[논 문] - 비파괴검사학회지
Journal of the Korean Society for Nondestructive Testing
Vol. 21, No. 4 (2001. 8)

Recent Ultrasonic Guided Wave Inspection Development Efforts

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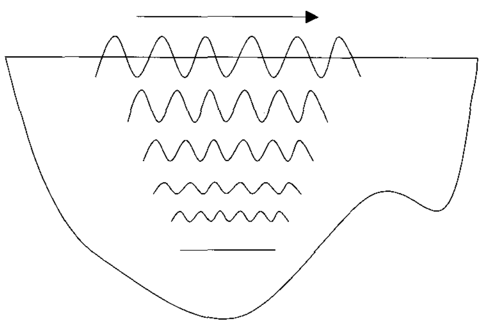
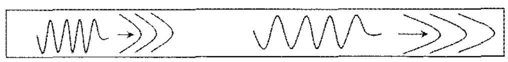
Abstract: The recognition of such natural wave guides as plates, rods, hollow cylinders, multi-layer structures or simply an interface between two materials combined with an increased understanding of the physics and wave mechanics of guided wave propagation has led to a significant increase in the number of guided wave inspection applications being developed each year. Of primary attention is the ability to inspect partially hidden structures, hard to access areas, and coated or insulated structures. An introduction to some physical consideration of guided waves followed by some sample problem descriptions in pipe, ice detection, fouling detection in the foods industry, aircraft, tar coated structures and acoustic microscopy is presented in this paper. A sample problem in Boundary Element Modeling is also presented to illustrate the move in guided wave analysis beyond detection and location analysis to quantification.

Introduction

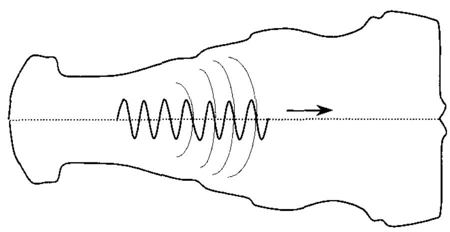
Boundaries are required for guided wave propagation to occur. Typical boundaries are illustrated in Figure 1 for a semi incident half space where Rayleigh surface waves travel over the boundary of a structure, even over curved surfaces. A Lamb wave is associated with having a boundary on both sides, the traditional problem associated with wave propagation in a homogeneous isotropic plate, but are also the kinds of waves that extend to pipes and multi-layered structures as well. Two boundaries in this case, are required whereby superposition of the waves as they bounce back and forth inside the structure leads to nice packets of energy that travel with certain group velocities, the results of



(a) Rayleigh(surface) wave schematic



(b) Lamb wave schematic



(c) Stonely wave schematic

Figure 1 Guided wave possibilities

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which can be traditionally found in dispersion curve mechanics. Another example shown in Figure 1 is associated with a Stoneley wave whereby a wave travels along an interface between two materials. Traditional bulk waves compared to guided waves, are those that travel in a semi-infinite or infinite media with no boundaries or constraints of wave propagation. The wave velocity for a bulk wave can be a dilatational velocity or a shear wave, the fastest possible that may propagate in a structure. For guided waves the wave velocity can take on an enormous range of values, even negative depending on the superposition characteristics of the waves as they refract and mode convert inside a structure.

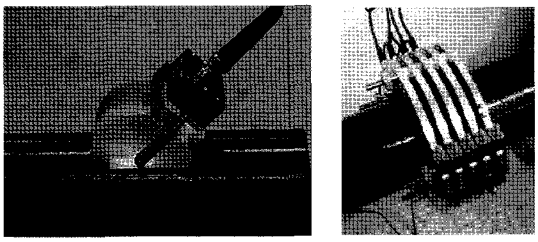
A summary of the benefits of guided waves is presented in Table 1. The explanations are self-explanatory and will not be discussed in detail at this point. Of primary significance however is the ability to inspect particularly hidden structures, hard to access areas, and coated or insulated structures.

Several excellent textbooks that cover the fundamentals of wave propagation and solid media can be found in references [1-6]. The basic principles of bulk wave and guided wave propagation are presented in detail. Pioneering efforts in ultrasonic nondestructive evaluation that go beyond some of the basic articles available for over a centry of wave mechanics includes material by Thompson, R.B, Datta, S.K., Mal, A.K., Nayfeh, A.H., Chimenti, D.E., Nagy, P.b., Adler, L., Rokhlin, S.I., Ditri, J.J., Rose, J.L., Pilarski, A. and Cawley, P. These materials are presented in references [7-15].

