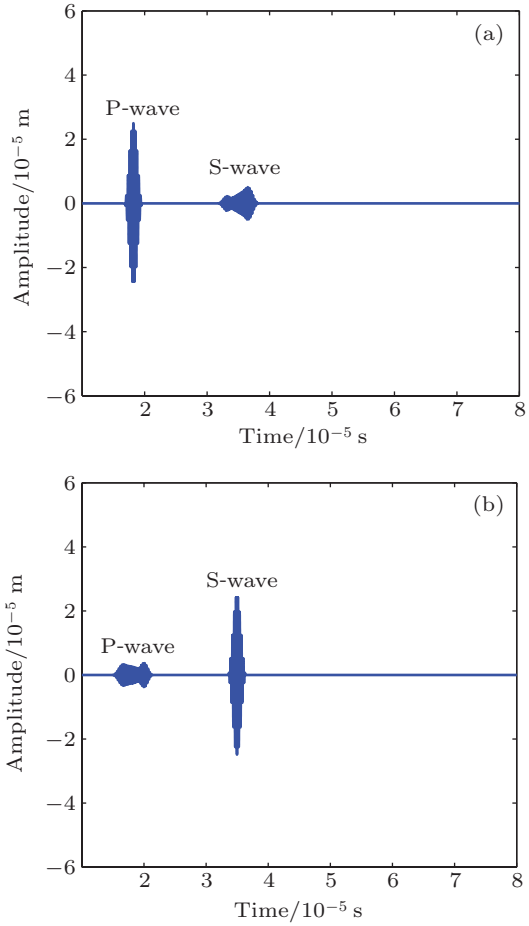


Fig. 6. (color online) Waveform of the vertical component of the displacement $u_z(t)$ at target location (0.09 m, 0.045 m) in the phased array method with time delay calculated based on (a) the P-wave velocity or (b) the S-wave velocity.

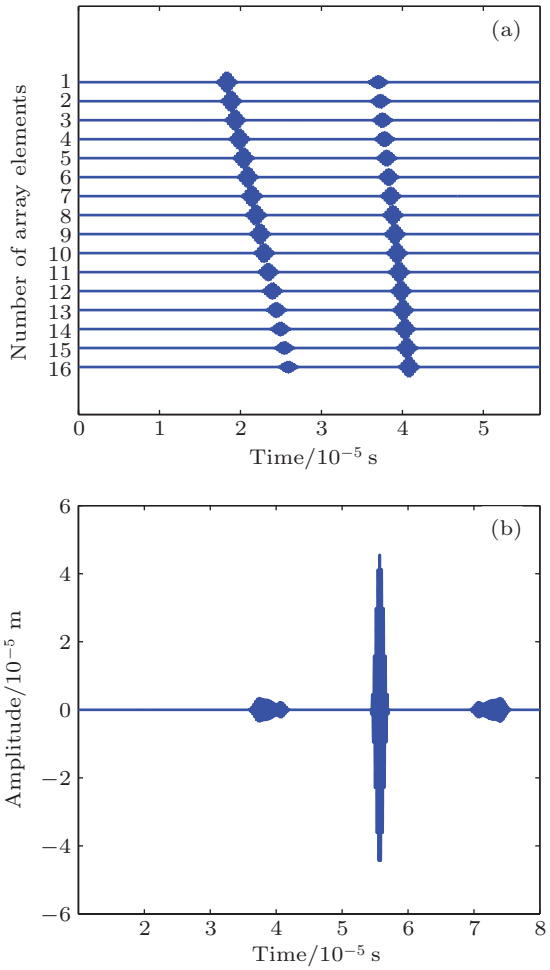


Fig. 7. (color online) (a) Excitation signals of the transducer elements and (b) waveform at the target location of (0.09 m, 0.045 m) when both the P-wave and the S-wave are used for focusing.

Figure 7 illustrates the same results as those shown in Figs. 3 and 5. For this target location, the amplitudes of the P-wave and the S-wave are comparable and therefore the excitation signals contain two pulses (Fig. 7(a)). The S-wave excited by the first pulse and the P-wave excited by the second pulse arrive at the target simultaneously to form the coherent superposition (Fig. 7(b)). Good focusing with a narrow beam and minor side-lobes is achieved.

The analysis of the three examples in which the target is located at three different directions indicates that multiple-wave focusing has two advantages. Firstly, it focuses the multi-wave energies on the target simultaneously and the signal-to-noise ratio is much improved compared with that in the phased array method; secondly, phase array focusing is based on the time delay for one particular type of wave and therefore the scanning range is relatively narrow. For instance, focusing with the time delay based on the P-wave velocity is only suitable for the region with small reflection angles of the acoustic beam, while focusing with the time delay based on the S-wave velocity is only suitable for the region with large reflection angles of the acoustic beam. However, the proposed method in this paper can give a very good focus no matter where the target location is.

4. Discussion and conclusion

The ultrasonic phased array method can only achieve focusing for a single type of wave and encounters difficulties when there are multiple types of waves in a medium. A new focusing and scanning method which can focus multiple types of waves is proposed. This method utilizes self-adaptive focusing characteristics of time reversal and makes all types of waves arrive at the target location simultaneously and focus on the target. The method also compensates for the shortcomings of ultrasonic phased array scanning which can only focus on a single type of wave. The proposed method also extends the scanning range of the focused beam.

Ultrasonic phase array focusing and scanning is realized by controlling the time delay of the transmitting pulse on each array element, while the proposed method obtains focusing and scanning by controlling the transmitted excitation pulse on transducer array elements. This method achieves focusing for multiple waves and the focusing effect is better than that of the phased array method although controlling the transmitted excitation pulse is more difficult than controlling the time delay. But in practice it is not difficult to control the transmit-

ted excitation pulse using the D/A transmitting technique. By using the FPGA and DSP chips and computer techniques, the time for calculating and transmitting the excitation pulses of the transducer array is very short. Multiple-wave focusing and scanning can achieve fast processing and real time application.

References

[1] Zhu X F, Zhou L, Zhang D and Gong X F 2005 *Chin. Phys.* **14** 1594

[2] Cui Z W, Liu J X, Yao G J and Wang K X 2010 *Chin. Phys.* B **19** 084301

[3] Cui Z W, Wang K X, Hu H S and Sun J G 2007 *Chin. Phys.* **16** 746

[4] Fink M 1992 *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* **39** 555

[5] Ing R K and Fink M 1998 *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* **45** 1032

[6] Wang C H, Rose J T and Chang F K 2004 *Smart Mater. Struct.* **13** 415

[7] Norville P D and Scott W R 2007 *J. Acoust. Soc. Am.* **122** EL95

[8] Zhang B X, Wang C H and Lu M H 2003 *Acoustical Physics* **49** 688

[9] Lu M H, Zhang B X and Wang C H 2004 *Chin. Phys. Lett.* **21** 1766

[10] Clay A C, Wooh S C, Azar L and Wang J Y 1999 *Journal of Nondestructive Evaluation* **18** 59

[11] Stepinski T 1998 *J. Nondestructive Testing* **3** 1998

[12] Chatillon S, Cattiaux G, Serre M and Roy O 2000 *Ultrasonics* **38** 131

[13] Song S J, Shin H J and Jang Y H 2002 *Nuclear Engineering and Design* **214** 151

[14] Deng F Q and Zhang B X 2006 *Chin. Phys. Lett.* **23** 3297

[15] Zhang B X, Shi F F, Wu X M and Gong J J 2010 *Chin. Phys. Lett.* **27** 094301

[16] Brekhovskikh L M 1980 *Waves in Layered Media* (New York: Academic Press)