7-1980

A Comparison of Acoustic Microscopy, Imaging, Holographic and Tomographic Procedures

C. F. Quate
Stanford University

A Comparison of Acoustic Microscopy, Imaging, Holographic and Tomographic Procedures

Abstract
In this paper we offer our view on the various systems that are used or should be used in the field of NDE. We conclude that imaging systems evolve around a given form of radiation and that a given imaging system is not easily adapted to an alternate form.

Keywords
Nondestructive Evaluation

Disciplines
Materials Science and Engineering

A COMPARISON OF ACOUSTIC MICROSCOPY, IMAGING, HOLOGRAPHIC AND TOMOGRAPHIC PROCEDURES

C. F. Quate
Edward L. Ginzton Laboratory
Stanford University, Stanford, California 94305

ABSTRACT

In this paper we offer our view on the various systems that are used or should be used in the field of NDE. We conclude that imaging systems evolve around a given form of radiation and that a given imaging system is not easily adapted to an alternate form.

INTRODUCTION

Imaging can be defined as a system for making the invisible visible. Optical waves are magnificent and optical imaging is the cornerstone. However, these cannot be used for the entire spectrum of applications - other forms of radiation must be employed.

The theme that we will follow in this paper starts with the premise that each form of radiation has characteristics which are unique. Each provides us with a form of imaging that allows us to examine selected properties with great clarity. In optics it is phase contrast, or differential interference contrast, that depends upon and exploits the two degrees of polarization. It is holography which exploits the non-linear properties and speed of photographic film and that has now been simplified with Speckle Interferometry. With the Scanning Electron Microscope it is the large depth of focus that gives us the three-dimensional images. With radio waves it is the side-looking radar and with X-rays it is tomography. With acoustic waves it is total internal reflection.

Our continuing theme relates to the great amount of effort that has been spent on the problem of transferring one technique for imaging to another form of radiation. Holography was invented for electron wave imaging and it tried out with X-rays but there was little progress until Leith and Upatnieks[1] realized that the proper radiation for holography was coherent optical waves. The results with ultrasonic holography are not commensurate with the work that has been done in that field. Side-looking radar was invented to exploit the path of a moving airplane.[2] There is nothing quite like that with other forms of radiation. Tomography is a powerful system for imaging with X-rays.[3] That system was invented for the purpose of using waves that travel in straight lines without refraction. It will be futile to try to adapt this to radiation that undergoes strong refraction. Similarly imaging through total internal reflection is unique to acoustic waves[4] - it will be unprofitable to try to adapt the system to optical waves.

In summary - holography with coherent optical waves works because of the speed and non-linear character of film. Detectors for acoustic energy are linear and much slower. Differential interference contrast in optical microscopes is based on the two modes of polarization with electromagnetic waves.[5] There is nothing equivalent for acoustic waves in liquids. Tomography is based on the constant velocity of X-rays and the absence of refraction. The refraction effects for other forms of radiation can be large and the simplicity of tomography is lost. Imaging through total internal reflection works for acoustic waves since the media carrying the energy has a velocity that is much less than the velocity of sound in the object. With optical waves the opposite is true. This unique property of ultrasonic imaging systems has not been fully recognized. Rollins at the Midwest Institute,[6] Breazeale at Tennessee,[7] and Andrews and Keightley[8] at the British Steel Corporation have carried out important work with this system. Hildebrand and Becker[9] at Battelle have exploited this phenomena in a direct imaging system.

IMAGING AND THE NEED FOR FOCUSING

In this section we will write down some simple, but fundamental, properties of imaging systems in order to establish a few points that we will need in later discussions. The most common and the most often used system for ultrasonic imaging is a simple probe that is moved mechanically to "paint" the image. We can represent this by the schematic of Fig. 1 where we display the diffraction pattern from a plane wave source. With a transducer of diameter D we eventually have a wave diverging with a half-angle β (= $1.22\lambda/D$). The beam extends for a distance $L \approx D/2\beta \simeq \frac{D^2}{2.44\lambda}$. If we wanted to use this system to probe to a depth of 25 cm (L) with a sound wavelength of 1 millimeter we would require $D \sim 25\lambda$. This determines the resolving power of this imaging system. We see that it is 50 times larger than a perfect system where the resolution can approach $\lambda/2$.

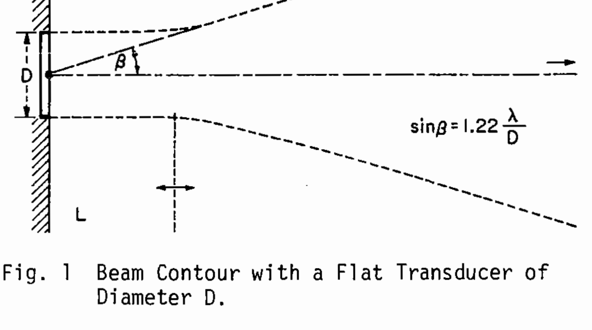


Fig. 1 Beam Contour with a Flat Transducer of Diameter D.

