J. Acoust. Soc. Jpn. (*E*) **14**, 1 (1993)

Stress effect to ultrasonic velocity and mechanical anisotropy of solid materials by water immersion sing-around method

Tohru Imamura

National Research Laboratory of Metrology,
1–1–4, Umezono, Tsukuba, Ibaraki, 305 Japan
(*Received 1 November 1991*)

Tensile stress is applied to the specimens of polymethyl methacrylate (PMMA) and polystyrene (PS), using a mechanical device composed of screws and a lever, and its effect to the ultrasonic velocity is observed by water immersion ultrasonic sing-around method for both compressional wave and shear wave. The incidence angle is set to be zero for the compressional wave, or to be the angle appropriately above the critical angle of the compressional wave for the shear wave. Relative ultrasonic velocity variation (RUVV) due to applied stress is linear for all cases, and the effect of RUVV for the shear wave is larger than that for the compressional wave. Next, mechanical anisotropy of injected polypropylene (PP) plate and burned extruded porous machinable ceramic plate are investigated by the similar inclined water immersion method. The relative ultrasonic velocity difference (RUVD) of the injected polypropylene plate ranges up to about 9%.

Keywords: Water immersion, Sing-around method, Stress effect, Mechanical anisotropy, Ultrasonic material measurement

PACS number: 43. 35. Zc

1. INTRODUCTION

Applied stress and residual stress in metals have been investigated by direct contact ultrasonic velocity measurement method.[1-11] But, the coupling of the transducer to the specimen causes some difficulty. Non-contact water immersion method[12-14] ensures stability and repeatability of the ultrasonic velocity measurement. In this paper are reported measurement of stress effect to ultrasonic velocity of solid materials and mechanical anisotropy[13-15] of them by water immersion sing-around method.[16] If the incidence angle from water to the specimen is above the critical angle of the compressional wave, only shear wave travels in the solid material by mode conversion at the water-solid interface. And this condition is appropriate for the measurement of stress effect to the ultrasonic velocity of solid materials and for that of mechanical anisotropy of them.

2. PRINCIPLE OF IMMERSION ULTRASONIC SING-AROUND METHOD

Figure 1 represents the principle of immersion ultrasonic sing-around method. Compressional wave is emitted to the water by the transmitting transducer. It is refracted at the water-solid interface and propagates in the solid. When the incidence angle (i) is smaller than the critical angle of the compressional wave, both compressional wave and shear wave propagate in it, except when the incidence angle is zero where only compressional wave propagates in it. If the incidence angle exceeds the critical angle of the compressional wave, only shear wave propagates in it. At the other interface, they are refracted again to the initial

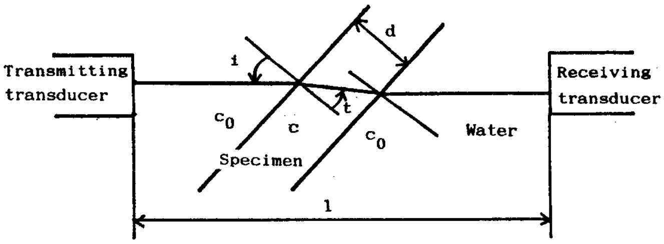

Fig. 1 Principle of ultrasonic refraction by immersion method.

incidence angle (i) and travel in water to the receiving transducer.

The time interval (τ) between the ultrasonic transmission by a transmitting transducer and the ultrasonic reception by a receiving transducer is expressed as

$$\tau=\frac{l-d\cdot\cos(t-i)/\cos(t)}{c_0}+\frac{d/\cos(t)}{c}, \quad (1)$$

where l is the distance between the transducers, d the thickness of the specimen, i the incidence angle, t the angle of refraction, c_0 the ultrasonic velocity of water and c the ultrasonic velocity of the specimen. The theory of refraction is expressed as

$$\frac{\sin(t)}{\sin(i)}=\frac{c}{c_0}. \quad (2)$$

Eqs. (1) and (2) hold for both the compressional wave and the shear wave on proper conditions. When the specimen is not placed, the time interval (τ_0) between the transmission and the reception is expressed as

$$\tau_0=\frac{1}{c_0}. \quad (3)$$

From Eqs. (1)–(3), c and t are derived as

$$c=\frac{1}{\dfrac{(\tau-\tau_0)\cos(t)}{d}+\dfrac{\cos(t-i)}{c_0}}, \quad (4)$$

$$t=\sin^{-1}\left(\frac{c_0}{c}\sin(i)\right). \quad (5)$$

The values of c and t can be computed from τ, τ_0, d, i and c_0 by Eqs. (4) and (5) with successive approximation, where the values of τ and τ_0 can be measured by the sing-around method.