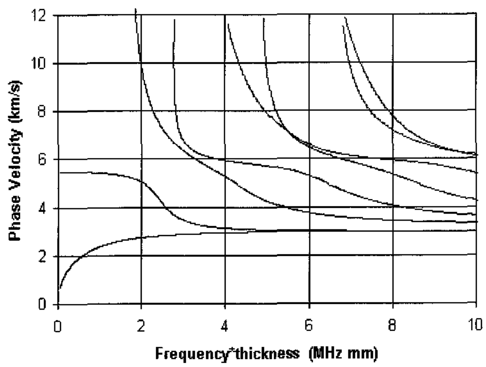
Even though the basic principles on guided wave mechanics have been presented in the literature for over a century, it is only now, since the interpretations and considerations for nondestructive evaluation have progressed so rapidly, that guided wave inspection is now becoming a reality. This increased understanding of the physics and wave mechanics of guided wave propagation has led to a significant increase in number of guided wave inspection applications being developed each year.

Sample Problems

The most common techniques for generating guided waves in a structure are illustrated in figure 2, where the mode activation possibilities can be possible, by way of an angle beam probe or a comb transducer. Illustrated in figure 2 is a sample problem of propagation in a pipe. A typical phase velocity dispersion curve is also illustrated in the figure that shows the excitation zones that can occur for either the angle beam probe or comb probe. For an angle beam probe, the excitation line is horizontal



(a) angle beam probe (b) comb probe



(c) Mode excitation zones (Angle beam shoe - constant phase velocity [horizontal line] determined form Snell's Law for a given angle. Comb transducer excites modes with a constant wavelength [sloped line] determined by the spacing of the elements.)

Figure 2 Lamb wave mode activation possibilities with a constant phase velocity, where frequency can be swept from one mode to another producing the wave packets of interest in ultrasonic nondestructive evaluation. The excitation line for a comb transducer is shown as a sloped line from the origin, as illustrated in figure 2. Again, frequency can be swept as you move from one mode to another in seeking out the best inspection possibilities for a particular structure. The horizontal phase velocity line for the angle beam probe can be computed by way of Snell's law. The sloped line for the comb transducer is associated with the spacing between the elements, whereby the slope changes as the spacing is either increased or decreased.

Investigators have been intrigued with long distance inspection of structures, in particular pipelines. See for example, Alleyne, Lowe, and Cawley [15]. Waves can travel several hundred meters to find defects using a guided wave pulse echo mode. A comb transducer model for guided wave nondestructive evaluation is presented by Rose, Pelts and Quarry [16] with an application to pipe inspection by Quarry and Rose [17]. A benefit of the comb transducer compared to the angle beam transducer, is an ability electronically to move the activation lines over the complete dispersion curve space, provided the frequency spectrum of the transducer being used is broad enough. The concepts for sweeping the activation line over dispersion curve space is presented by Li and Rose [18], whereby time delay profiling is used to fool the transducer into thinking it has a different spacing and hence produces an ability of different activation lines and zones in dispersion curve space.

The dispersion curves found in the literature are associated with an infinite plane wave at oblique incidence propagating onto a structure. Unfortunately, the finite size of the transducer and the actual vibration pattern of the transducer gives rise to a phase velocity spectrum, whereby the ability to produce a particular mode and frequency precisely, becomes just about impossible. One must consider both the phase velocity spectrum and the frequency spectrum in trying to get onto the dispersion curve mode and frequency of choice for a particular inspection application. Ditri and Rose [19], Rose, Ditri and Pilarski [20], and Pelts and Rose [21] present the source influence concepts associated with guided wave propagation in various structures, including composite material structures. A sample result presented in figure 3 shows an actual phase velocity spectrum that occurs. For a sample problem in a plate with excitation frequency 4.3 MHz and bandwidth of .6 MHz, notice the change in the phase velocity spectrum as the phase velocity is changed from 3 mm/msec on up to normal excitation, as illustrated in the diagram for a transducer diameter of 3.175 mm. It is shown in Rose [6], how an increased diameter generally decreases the phase velocity spectrum associated with guided wave propagation. In this example, it is shown how the phase velocity spectrum varies as the phase velocity and incident angle are changed. It is interesting to note that the popular acousto-ultrasonic technique with an incident angle of 0° actually produces a guided wave in a structure with a fairly large phase velocity spectrum.

