1999년도 한국음향학회 학술발표대회 논문집 제18권 제1(s)호

파형 변환된 레이리파를 이용한 초음파영상복원

Ultrasonic Image Reconstruction using Mode-Converted Rayleigh Wave

Dong-Man Suh*

*Dept. of Electric, Kunjang College

ABSTRACT

In this paper, ultrasonic tomography by the Mode-Converted Rayleigh wave (MCRW) in the back-scattered direction is presented. When a beam with a short pulse and narrow beam width enters a reflector with smooth surface, in general, two major arrivals can be observed in the output waveform: the specular reflection and the radiation of the MCRW from the reflector surface. The time-delay between the two waves is relatively large and thus can be measured easily. This large time-delay is due to the fact that the MCRW is slower than incident wave. In our method, this large time-delay is used for ultrasonic image reconstruction. To effectively detect the MCRW, the arrayed-receiving transducers are circularly arranged around the transmitter. In addition, a deconvolution method is employed to remove specular echo signals for reconstructing the MCRW image.

I. Introduction

The size, shape, and orientation of a crack in materials are important for the failure prediction in nondestructive evaluation (NDE). However, it is still a difficult problem to determine the size and nature of flaws. Recently, a small crack detection and sizing technique using Mode-Converted Rayleigh wave (MCRW) was proposed [1,2,3]. By the technique, it is possible to detect a crack as small as 1-2 mm. In this paper, it is shown that the MCRW can be successfully used for ultrasonic imaging. In conventional ultrasonic imaging methods, the specular reflections are usually used for image reconstruction. However, these techniques are not efficient in some cases due to multiple specular reflections, and Mode-Converted acoustic wave [4].

In our method, the MCRW is used for ultrasonic image reconstruction, and the specular reflection is only used for range reference in the image. To effectively detect the MCRW, the small aperture transducers are used and the transducers are circularly arranged around the transmitter. In addition, deconvolution method [5] is used to remove the specular reflections from a crack.

Section II describes crack sizing method using Rayleigh wave. Image reconstruction using Mode-Converted Rayleigh wave technique is proposed in section III. Deconvolution technique for removing the specular reflections is described in section IV.

II. Crack Sizing by Rayleigh Wave

Fig. 1(a) schematically shows Rayleigh wave method for crack sizing. It is assumed that the distance of the transducer to the crack is large compared with the height (or diameter) of the flat bottom hole, and that the beam width of transducer is narrow. Also, the incident beam is assumed to be perpendicular to the crack surface. Then, the signals received at the transducer P1 are: the specular reflection and the trailing Rayleigh wave signals (refer to Fig. 1(b)). The pulse-echo signals will be dominated by a specular reflection from the center of a crack face. In Fig. 1(b), the Rayleigh wave signals are very small compared with the specular reflection signals and, in many cases, they cannot be distinguished.

Fig. 1(c) shows the signal received at the transducer 2 (or, transducer 3). The first echo is specular reflection. The second echo is Rayleigh wave which travels from the opposite end of the crack along the surface and turns 90 degrees to the transducer. (It is assumed that the beam width s narrower than the crack diameter.)

By comparing Fig. 1(b) and Fig. 1(c), it is clear that the transducers need to be arranged appropriately to separate the Rayleigh wave signal from the specular echo signals. In this paper, the transducers are arranged as shown in Fig. 1(d) where P1 is the transmitter $P2 \sim P_N$ are receivers. In Fig. 1(c), Δt is defined as the delay time between the specular signal and the Rayleigh wave signal. it can be shown that Δt is given by

$$\Delta t = h / 2V_R \qquad (1)$$

where V_R = Rayleigh wave velocity (2900 m/sec in steel, approximately 92% of transverse wave velocity), h = crack face diameter (height).

To verify the theory, a carbon steel test specimen with a flat bottom hole (FBH) was fabricated and measurements were carried out using Panametrics Model 5601A Pulser/Receiver and Lecroy 9310 digital oscilloscope. Fig. 2(a) shows the A-scan display of the signals by pulse/echo from flat bottom hole (diameter 2 mm: Trienco Inc. 4340-5-0025 steel block) with the 10MHz transducer. As can be seen from Fig. 2(a), it is difficult to differentiate the Rayleigh wave from the specular reflection wave. Fig. 2(b) shows A-scan display of the signals by pitch/catch method with the 10MHz transducers. The signals reflected from the FBH are the specular reflections and the trailing Rayleigh wave signals. Also, another experimental signals by pitch/catch method from FBH (diameter 2 mm: Trienco Inc. 4340-5-0038 steel block) by 10MHz transducers is shown in Fig. 3. As can be seen from Fig. 2(b) and Fig. 3, the Rayleigh wave can be easily differentiated from the specular reflection wave if the signal is collected by pitch/catch method.

