Scanning Tomographic Acoustic Microscope System by Using Transverse waves

*Daesik Ko

Abstract

We propose to use transverse waves instead of longitudinal waves in a scanning tomographic acoustic microscope (STAM) and new type of multiple-transducer scheme with the functions of mulitple-angle and multiple-frequency tomography. Proposed multiple-transducer scheme has three insonification angles and three resonance frequencies in order to operate in the transverse wave mode and multiple-angle and multiple frequency tomography for the STAM.

In order to evaluate the performance of proposed transducer scheme we have simulated tomographic reconstruction with back-and-forth propagation (BFP) algorithm. Simulation results showed that proposed multiple-transducer scheme is capable of obtaining good resolution with transverse wave mode and multiple-frequency tomography. It is also showed that proposed scheme is an efficient rotation scheme by proportion to the number of projections.

Ⅰ. Introduction

The STAM(scanning tomographic acoustic microscope) has been proposed as a method to overcome the limitations of the SLAM(scanning laser acoustic microscope). The SLAM operates in the transmission mode and is designed for high resolution, real time imaging of thin specimens close to the coverslip. However, the SLAM produces only shadowgraphs and therefore has no axial resolution. For tomographic reconstruction of planar objects, an algorithm based on BFP(back-and-forth propagation) is used. The BFP is an efficient method for tomographic reconstruction when the layers of interest in the specimen are planar. The data for the STAM can be obtained by changing the angular direction of the insonifying acoustic waves. In order to accomplish this, transducer rotation and specimen rotation methods were proposed [1, 2, 3].

The STAM can be operated in the multiple-angle or multiple-frequency tomography. Mulitple-angle tomography is achieved by changing the insonification angle to obtain the tomographic projections, while the insonification frequency is changed for multiple-frequency tomography [4].

On the other hand, if the specimen is solid, as the insonifying acoustic wave travels from the water tank of the STAM into the solid specimen there will be mode conversion from longitudinal to transverse waves. Typically, the wavelength of transverse waves is shorter than that of the longitudinal waves. The resolution of the STAM depends on the available angular view and the acoustic wavelength. By using transverse waves, since the wavelength of acoustic wave could be decreased, we are able to achieve the high resolution with transverse-wave mode [5, 6].

In this paper, we designed an multiple-transducer scheme for generation of the transverse wave within the solid specimen and multiple-angle and multiple-frequency tomography. In order to investigate the characteristics of proposed multiple-transducer scheme, we studied the principles of the multiple-angle and multiple-frequency tomography and simulated the tomographic reconstructions using BFP algorithm with aluminum specimen and compared the quality of tomograms.

Ⅱ. Multiple-angle and Multiple-Frequency Tomography

1. The STAM using transverse waves

Fig. 1 shows the data acquisition system of the STAM. The sum frequency of f_1 and f_2 is bandpass filtered and fed into the acoustic transducer which generates the plane waves $u(x, y, z)$. The transmitted wavefield $v(x, y, z)$ propagates to the coverslip at $z=z_1$, where the acoustic wavefield is detected by a scanned laser. A photodetector placed after the knife-edge converts the laser light signal into an electrical signal, which is then fed into the quadrature receiver. The output of the quadrature receiver is digitized for computer processing [2, 4].

The insonifying acoustic wave can be written as

$$u(x, y, z) = u_0 \exp(j2\pi(f_{xi} x + f_{yi} y + f_{zi} z)) \tag{2.1}$$

---

*Department of Electronic Engineering, Mokwon University.

Manuscript Received: June 16, 1997.