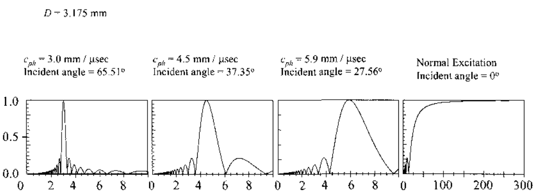


Figure 3 Phase velocity spectra showing excitation amplitude verus phase velocity value : frequency = 4.3 MHz, bandwidth = 0.6 MHz

Let us now consider the subject of wave structure across the thickness of a plate. As we move along a particular mode with changing frequency, the wave structure changes drastically from one position to another. A sample problem is illustrated in figure 4 that shows wave structure for various frequency values on the S1 mode of an aluminum plate. It is shown how the in-plane excitation across the thickness changes as frequency times thickness value changes from 3.5 on up to 6.5. Notice that for a fd value of 3.5, the in-plane excitation on the outer surface is a maximum, whereas the out-of-plane excitation is 0. On the other hand, as the fd value changes to 6.5 it can be shown that the in-plane excitation on the outer surface is practically 0, but the out-of-plane excitation is quite large. Variations of this sort occur for every mode on every dispersion curve, as you move from one frequency position to another. Consider now an example of ice detection where a guided wave might be used to propagate along the surface of a structure to allow interaction with a coating on the surface that could be either ice, glycol or water. A sample application is illustrated in figure 5 along the leading edge of an aircraft structure where guided sensors and a reflector are mounted below the wing surface illustrated in figure 5. The energy would then propagate along the inside surface producing a Lamb wave in the skin that would enable us to come up with a decision algorithm for either ice, glycol, or water detection on the surface of the structure. Note that for the case of wave structure in figure 4 for an fd value of 3.5, with the excitation on the outer surface of dominant in-plane displacement, the energy would leak into the ice, minimally into the glycol, not at all into the water. On the other hand, for a wave structure like that depicted for an fd value of 6.5, we would find that the dominant out-of-plane displacement on the surface would leak into the ice, glycol, and water. It is easy to see how an algorithm could be developed that would provide us with a decision making process for determining the contaminant possibility on the surface of an aircraft as being either ice, glycol, or water. The basic methodology for the energy leakage approach is presented in the paper by Pilarski, Ditri, and Rose [14] where a mathematical demonstration is carried out to show how for a particular wave velocity value, the

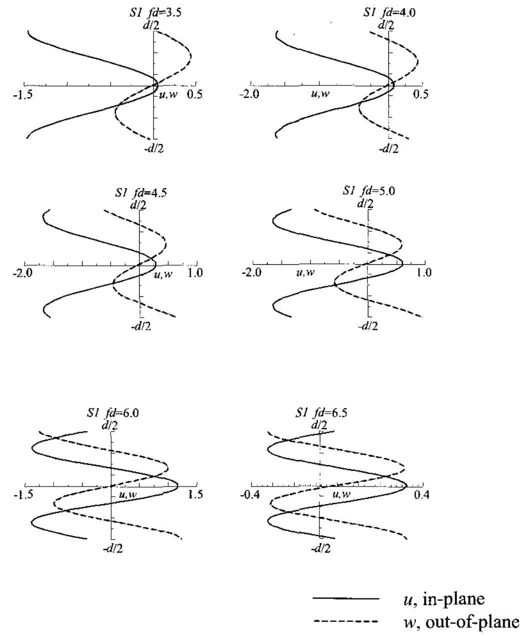


Figure 4 Wave structure for various points on the S1 mode of an aluminum plate

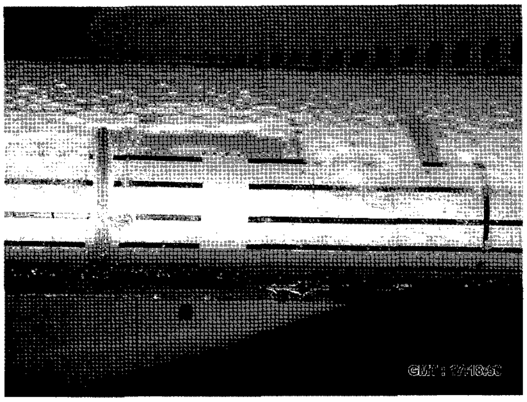


Figure 5 Wing ice detection with guided waves

Figure 6 A revolutionary guided wave inspection approach to fouling detection in the foods industry