III. Ultrasonic Imaging by Mode-Converted Rayleigh Wave

Using the results from section 2, ultrasonic imaging method by MCRW is proposed as follows:

1. The highest specular echo from the center of reflector surface is arranged at the image center.

2. Each Rayleigh wave from the circularly arrayed-receivers is perpendicularly arranged to the image center (MCRW is orthogonal to the axial beam direction).

To show the validity of the proposed method, test specimens whit flat-bottom holes are test with 5MHz and 10MHz array transducers. To obtain the MCRW image, transducers are arranged circularly as shown in Fig. 1(d). Fig. 4 is the MCRW image by the pitch/catch signals from FBH, In this Figure In this image, the strongest specular echo is arranged at the center of the image and the Rayleigh wave signals are arranged circularly by 10 degrees angle increment. In his figure, the region of interest is 2 mm wide. Next section significantly by using deconvolution technique.

IV. Image Reconstruction by Deconvolution

To obtain a good MCRW image, it is important to minimize the effect of specular echo on MCRW. In this section, it is shown that deconvolution technique can be used to suppress the effect of specular echo on MCRW. Given a reference signal $a(n)$, we want to find the mathematical operator $f(n)$ that will transfer $a(n)$ into a desired waveform $d(n)$ by the convolution of $a(n)$ with $f(n)$, i.e.,

$$d(n)=a(n)*f(n), \qquad (2)$$

where (*) means the convolution operation. However, the finite length of $f(n)$ will introduce errors and consequently the waveform computed by the convolution of $a(n)$ with the finite-length $f(n)$ is not equal to the desired waveform $d(n)$. The optimum operator $f(n)$ with the length of m+1 can be obtained by solving the following equation

$$\sum_{s=0}^{m} f(s) r_{j-s} = g_j \quad j=0,1,\cdots m, \qquad (3)$$

where

$$\begin{aligned} r_{j-s} &= \sum_{n=0}^{m+N} a(n-s)a(n-j), \\ g_j &= \sum_{n=0}^{m+N} d(n)a(n-j). \end{aligned} \qquad (4)$$

Notice that r_{j-s} is the autocorrelation of $a(n)$ and g_j is the correlation of $d(n)$ with $a(n)$. The minimized error will then be

$$E_{min} = \sum_{n=0}^{\infty} d(n)^2 - \sum_{n=0}^{\infty} f(n)g(n). \qquad (5)$$

In our method, specular reflection signal by the pulser/echo method (e.g., the signal in Fig. 2(a)) is used as reference signal. Also, zero is chosen to be the desired signal. (Obviously, the operator $f(n)$ should be nonzero.) By applying the operator to the signal in Fig. 2(b), the restored signal is obtained as shown in Fig. 5. From Fig. 5, 2 and 3-dimensinal FBH image by MCRW image method are obtained as shown in Fig. 6. The measured time delay Δ t is 0.35μ sec (50% of peak value in Fig. 5). When it is assumed the velocity of Rayleigh wave is 2.9 mm/μ sec in the steel, the crack size is estimated 2 mm (2.9 mm/ μ sec x 0.35 μ sec x 2). From this method, the defect size is successfully predicted.

V. Conclusions

An image reconstruction method based on mode-converted Rayleigh wave was proposed. By the proposed method, the Rayleigh wave signals can be differentiated from the specular reflection signals although the Rayleigh wave signal amplitude is much weaker than the pulser/echo signal. By experiments, it was shown that an image could be successfully restored by MCRW image method. This method also provides accurate prediction of the defect shape

References

[1] D. M. Suh and W. W. Kim, "A new ultrasonic technique for detection and sizing of small cracks in studs and bolts," *Journal of Nondestructive Evaluation*, vol. 14, no. 4, pp. 201-206, 1995.

[2] D. M. Suh, W. W. Kim, and J. G. Chung, "A Rayleigh wave technique for detection and sizing of small cracks in studs and bolts," in *Proceedings of 1996 IEEE Ultrasonics Symposium*(San Antonio, TX*)*, pp. 673-676, Nov. 1996.