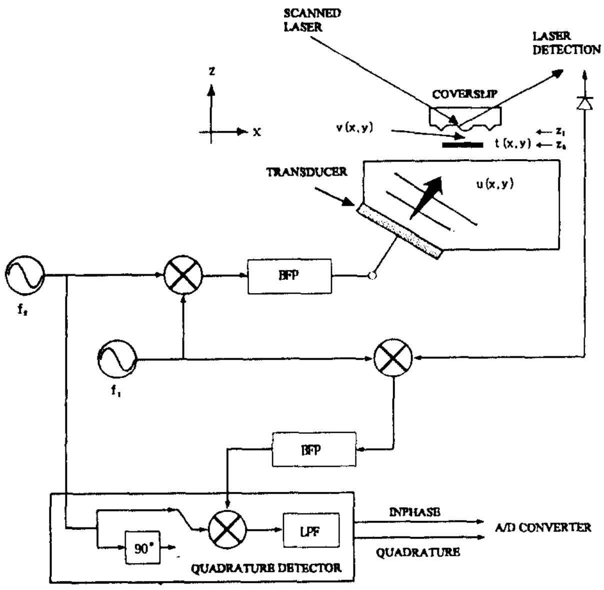


Figure 1. Data acqusition system of the STAM.

where u_0 is the amplitude of the plane wave, λ is the acoustic wavelength, and $f_{zi}=\sqrt{1/\lambda^2-f_{xi}^2-f_{yi}^2}$, f_{xi}, f_{yi} are the spatial frequencies of the plane wave. At the object plane, $z=z_0$, the wavefield is modulated by the object transmittance, $t(x, y, z_0)$, and the transmitted wavefield is given by Eq. (2.2)

$$v(x, y, z_0)=ut(x, y, z_0)t(x, y, z_0) \tag{2.2}$$

By reference [4], the back-propagation operator is constructed by ignoring the evanescent waves, thus the reconstructed transmittance is a low-pass version of the actual transmittance

$$P(f_x, f_y)=T(f_x, f_y)\exp(j2\pi f_{zi} z_0),\ (f_x+f_{xi})^2+(f_y+f_{yi})^2 < \frac{1}{\lambda^2} \tag{2.3}$$

Since the conventional STAM system operates at oblique incidence mode, mode conversion of the insonifying acoustic waves takes place at the interface of water-solid specimen and solid specimen-water. Therefore, we must consider the mode conversion of insonifying acoustic waves if in a solid specimen. Fig. 2 shows mode conversion of the acoustic waves in STAM and the critical angles of the longitudinal and transverse waves of the solid specimen are obtained by Snell's law [5, 6, 7]. If the insonification angle is lower than longitudinal-wave critical angle of the solid specimen, we can operate at the longitudinal wave mode, whereas we can operate at the transverse wave mode for insonification angle between longitudinal-and transverse-wave critical angle. Typically, the wavelength of the transverse wave is shorter than that of the longitudinal wave at the same incidental frequency, and the available angular view of the transverse waves is lager than that of the longitudinal waves.

2. Multiple-angle and mulitple-frequency tomography

The STAM can be operated for the multiple-angle or multiple-frequency tomography. In multiple-frequency tomography, projections acquired using different acoustic frequencies are combined to form the tomographic reconstuction. The spatial frequencies for the insonification plane wave are given by

$$\begin{aligned} f_{xi}^{(k)} &= \frac{\sin(\theta)}{\lambda_k} \\ f_{yi}^{(k)} &= 0 \\ f_{zi}^{(k)} &= \frac{\cos(\theta)}{\lambda_k} \end{aligned} \tag{2.4}$$

where θ is as shown in Fig. 2. Given a set of N projections $v_k(x, y, z_0)$, $k=1, 2, \ldots N$, the object plane $t(x, y)$ can be reconstructed using the BFP algorithm. If we use the insonification angle for generation of the transverse wave, we have to replace the wavelength in Eq. (2.4) by that of a transverse wave. The reconstruction equation for the BFP algorithm is given by [2, 3],

$$\hat{t}(x, y)=\frac{\sum_{k=1}^{N} u_k^*(x, y, z_0)v_k(x, y, z_0)}{\sum_{k=1}^{N} |u_k(x, y, z_0)|^2}. \tag{2.5}$$