3. MEASURING PROCEDURE

Figure 2 shows a block diagram of the measuring system when the shear wave propagates in the specimen and stress is applied to it. The specimen is

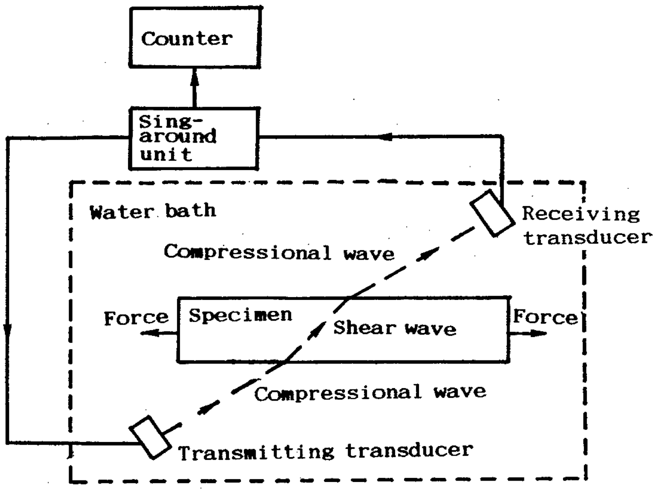

Fig. 2 Block diagram of stress measurement by the water immersion ultrasonic sing-around method.

immersed in a water bath. The water temperature is kept constant by controlling proportionally the electric current in the heating wire. For the purpose of controlling the electric current, the height of the mercury of the thermometer with coil glass tube in the water bath is detected by the photo-sensor. The fluctuation of the water temperature is within ± 10 mK at 303 K. The incidence angle into the specimen can be varied from 0° to 50°. Tensile stress is applied to the specimen using a mechanical tension device composed of screws and a lever, and its effect to the ultrasonic velocity is observed.

In the ultrasonic sing-around method, the electric pulse is applied to the transmitting transducer to emit ultrasound in the medium. The ultrasonic wave travels in water, then goes through the specimen and again travels in water. It is detected by the receiving transducer and the electrical signal is generated. When the received signal exceeds the set level, the electric pulse is again generated and applied to the transmitting transducer, and the system sings around. The sing-around period is measured by the universal counter together with the system in which only water is along the ultrasonic path. The central frequency of the ultrasonic wave is 2 MHz, and the sing-around period is measured with the resolution of 1 ns.

4. RESULTS AND DISCUSSION

4.1 Receiving Amplitude and Sing-Around Period with Incidence Angle for Solid Materials

Preliminarily, the amplitude of electrical signal of the receiving transducer and the sing-around period are measured as varying the incidence angle. Figure 3 shows the result of measurement when a polymethyl methacrylate (PMMA) plate of 10 mm in thickness is used as a specimen. Closed circles represent the amplitude and open circles the sing-around period. The amplitude reaches a minimum at the incidence angle of about 30°. At this angle the sing-around period jumps by about 5 μs. From this figure we can find that the compressional wave dominates the sing-around period below the critical angle. This is because the compressional wave propagates faster than the shear wave. And the shear wave dominates the period above the critical angle. Figure 4 shows the result for polystyrene (PS). It has a similar feature as PMMA at the incidence angle of about 35°. Figure 5 shows the result for a polypropylene (PP) plate of 2 mm in thickness. It has the similar feature as before, but the jump of sing-around period at the angle of about 40° is about 1 μs as the thickness of the plate is 2 mm. Figure 6 shows the result for a burned extruded porous machinable ceramic disk of 5 mm in thickness after saturation of water into the pores. This has a jump of sing-around period of about 1 μs at the angle of about 15.°

From the above results, the incidence angle for the measurement of stress effect for PMMA is set to be 0° for the compressional wave and to be 41° for the shear wave. The similar angle for PS is set to be 0° for the compressional wave and to be 45° for the shear wave. The incidence angles for the measurement of mechanical anisotropy of the PP plates and for that of the burned extruded porous machinable ceramic plate are set to be 46° and 23° respectively.