[3] D. M. Suh, W. W. Kim, and J. G. Chung, "Ultrasonic inspection of studs (bolts) using dynamic predictive deconvolution and wave shaping," *IEEE Ultrasonics, Ferroelectrics, and Frequency Control.* Vol. 46, No. 2, pp. 457-463, Mar. 1999

[4] D. K. Peterson, S. D. Bennett, and G. S. Kino, "Locating and sizing surface-breaking cracks with a synthetic acoustic-imaging system," *Materials Evaluation*, American Society for Nondestructive Testing, Columbus, OH, pp. 451-457, Apr. 1984.

[5] R. N. Carpenter, and P. R. Stepanishen, "An improvement in the range resolution of ultrasonic pulse echo system by deconvolution," *J. Acoust. Soc. Am.*, vol. 75, no. 4, pp. 1084-1091, Apr. 1984.

[6] S. F. Burch, "Comparison of SAFT and two-dimensional deconvolution," *Ultrasonics*, vol. 25, Sep. 1987.

[7] M. Berger, D. Bruck, M. Fisher, K. J. Langenberg, J. Oberst, and V. Schmitz, "Potential and Limits of Holographic Reconstruction Algoriths," *Journal of Nondestr. Eval.*, Vol. 2, 1981, pp. 85-112.