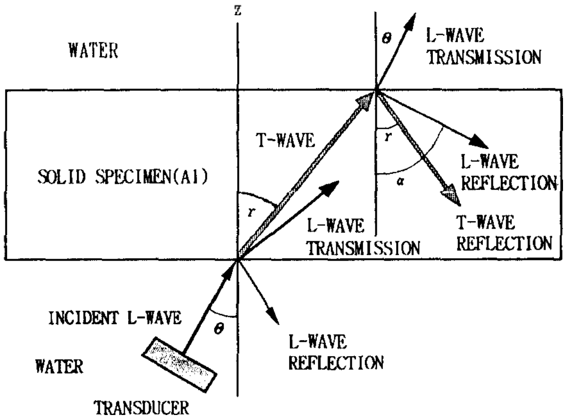


Figure 2. Mode conversion of the acoustic waves in STAM. (L: Longitudinal wave, T: Transverse wave)

The transmitted wavefield at the object plane, $v(x, y, z_0)$, can be obtained by back propagating the received wavefield to the object plane. We use the plane wave model and substitute Eq. (2.1) into Eq. (2.5) to obtain

$$\hat{t}(x, y) = \frac{1}{Nu_o} \sum_{k=1}^{N} \hat{v}(x, y, z_0)\exp(-j2\pi(f_{xi}x + f_{yi}y + f_{zi}z))$$
$$= \frac{1}{Nu_o} \sum_{k=1}^{N} p(x, y) \qquad (2.6)$$

By ignoring the evanescent waves, we have

$$\hat{t}(x, y) = \frac{1}{Nu_o} \sum_{k=1}^{N} t^{(k)}_{l,P}(x, y), \qquad (2.7)$$

where the Fourier transform of $t^{(k)}_{l,P}$ is given by

$$T^{(k)}_{l,P}(f_x, f_y) = \begin{cases} T(f_x, f_y), & (f_x + f^{(k)}_{xi})^2 + (f_y + f^{(k)}_{yi})^2 < \frac{1}{\lambda_k^2} \\ 0, & \textit{otherwise} \end{cases} \qquad (2.8)$$

As shown in Eq. (2. 8), the circular passband is centered at $(-f_{xi}, -f_{yi})$ with radius $1/\lambda_k$.

In multiple-angle tomography, the frequency of the acoustic wave is kept constant while the insonification angle is varied for the different projections. Thus, the spatial frequencies for the insonification plane wave are given by

$$f^{(k)}_{xi} = \frac{\sin(\theta_k)\cos(\phi_k)}{\lambda}$$
$$f^{(k)}_{yi} = \frac{\sin(\theta_k)\sin(\phi_k)}{\lambda} \qquad (2.9)$$
$$f^{(k)}_{zi} = \frac{\cos(\theta_k)}{\lambda}$$

where θ and ϕ are the spherical angles of the insonifying acoustic wave. Two schemes of obtaining multiple-angle projections have been studied. One method is the transducer rotation scheme in which ϕ is held constant and θ is varied. The other method is the specimen rotation scheme in which θ is held constant while ϕ is varid. Both methods have their respective advantages in terms of the resolution in the recostructed tomogram, however, only the specimen rotation scheme can be practically implemented [3].

Fig. 3 shows the example of the Fourier aperture for multiple-frequency tomography using proposed system. In Figure 3, λ and λ_S are wavelengths of the longitudinal and transverse wave, respectively, $P(f_x, f_y)$ and $T(f_x, f_y)$ are defined in Eq. (2.8).