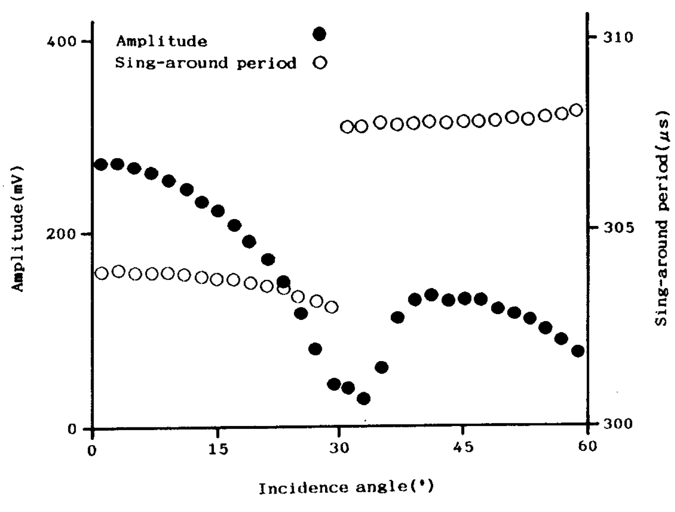

Fig. 3 Receiving amplitude and sing-around period with incidence angle for a polymethyl methacrylate (PMMA) plate (10 mm in thickness) in water.

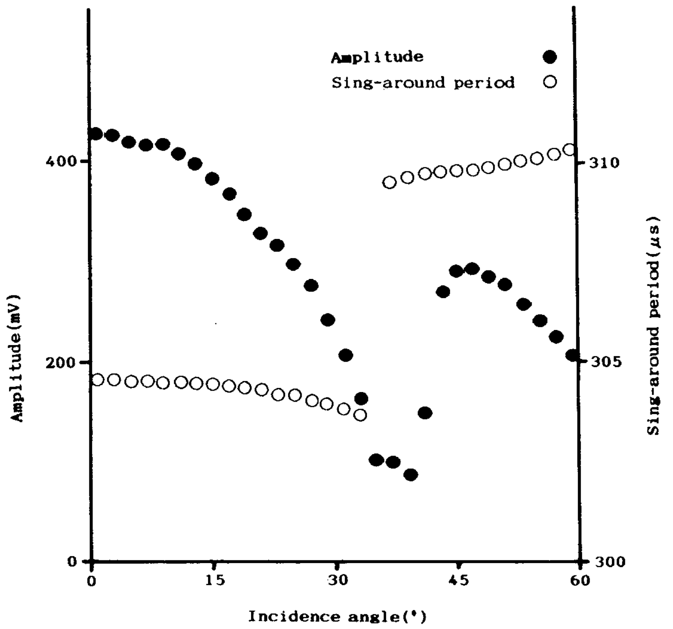

Fig. 4 Receiving amplitude and sing-around period with incidence angle for a polystyrene (PS) plate (10 mm in thickness) in water.

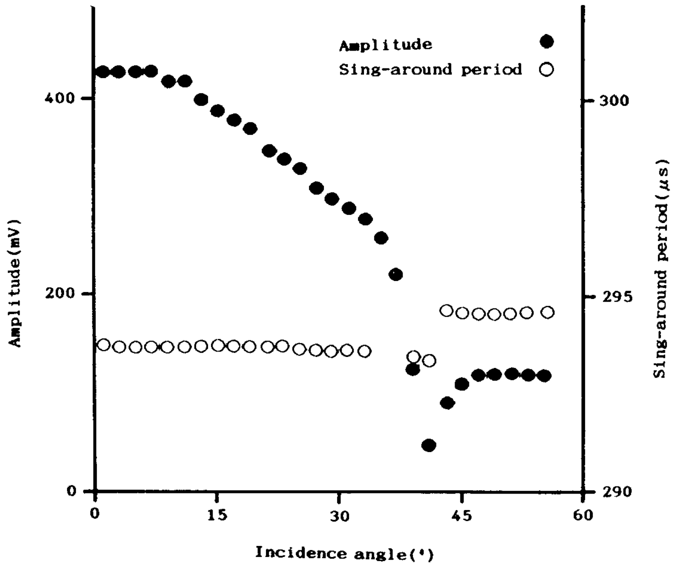

Fig. 5 Receiving amplitude and sing-around period with incidence angle for an injected polypropylene (PP) plate (2 mm in thickness) in water.