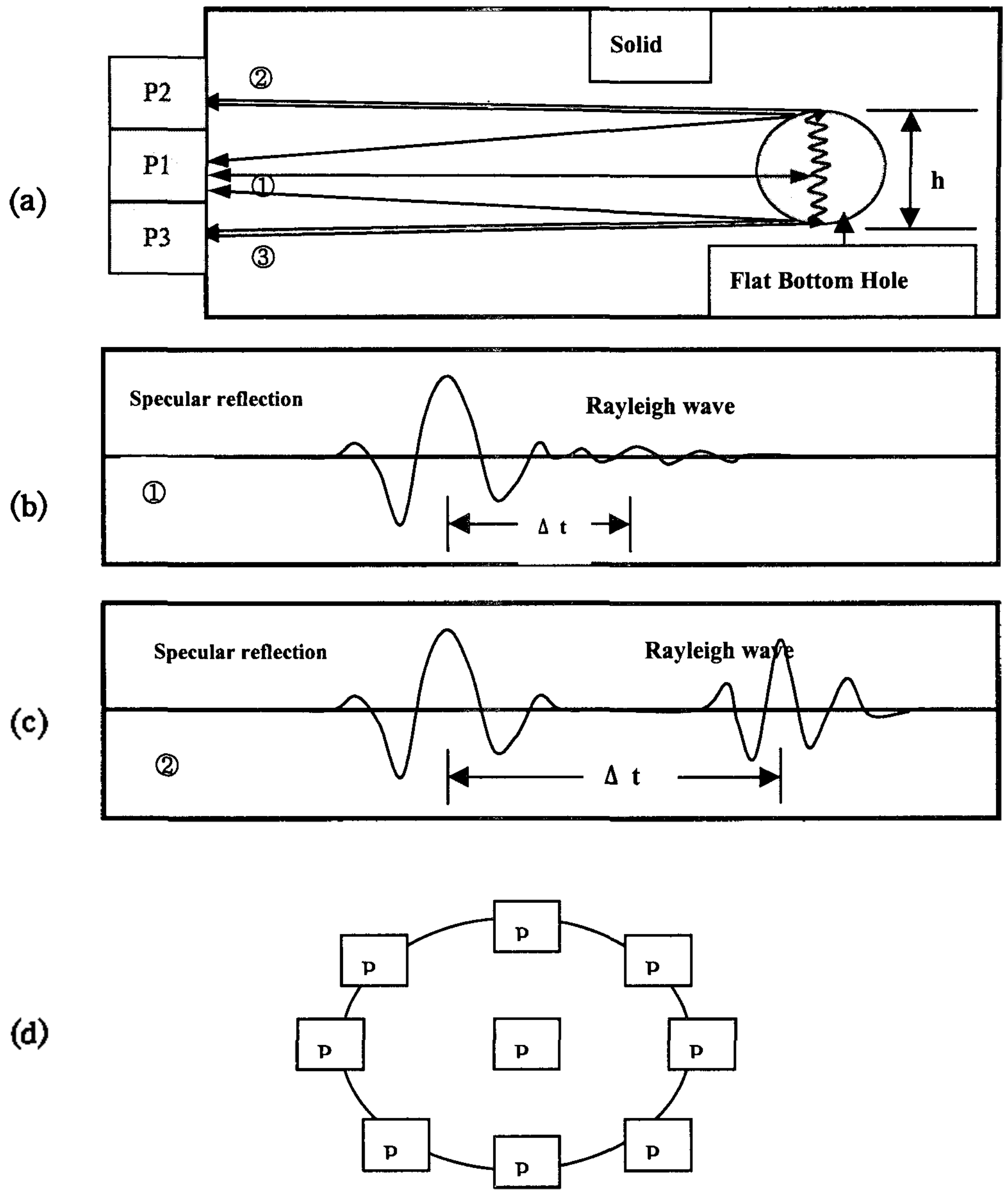

Figure 1. Schematic showing the Mode Converted Rayleigh Wave technique: (a) ray paths, (b) specular reflection signals by pulser/echo method (c) Rayleigh wave signals by pitch/catch method and (d) circularly arranged transducers.

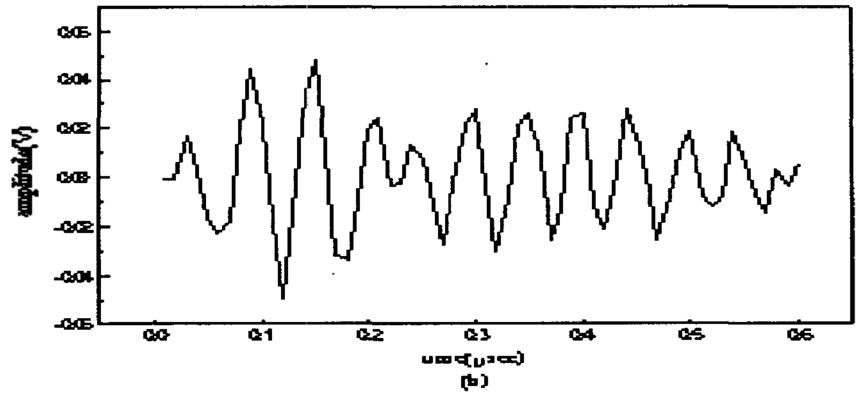

Figure 2. Ultrasonic signals from the flat bottom hole (2.0 mm diameter):

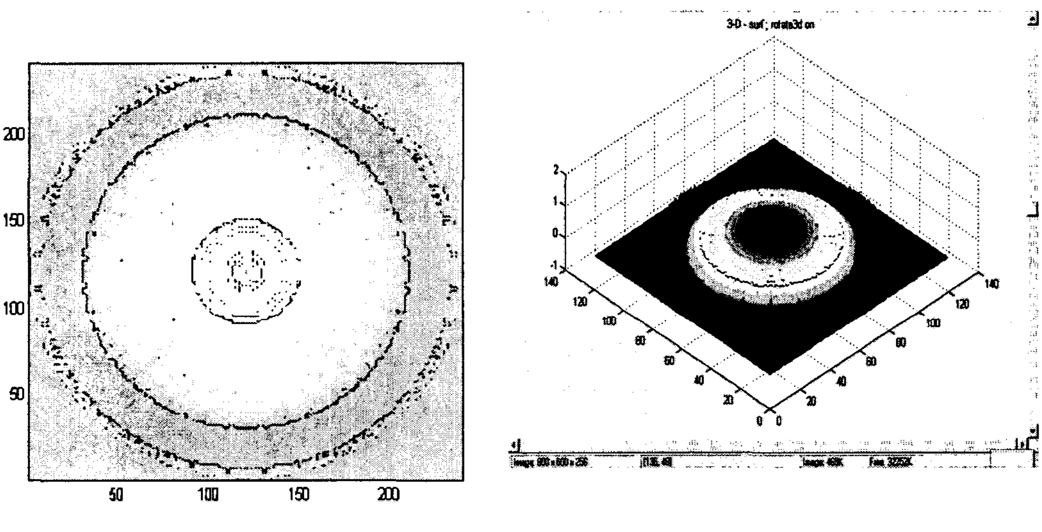

Figure 6. Reconstructed MCRW images by applying MCRW image technique to the signals in Fig. 2