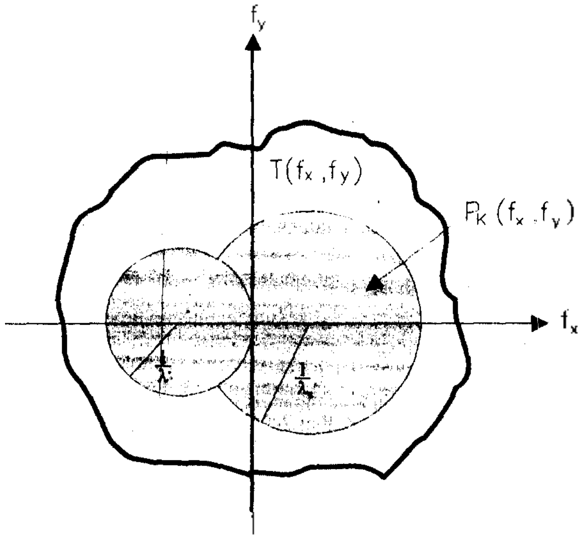
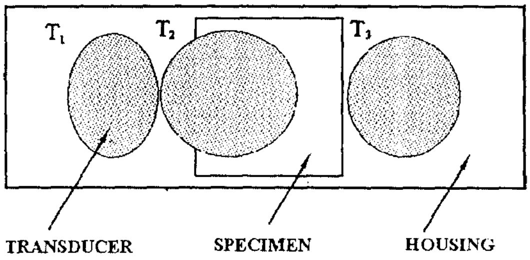


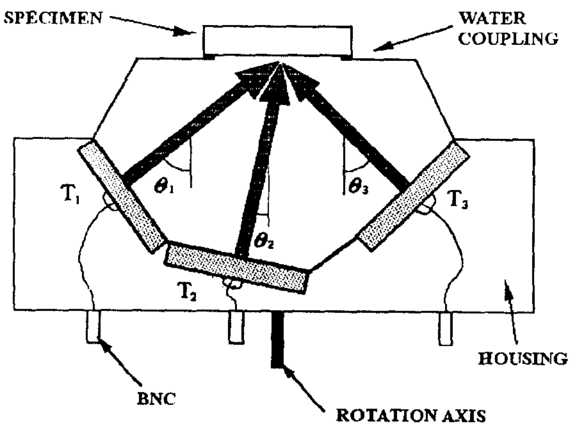
Figure 3. Fourier aperture for multiple-frequency tomography tomography using our multiple-transducer scheme
(a) Top view (b) Side view

3. Design of the multiple-transducer scheme

In order to operate STAM in the transverse wave and the multiple-frequency tomography mode, the multiple-transducer scheme was designed as shown in Fig. 4.



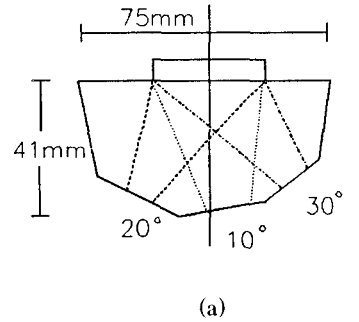
(a) Top view



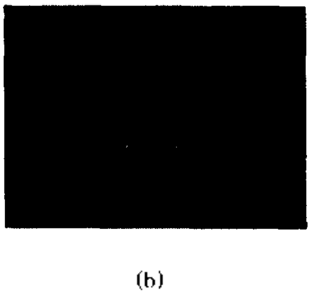
(b) Side view

Figure 4. Multiple-transducer scheme.

Proposed multiple-transducer scheme has a multiplicity of fixed three transducers and different resonance frequencies. The different insonification angles of three fixed transducer are designed for operating the STAM in longitudinal and transverse wave mode, respectively. Since proposed scheme also has the rotation axis, we can obtain the effect of the linear and rotational scan for projections. As an example, if proposed multiple-transducer scheme is rotated three times, we can obtain nine projections by combining of three transducer rotaion and three specimen rotaion. The different resonance frequencies of each transducer can be used to extend the range of the frequency variation for multiple-frequency tomography. Typically, the range of frequency variation of the STAM is limited to approximately 10 percent of the resonance frequency of the transducer [8]. For example, if the lowest resonance frequency of proposed transducer is 100MHz, the insonification frequencies can be used 95MHz, 100MHz, 105MHz, respectively, for three projections. Then resonance frequencies of the second and third transducer are 115MHz and 130MHz, respectively. Thus the insonification frequencies of the second and third transducer can be used 110MHz, 115MHz, 120MHz, 125MHz, 130MHz, and 135MHz, respectively. Fig. 5 shows multiple-transducer scheme which is implemented in this study.