dilatational wave velocity, that for horizontal line activation in a dispersion curve, the intersection points with all of the symmetric mode would produce dominant in-plane displacement. These are the special points that can be used for ice detection. This concept is also being carried forward today in a new guided wave inspection approach to fouling detection in the foods industry. Sample data collection is illustrated in figure 6. In order to determine the amount of fouling inside a pipe during food manufacture, as in the Penn State Creamery illustrated in figure 6, where a thin film would develop over long periods of operation on the inside surface hence calling for pipe cleaning. Guided waves can be used to examine the amount of energy leakage into the film and hence determine when pipes should be cleaned. The build-up is such that the energy leakage increases with time and by careful calibration and mode and frequency choice, and follow-up techniques can be developed for the food industry to produce immense savings with respect to food manufacture and down time for cleaning of the system.

Let's consider now a very new application of guided waves for the sample problem of boiler tubing inspection illustrated in figure 7. In this case, transducer access over a part of the structure, of less than 180(circumferential loading is all that is possible, but one must be able to inspect the far side of the structure, the back side. Some interesting work is being carried by Li

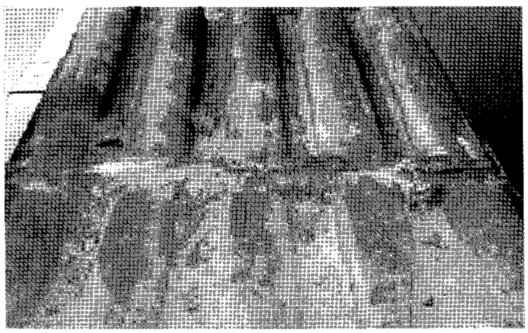
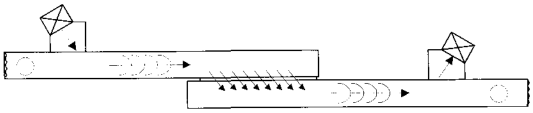
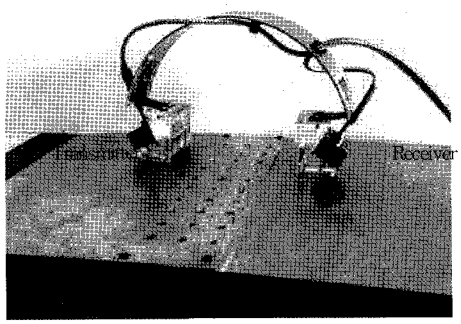


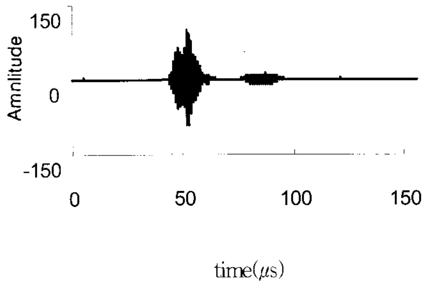
Figure 7 Boiler tubing guided wave inspection potential with less than 180° circumferential loading



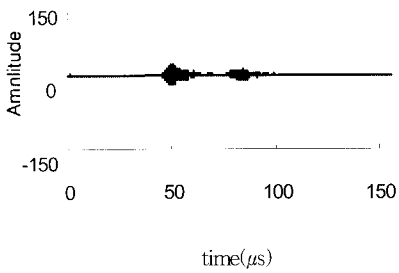
(a) Ultrasonic through-transmission approach for Lap Splice joint inspection



(b) Double spring "hopping probe" used for the inspection of a Lap Splice joint



(i) good bonded region



(ii) poorly bonded region

(c) Signal of a Lap Splice joint inspection showing good and poor results f = 1.5 MHz, = 31

Figure 8 A lap splice inspection sample problem and Rose [22] where the utilization on non-axisymmetric guided waves in a hollow cylinder by way of partial loading around the circumference can be used to place a transducer on one side of the tubular structure, yet still inspect the far side. This is made possible by tuning of phase velocity and frequency for the non-axiasymmetric mode that actually causes focusing to occur at all points inside the structure along the entire length for different combinations of phase velocity, frequency and partial loading excitation.

A countless number of guided wave applications are being introduced in the aerospace industry. A sample lap splice inspection problem is illustrated in figure 8. The protocol is to show that ultrasonic energy can travel across the lap splice joint from transmitter to receiver. Note that this is only possible for certain combinations of phase velocity and frequency where the wave structure is appropriate to cause ultrasonic energy leakage into material 2. If this combination can be found, it is easy to compare a good bonded region with a poorly bonded region. These concepts are extended to tear strap joints and other structures in the aerospace industry. The concept is a simple one, but guided waves and the proper tuning process can make this inspection a reality. Additional problems in aerospace component inspection can be found in Rose and Soley [23].