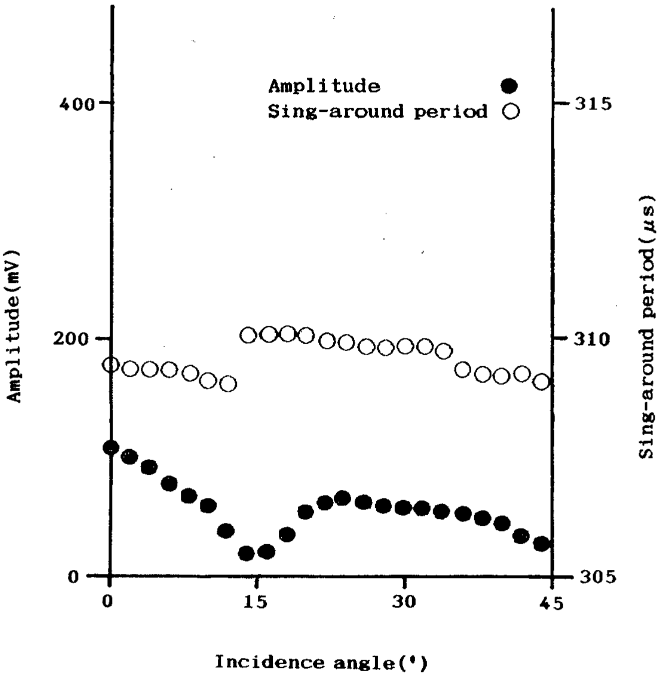

Fig. 6 Receiving amplitude and sing-around period with incidence angle for a burned extruded machinable ceramic plate (5 mm in thickness) in water.

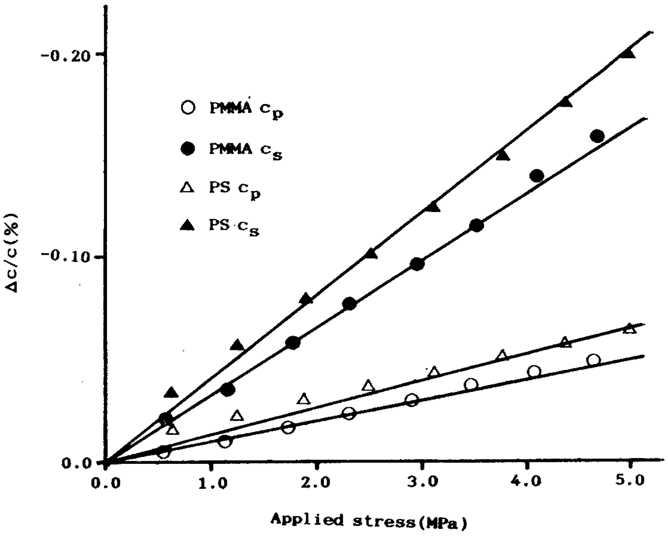

Fig. 7 Relative ultrasonic velocity variation (RUVV) due to applied stress in water for polymethyl methacrylate (PMMA) and polystyrene (PS).

4.2 Ultrasonic Velocity Variation with Applied Stress

The specimen of polymethyl methacrylate (PMMA) or polystyrene (PS) of 300 mm in length and 50 mm × 10 mm in cross section is clamped and stretched by rods through holes which are drilled at the places near its ends. The stress in the specimen is measured by strain gauges bonded on it. The stress-strain relation is determined preliminarily by a tension tester which is calibrated by dead weights.

Figure 7 shows the relative ultrasonic velocity variation (RUVV) due to applied stress in water for PMMA and for PS. The stress is applied up to about 5 MPa. The effect of stress for shear wave is larger than that for compressional wave. RUVV against stress is linear for all cases. In computing RUVV, specimen shrinkage is taken into account, by using a strain meter and Poisson's ratio which are derived by the ultrasonic velocity of the compressional wave and by that of the shear wave.

4.3 Mechanical Anisotropy

Injected polypropylene (PP) plates and a burned extruded porous machinable ceramic plate are investigated their mechanical anisotropy by the water immersion ultrasonic sing-around velocity measurement.