(a)



(b)

Figure 5. Implemented multiple-transducer scheme (a)geometry (b)photo

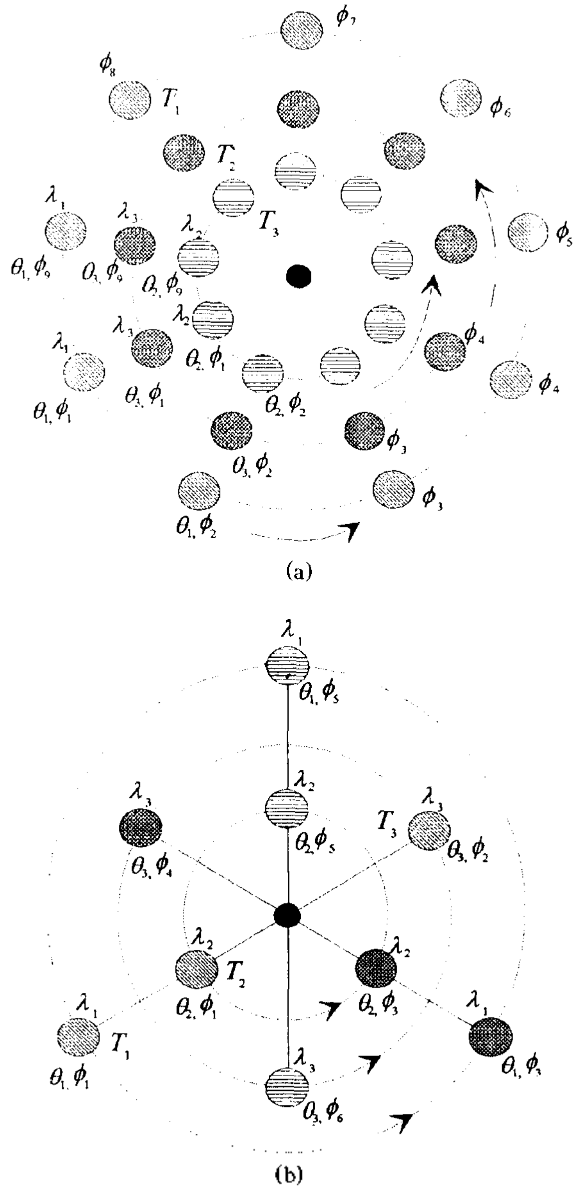
Since multiple-transducer scheme is able to operate at multiple frequency and multiple angle tomography, the spatial fequencies for the proposed multiple-transducer scheme are given by Eq. (2.10).

$$f_{xi}^{(k)} = \frac{\sin(\theta_k)\cos(\phi_k)}{\lambda_k}$$

$$f_{yi}^{(k)} = \frac{\sin(\theta_k)\sin(\phi_k)}{\lambda_k} \qquad (2.10)$$

$$f_{zi}^{(k)} = \frac{\cos(\theta_k)}{\lambda_k}$$

In transverse wave mode, we have to change the wavelengths of the longitudinal waves into the wavelengths of



(b)

Figure 6. Various projection methods using our scheme. (a) Nine projections using specimen rotation for each transducer, respectively. (b) Nine projections using three rotations of our scheme.

the transverse wave in Eq. (2.10). Since proposed scheme has the different insonification angles and resonance frequencies and rotation axis, we are able to achieve various projection methods as shown in Fig. 6.

Fig. 6-(a) shows nine projections by rotating proposed scheme or specimen three times. Fig. 6-(b) shows also three case of nine projections by rotating specimen with each transducer, respectively. We have shown that multiple-angle and multiple-frequency is used for projections in Fig. 6 and if we need a number of projections, we can combine various projection methods of the Fig. 6.