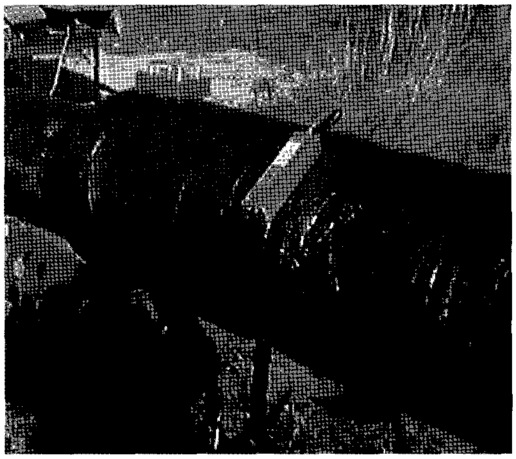


Figure 9 Guided wave inspection potential under tar coatings

Another problem of enormous interest is associated with guided wave inspection possibilities under tar coatings as illustrated in Figure 9. Millions of miles of structures around the world are coated with tar and other materials to reduce corrosion with respect to the surrounding environment. With traditional bulk wave ultrasonic inspection techniques the process becomes very difficult and tedious on a point-by-point basis. The possibility of using guided waves from one position to another, though, is often possible by finding the proper modes, either Lamb wave mode or horizontal shear modes that can be generated in the structure, and that with appropriate phase velocity and frequency tuning can find a mode and frequency that would have minimal energy loss into the coating material. Both piezoelectric and EMAT devices are being considered for the studies.

Going beyond the very successful detection and screening phase of guided wave analysis, some of the newest work being carried out is associated with

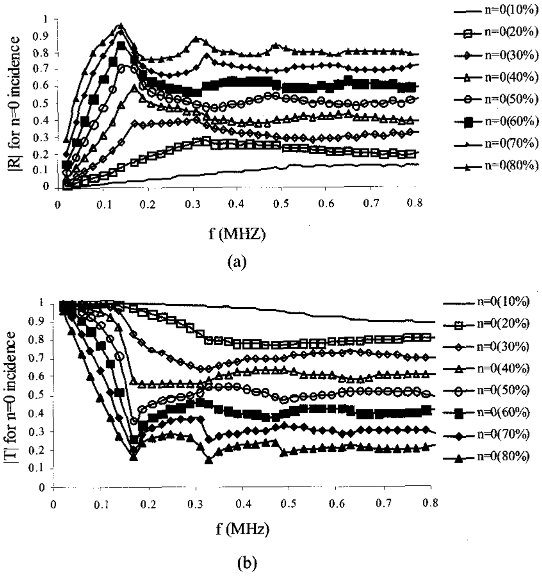


Figure 10 Reflection(a) and Transmission(b) coefficients for Shear Horiaontal n=0 mode under n=0 incident mode for 0.012" elliptical defect width(notch) and 10%, 20%,…80% through plate thickness depth

quantification analysis for defect characteristics and sizing. Some early work in Boundary Element Modeling that examines mode and frequency impingement onto a particular defect and the possibility of flaw sizing is presented in references [24], [25]. A sample result is illustrated in Figure 10 for a shear horizontal wave propagation with n = 0 mode under n = 0 incident mode for very sharp elliptical type defects or notches with the sizes going from 10% to 80% through plate thickness. These are some of the best results that have been found to date with the potential of sizing with guided waves. Note that over a fairly large frequency range, there is a monotonic increase in amplitude of the reflection factor of the shear horizontal wave, as the defect gets larger. There is also a monotonic decrease in the transmission factor over a large frequency range as the defect decreases in size. This is a result that one would hope for, but it might be pointed out, that only under very special conditions of Lamb wave or shear horizontal wave propagation can this monotonic increase situation actually occur.