The injected PP plates of 100 mm × 100 mm × 2 mm are cut into square nine pieces which are immersed in water separately. The incidence angle is set to be 46°. Figure 8 shows the relative ultrasonic velocity difference ($(c_{//}-c_{\perp})/c_{\perp}$ (%), RUVD), where $c_{//}$ is the ultrasonic velocity of the PP plate when the plane which shows the principle of refraction (Fig. 1) includes the injection direction shown by arrows, and $c_{\perp}$ is that when the plane includes

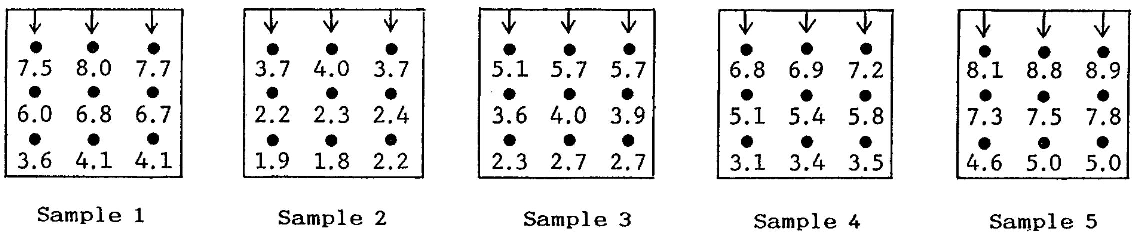

Fig. 8 Relative ultrasonic velocity difference ($(c_{//}-c_{\perp})/c_{\perp}$ (%), RUVD; → direction of injection) of the polypropylene (PP) plate in water.

the direction that is perpendicular to injection. Table 1 represents the melt flow rate (MFR) and the injection conditions of the sample used in the experiment. For all the samples, $c_{//}$ is larger than $c_{\perp}$. RUVD which is near the slit nozzle is larger than that which is far from it. This reaches a maximum of about 9%. Figure 9 shows RUVD of PP plate with variation of melt flow rate (MFR). As the MFR increases, RUVD decreases. The sample 1 which had low cylinder temperature (473 K) with high MFR (24.5 g/10 min) corresponds to the sample 4 which had high cylinder temperature (513 K) with low MFR (4.8 g/10 min).

Table 1 Melt flow rate and injection conditions of the sample.

Sample	1	2	3	4	5
MFR (g/10 min)	24.5	24.5	11.6	4.8	2.3
Cylinder temperature (K)	473	513	513	513	513
Injection pressure (MPa)	49	49	49	49	66

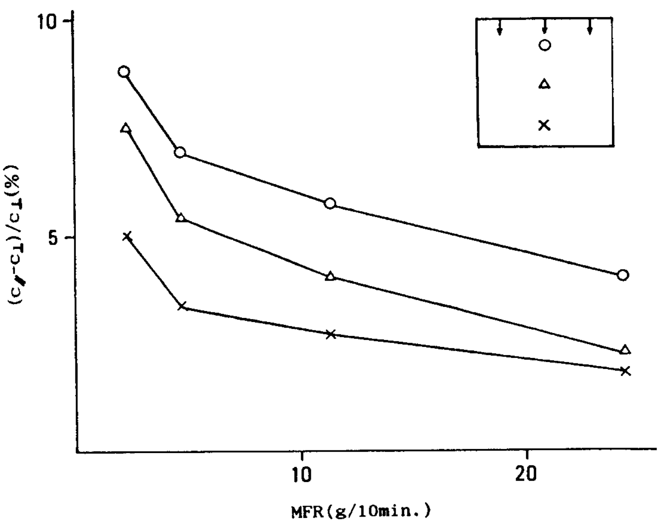

Fig. 9 Relative ultrasonic velocity difference ($(c_{//}-c_{\perp})/c_{\perp}$ (%), RUVD) of the polypropylene (PP) plate with melt flow rate (MFR).

Fig. 10 Ultrasonic velocity of a burned extruded porous machinable ceramic disk in water with the rotation around the normal axis of the specimen.

Figure 10 shows ultrasonic velocity of a burned extruded machinable ceramic disk in water. The incidence angle is set to be 23°. The disk specimen is rotated around the normal of the specimen, and the measurement is carried down with the interval of 15°. Ultrasonic velocity has two peaks separated by about 180°. The maximum relative difference is about 5%.