Ⅲ. Experimented Simulation Results

In order to investigate the performance of transverse-waves imaging and proposed multiple-transducer scheme, a planar aluminum is used as specimen in this simulation. The object is assumed to be attenuation-free with respect to the acoustic waves except for two horizental thin layers four wavelengths apart. Different patterns involving a structure that is assumed to be 50 percents transparent to the acoustic waves are contained in the two layers. For our simulations we assumed perfect detection, that is that the data were noise-free and that the evanescent waves were neglected.

In order to see the effect of multiple-transducer scheme, we simulated nine projections of Fig. 6-(a) and Fig. 6-(b), respectively. If the insonification angles of T_1, T_2 and T_3 transducer in proposed scheme are 20°, 10°and −15°, respectively. Since the longitudinal critical angle of the aluminum is 12.9°, transducer T_1 and T_3 will be operated in transverse wave mode and transducer T_2 awill be operated in longitudinal wave mode, respectively.

Fig. 7-(a) shows the results using T_2 transducer of Fig. 6-(a), which is conventional STAM. Fig. 7-(b) shows the results using projection mothod of the Fig. 6-(b). In this case, since we rotate only three times the transducer or specimen for nine projections, the random error cause of the movement of the specimen or transducer can be reduced. We also can achive both the effect of the linear and rotational scan methods.

Finally, in order to show the usefulness of the transverse wave mode in solid speciemen, we compared the transverse wave mode with the longitudinal wave mode. Fig. 8-(a) and 8-(b) show tomograms obtained by specimen rotation with the longitudinal and transverse waves, respectively. Both Fig. 8-(a) and 8-(b) were reconstructed from nine projections with the insonification angle of 47°. That is, when the incident angles are 10°for the longitudinal wave and 21° for transverse wave in water, both the refracted angles of the longitudinal and transverse wave in aluminum are 47°. As shown in Fig 8, the resolution of the transverse-wave tomograms is better than that of the longitudinal-wave tomograms.

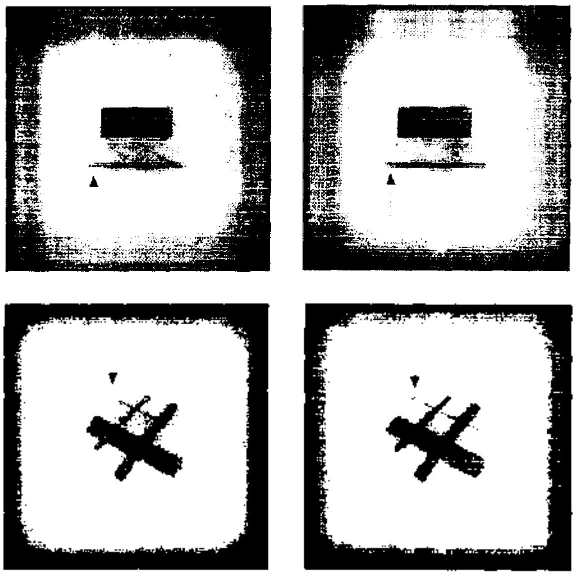

(a) (b)

Figure 7. Simulated tomograms obtained from nine projections with our scheme. (a) Nine rotations of Fig. 6-(a). (b) Three rotations of Fig. 6-(b).

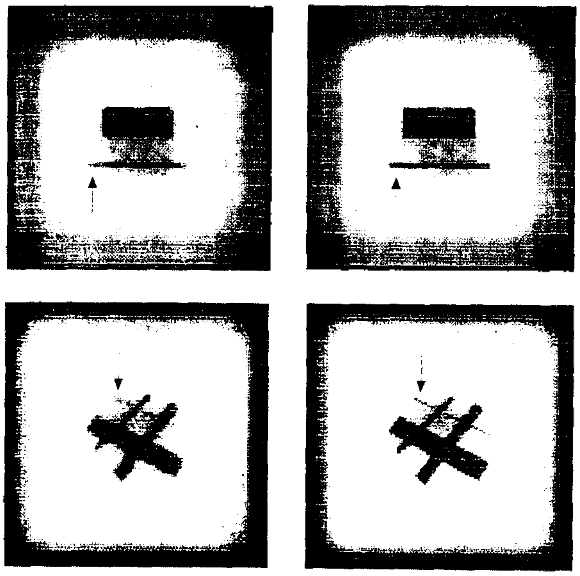

(a) (b)