Guided wave propagation in multi-layered media with particular attention on developing low attenuation

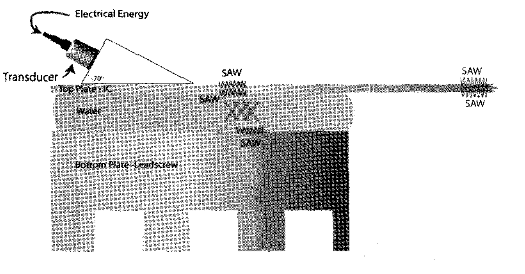


Figure 11 Diagram of predicted radiation patterns in plates

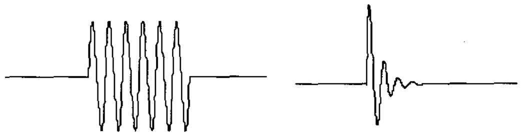


Figure 12 Waveform (a) Tone-burst wave (b) Pulse wave

wave-guides for leaky surface acoustic waves was demonstrated. Through experiments and modeling, this wave-guide was realized in a flat geometry. A unique wave was created in a two-plate system separated by a layer of water. First, a Lamb wave was created in the upper plate by placing a transducer on a wedge on top of the plate at an appropriate angle and frequency. This wave was created to act like quasi-Rayleigh (surface) waves on both surfaces of the plate. The wave on the bottom surface of the upper plate then leaked through the water into the upper surface of the lower plate (Figure 11). It was shown both experimentally and theoretically that the wave on the surfaces of the plates in contact with the water, leak constructively to create a leaky-wave that can travel great distances [30]. It is a well-known fact that a surface wave on a liquid/solid interface radiates acoustic energy into the liquid and is therefore rapidly attenuated. It was shown by experiments and calculations that the proximity of another surface sustains a surface wave through long distances for layers of both plates and concentric tubes. In addition, even when the surface wave is reflected from a distant edge, the returning wave is sustained in the multi-layer system and can be easily detected. The applications range from seismic prospecting for an oil bearing stratum through a water table, to detecting a crack through a double-wall heat exchanger and to determining the position of the top of an industrial lead screw separated with pressurized high temperature water from another wall.

Another application of guided waves lies increasingly in the field of acoustic microscopy [31-35]. Recent developments in nanotechnology require NDE in smaller and smaller components, such as MEMS. The use of Rayleigh waves at very high frequencies (GHz) allows the characterization and flaw finding on a very small scale indeed. Typical wavelengths are in the micrometer range, so that submicron resolution can be achieved in some cases.

It has been very popular to nondestructively visualize internal structures of opaque objects, and to obtain acoustic characteristics of the specimens by instruments utilizing the basic features of ultrasound (e.g., reflection, transmission, refraction and diffraction). However, the frequencies of the ultrasound used for these instruments range typically from 20 kHz to 10 MHz, limiting the resolution of the process. Furthermore, most of their transducers do not have features to focus ultrasound so that the diameters of the ultrasonic beams would be small enough to form an image having the resolution and/or the contrast that the optical microscopes do. In addition, traditional ultrasonic imaging cannot provide data on the elasticity of the small area of specimen.

Therefore, scanning acoustic microscopy is a viable non-destructive method that has high resolution defect visualization to determine elastic parameters in both the medical and the industrial fields. Because the SAM uses acoustic waves, it can penetrate into optically opaque materials non-destructively. In addition, the contrast mechanism of the SAM depends only on the reflection from objects with different acoustic properties and, thus, chemical agents for staining the tissues or the cells are not necessary so that the living tissues or cells may be clearly observed. Since the beam is focused (up to sub-micrometer size) and has a high frequency (10 MHz to 3 GHz) the resolution of the system is on the order of optical microscopes. In addition to the image formation, the SAM can detect the amplitude and the phase of the reflected wave. By analyzing them, the elastic properties of the specimen can be quantitatively determined.

The SAM has two modes. One is the so-called "tone-burst-wave mode" using tone-burst waves (See Figure. 12(a)), and substantially operating in the frequency range between 100 MHz and 3 GHz. Figure 13 is a schematic diagram of a scanning acoustic microscope (burst-wave mode).

In this frequency range, the wavelengths of the waves in water range from 15.0 μm to 0.5 μm. Therefore, an image formed in the tone-burst-wave mode is highly resolved. However, the penetration depth of the waves is limited by attenuation. The tone-burst-wave mode is for penetrations substantially up to 300 μm. Hence, the tone-burst-wave mode is applicable for observing the surface and the sub-surface of specimens. The other is the so-called "pulse-wave mode" using a spike pulse wave or only a few cycles (See Figure. 12(b)), and substantially operating in the frequency range between 10 MHz and 100 MHz. Therefore, resolution of an image formed in this mode is limited. However, the pulse-wave mode is for penetrations substantially up to 1 cm. Hence, the pulse-wave mode is usually applicable for observing a deep interior of specimens.