5. CONCLUSION

Stress effect to ultrasonic velocity and mechanical anisotropy of solid materials are investigated by water immersion sing-around method. Relative ultrasonic velocity variation (RUVV) against stress up to about 5 MPa is linear for both polymethyl methacrylate and polystyrene. The effect of stress for shear wave is larger than that for compressional wave. Relative ultrasonic velocity difference (RUVD) due to mechanical anisotropy of injected polypropylene plate ranges up to about 9%. The distribution of RUVD corresponds to melt flow rate and injection conditions of PP plates.

ACKNOWLEDGEMENTS

The author is grateful to Mr. K. Kobayashi of Mitsubishi Petrochemical Co., Ltd. for his kind cooperation in preparing the injected plates of polypropylene, and is also grateful to Dr. S. Iwata of Ishihara Chemical Co., Ltd. for his preparation of the burned extruded machinable ceramic plate.

REFERENCES

1) D. S. Hughes and J. L. Kelly, "Second-order elastic deformation of solids," Phys. Rev. **92**, 1145–1149 (1953).
2) D. I. Crecraft, "The measurement of applied and residual stresses in metals using ultrasonic waves," J. Sound Vib. **5**, 173–192 (1967).
3) T. Tokuoka and Y. Iwashimizu, "Acoustical birefringence of ultrasonic waves in deformed isotropic elastic materials," Int. J. Solids Struct. **4**, 383–389 (1968).

4) Y. Iwashimizu and K. Kubomura, "Stress-induced rotation of polarization directions of elastic waves in slightly anisotropic materials," Int. J. Solids Struct. **9**, 99–114 (1973).
5) K. Okada, "Stress-acoustic relations for stress measurement by ultrasonic technique," J. Acoust. Soc. Jpn. (E) **1**, 193–200 (1980).
6) K. Okada, "Acoustoelastic stress-measurement in rolled materials," Jpn. J. Appl. Phys. **S20-3**, 189–192 (1981).
7) K. Okada, "On a hysteresis property in acousto-elastic effect," Jpn. J. Appl. Phys. **S21-3**, 126–128 (1982).
8) K. Okada, "Two-dimensional acoustoelasticity using pulse echo overlap technique," Jpn. J. Appl. Phys. **S22-3**, 57–59 (1983).
9) J. C. Albert, O. Cassier, B. Chamont, M. Arminjon, and F. Goncalves, "Application of polarized shear waves to evaluate anisotropy of steel sheets," Proc. 2nd Int. Symp. Nondestr. Charact. Mater. (Plenum Press, New York, 1987), pp. 515–521.
10) R. B. Mignogna, P. P. Delsanto, A. V. Clark Jr., R. B. Rath, and C. L. Vold, "Ultrasonic measurements on textured materials," Proc. 2nd Int. Symp. Nondestr. Charact. Mater. (Plenum Press, New York, 1987), pp. 545–553.
11) P. P. Delsanto, R. B. Mignogna, and A. V. Clark, Jr., "Ultrasonic texture and stress measurements in anisotropic polycrystalline aggregates," J. Acoust. Soc. Am. **87**, 215–224 (1990).
12) G. S. Kino, J. B. Hunter, G. C. Johnson, A. R. Selfridge, D. M. Barnett, G. Hermann, and C. R. Steele, "Acoustoelastic imaging of stress fields," J. Appl. Phys. **50**, 2607–2613 (1979).
13) T. Imamura, "Non-contact ultrasonic velocity measurement of plastics by sing-around method; stress effect and anisotropy," Jpn. J. Appl. Phys. **S23-1**, 81–82 (1984).
14) T. Imamura, "Measurement of mechanical anisotropy of solid materials by ultrasonic sing-around method," Proc. 12th Int. Congr. Acoust. G5-3 (1986).
15) L. D. Coxon and J. R. White, "Residual stresses and aging in injection molded polypropylene," Polym. Eng. Sci. **20**, 230–236 (1980).
16) N. P. Cedrone and D. R. Curran, "Electronic pulse method for measuring the velocity of sound in liquids and solids," J. Acoust. Soc. Am. **26**, 963–966 (1954).

Tohru Imamura was born in Nagoya, Japan on September 29, 1945. He received the B. Sci. from the University of Tokyo in 1969. Since then, he has been with the National Research Laboratory of Metrology, AIST, MITI. His interests are in numerical analysis of ultrasonic propagation, ultrasonic measurement of materials, and history and role of standards.