Figure 8. Simulated tomograms obtain from nine projections with our scheme (a) Longitudinal wave mode (b) Transverse wave mode

Ⅳ. Conclusions

In this paper, we used transverse waves instead of longitudinal waves for resolution enhancement and proposed a new type of the multiple-transducer scheme for STAM. For nondestructive testing applications of the STAM, we have to consider the mode conversion of the insonifying acoustic waves, and we showed that transverse wave mode have advantages to longitudinal wave mode. Our multiple-transducer scheme was designed for transverse-wave imaging and efficient multiple-frequency and multiple-angle tomography with three fixed-transducer.

Experiment showed that proposed multiple-transducer scheme is useful for resolution enhancement of the STAM by using multiple-angle and multiple-frequency tomography of new type. And results also showed that proposed scheme is powerful for the transverse-wave imaging in solid specimen.

Acknowledgment

"This paper was supported by NON DIRECTED RESEARCH FUND, Korea Research Foundation, 1996," and I thank Professor Glen Wade's research group for helpful comments.

References

1. C. H. Chen, "Some Results in Diffraction Tomography using Plane-Wave Illumination," Ph. D. Dissertation, University of California Santa Barbara, 1987.
2. R. Y. Chiao, H. Lee, "Recent Advances in Scanning Tomographic Acoustic Microscpoy," *International Journal of Imaging Systems and Technology*, Vol 3, pp. 334-353(1991).
3. Z. C. Lin, H. Lee, and G. Wade, "Scanning Tomographic Acoustic Microscope: A Review," *IEEE Trans. Sonics Ultrason.*, Vol. SU-32, pp. 168-180(1985).
4. R. Y. Chiao and H. Lee, "Initial Phase Estimation and Tomographic Reconstruction for Multiple-frequency Acoustic Tomography," *Acoustical Imaging*, Vol. 18, pp. 261-271 (1991).
5. D. S. Ko, A. Meyyappan and G. Wade, "A Planar Ultrasonic Tomography using Shear Waves," *IEEE Southwest Symposium on Image Anaysis and Interpretation*, pp. 85-88 (1996).
6. D. S. Ko and A. Meyyappan, "Scanning Tomographic Acoustic Microscopy Using Shear Waves," *IEEE Trans. on UFFC.*, Vol. 44, No. 2 pp. 425-430(1997).
7. J. Krautkramer and H. Krautkramer, *Ultrasonic Testing of Material*, 4th Ed., Springer-Verlag, 1990.
8. A. Meyyappan and G. Wade, "Data Acquisition for Scanning Tomographic Acoustic Microscopy," *Acoustical Imaging*, Vol. 16, pp. 543-551(1988).

▲Daesik Ko

Daesik Ko received the B.S., M.S. and Ph.D degree in Electronic Engineering from Kyunghee University, Seoul, Korea, in 1982, 1987 and 1991, respectively.

From 1995 to 1996, he joined Dept. of Electrical and Computer Engineering of the University of California, Sanata Barbara (UCSB) as a Post-Doctoral researcher, where he worked on Acoustic Microscopy (SLAM, STAM) and Signal processing.

He is currently working with Dept. of Electronic Engineering of Mokwon University as an Associate Professor. He received Distinguish research Award from Acoustical Society of Korea and Mokwon University in 1996, respectively. He is currently a member of the IEEE and Editor of the Acoustical Society of Korea, and his research interests are signal processing, real-time Internet communications and 3-D sound.