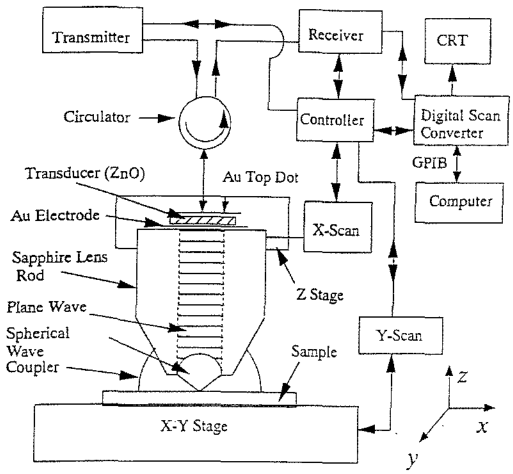
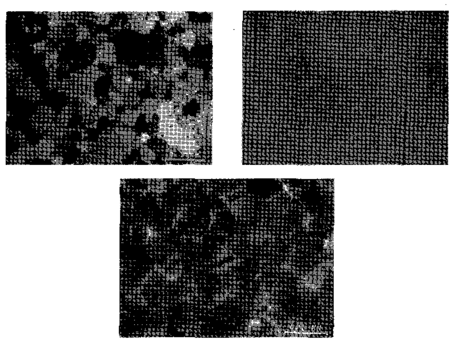


Figure 13 Schematic diagram of a scanning acoustic microscope (burst-wave mode)



(a) z = 0 μm (aperture angle is 120°)
(b) z = -25 μm (aperture angle is 120°)
(c) z = -25 μm (aperture angle is 60°)

Figure 14 Manganese-Zinc-Ferrite Frequency:400MHz

Figure 14 (a) is the acoustic image of polycrystalline manganese-zinc ferrite with an operating frequency of 400MHz and with the acoustic lens focused on the surface ($z=0\,\mu m$). Also, Figures 14(b), and 14(c) are the acoustic images of the same specimen with the acoustic lens focused into the interior ($z=-25\,\mu m$), and the same areas were scanned. The acoustic lenses having aperture angles 120° and 60° were used respectively. Grains are not clearly seen in Figures. 14(a), 14(c), but observed with significant contrast in Figure. 14(b).

Furthermore, the contrast in the images formed by the acoustic lens having the aperture angle 120° changes in accordance with the position of the focal point controlled by the movement of the acoustic lens along the Z-axis. This contrast mechanism is explained by the change of the receiving voltage at the transducer associated with the excitation of the SAW.

When the aperture angle of the acoustic lens is large, surface acoustic waves are generated because the incident angle goes beyond the Rayleigh critical angle. Therefore the contrast in Figure 14 (b) is caused by the generation of the SAW. The aperture angle of the acoustic lens used for forming the image shown in Figure 14(c) is not large enough to generate the surface acoustic waves. Examples are given in Figures 15 and 16.

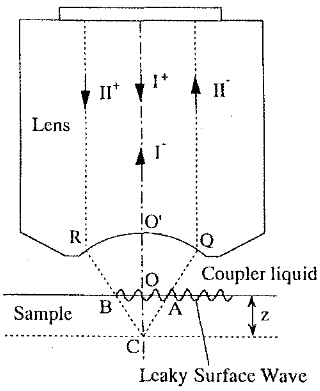
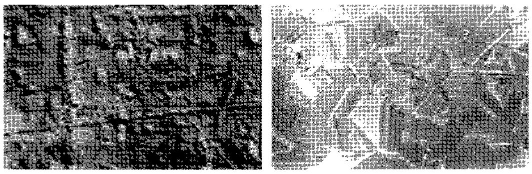


Figure 15 Cross-sectional geometry of spherical acoustic lens, explaining the mechanism of the V(z) curves

When a specimen includes an elastic discontinuity, such as an edge, a step, a crack, or a joint interface, an acoustic image of the elastically discontinuous and peripheral portions visualized by the scanning acoustic microscope shows unique contrast such as fringes or black stripes. As a model shown in Figure 17, this type of contrast appears as an interference effect of surface acoustic waves incident on and reflected from elastic discontinuities.



(a) Incident acoustic waves are scattered by surface roughness of the specimen. Therefore, the interior portions are difficult to observe.
(b) SAM image of the specimen having polished surface
Specimen : Stainless Steel (SUS 304)
Frequency : 800 MHz

Figure 16 Surface roughness

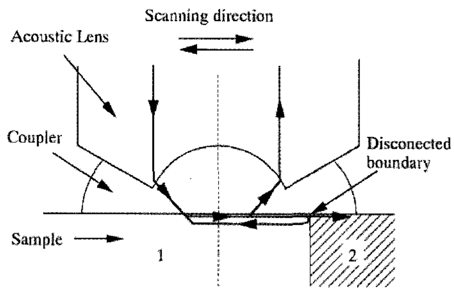


Figure 17 Model of Rayleigh wave excitation at boundary

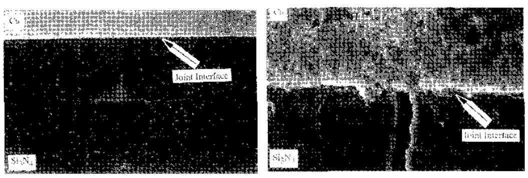


Figure 18 Scanning Electron Microscope (SEM) image
(a) Schematic view (b) Magnified image

Figure. 18(a) is an image obtained by the scanning electron microscope (SEM) of Cu/Si_3N_4 interface after Si_3N_4 portion given the micro-Vickers indentation.

Figure. 18(b) is the magnified SEM image of the portion having the vertical radial crack reached the Cu/Si_3N_4 interface. The SEM with higher magnification could not reveal any delamination. The assumption was that an opened delamination on the surface, when the indentation was completed, soon closed due to change of time and relief of stress.

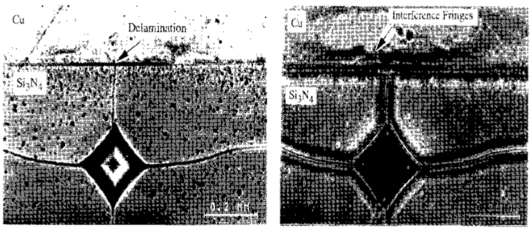


Figure 19 SAM images (a) Z=-40 μm (b) Z= -100 μm Frequency: 400MHz

Figures 19(a), and 19(b) are the SAM images. A frequency of 400MHz was chosen for the visualization. The scanning width was 1.0 mm. In Figures 19(a) and 19(b), the acoustic lens was defocused 40 μm and 100 μm respectively. With no further preparation, the SAM gave the image of the same specimen at the similar magnifications and reveled the delamination (See Figure 19(a)). Moreover, the delamination was observed with enhanced contrast (Figure 19(b)). It can be explained by the SAW scattering mechanism. That is, when an acoustic lens having a high numerical aperture is defocused, an ultrasonic beam is incident at a certain range of angles onto the specimen. In this experiment, the aperture angle of the acoustic lens was 120° . At a certain incident angle, the SAW is excited, traveled on the surface of the specimen, and reflected back from the interface (See Figure 17). These reflected SAW give the enhanced contrast for discontinuities of the specimen in acoustic images. Figures 18 and 19 present additional examples of applications in acoustic microscopy.

Concluding Remarks

Some other recent guided wave inspection possibilities can be found in Li and Rose [28] where a concrete structure embedded in concrete is inspected quite nicely with shear horizontal waves. In Rose and Avioli [29], guided wave analysis is applied to broken rail detection over very long distances along the rail. In Rose and Zha [30], flexural mode tuning is introduced for pipe elbow inspection where it is shown that an application of time wave profiling around the circumferential elements can be used to focus energy anywhere inside the structure. We are then able to inspect inside an elbow region or beyond with guided wave analysis. In Jansen and Hutchins [31], tomographic techniques are introduced that make use of guided wave analysis. These techniques allow us to look at defect analysis and density gradients inside a variety of different structures. In Kwun and Bartels [32], magnetostrictive type sensors are being used to generate guided waves in materials as a demonstration of some of the new technologies that are being considered today to produce guided waves in structures, going beyond ordinary angle beam piezoelectrics, comb type piezoelectrics, EMAT transducers, and now to magnetostrictive sensors. For nanotechnology and Mems Acoustic Microscopy is a high frequency form of the use of guided waves on a very small scale to provide diagnostic information.

We've only touched the surface with respect to the number of inspection applications that could be carried out with guided wave analysis. Again, as an increased understanding of the physics and mechanics of wave propagation occurs, the number of applications will continue to rapidly expand. The transducer design and fabrication technology will also improve tremendously, that will reduce the cost of applying these new techniques in the future. The future will also call for very small leave in place type sensors on a structure in such a way that we could consider smart structure technology utilization of guided waves for inspection and structural evaluation. Wireless activity will also expand the interest and use of guided wave analyses.

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