The higher resolution requires that we focus the energy with some kind of lens. The fundamental relations sketched in Fig. 2 where we show a single lens with images two sources spaced apart by a distance d. The minimum value of d is determined by the diffraction patterns of these two point sources in the image plane. The Rayleigh criteria for resolution establishes the minimum angle for the separated points as $1.22\lambda/D$. It is the same angle as the angle of divergence for the plane wave source of Fig. 1. The minimum distance, d , is now given by

$$\frac{1.22\lambda}{D} L \ .$$

But we can see that $D/2L = \sin\theta$ where θ is the maximum angle of acceptance for this lens. It is known as the numerical aperture, N.A. In these terms the resolution as defined by the minimum separation between two resolvable points is given by

$$\frac{0.61\lambda}{N.A.} \ .$$

This resolving power requires an ideal lens (without aberrations) and a large numerical aperture.

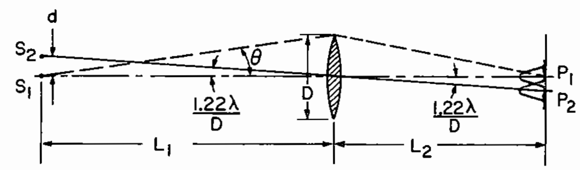


Fig. 2 Minimum spacing, d , is determined by overlap of diffraction patterns P_1 and P_2 . The spacing d must be greater than $\frac{1.22\lambda}{2\sin\theta} = \frac{.61\lambda}{N.A.}$.

In turn, it depends on the refraction of waves at the lens interface. Let us look at that phenomena for three systems of waves, acoustic, optical and X-rays. The refraction angle as determined by Snells law is determined by the velocity difference at the interface. For acoustic waves at a solid-liquid interface can be as high as 10 to 1. For optical waves a velocity ratio of 2 to 1 is possible but it is more usual to find a ratio of 1.5 to 1. With X-rays there is no velocity difference. All of this is sketched in Fig. 3(a). In Fig. 3(b) we see how this translates into the action of a lens. For acoustic waves the large angle of refraction brings the waves into focus near the center of curvature. For optical waves the focal distance is 3 or 4 times the radius of the lens surface. For X-rays the focal length is infinity (i.e. no focussing). This means that we do not have a lens for X-rays and most X-ray images are mere "shadowgraphs". It is the basic reason that tomography works so well. Optical lens formed with a single spherical surface suffer from a large degree of spherical aberrations and these are overcome with multiple surfaces in compound lens. A small acoustic lens with a single surface is free from aberrations and this is the basic reason that the scanning acoustic microscope works so well. At low frequencies where we need a longer reach for the beam the lens must necessarily be large. This increases the aberrations and

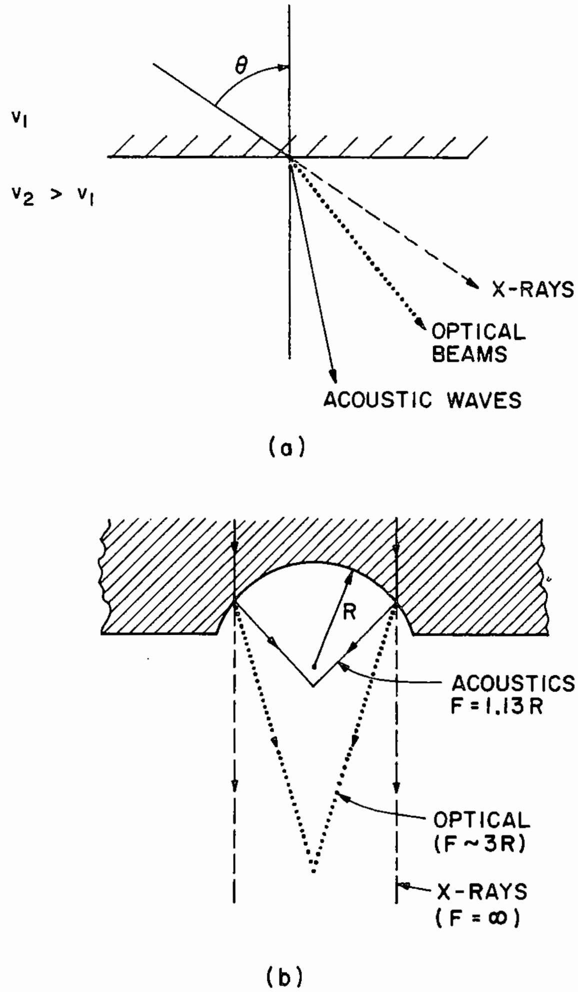


Fig. 3 Refraction and focusing for three forms of radiation.

makes it difficult to put in motion. The preferable solution is electronically scanned arrays. There are two points that I would like to raise in connection with scanned arrays and acoustic imaging. The arrays that I am familiar with control the phase of the electrical signal feeding each element - often with a continuous variation of phase. It is not necessary to use a continuous variation - discrete steps of 22.5° will do the job. For this we only need four elements in series (1) $\Delta\phi_1 = 22.5^\circ$, (2) $\Delta\phi_2 = 45^\circ$, (3) $\Delta\phi_3 = 90^\circ$ and (4) $\Delta\phi_4 = 180^\circ$. This simplifies the problem in microwave systems.[10] If we think about it there may be a way to use this to simplify the phase shifting networks for acoustic arrays. We should also give consideration to a phase shift in the acoustic element rather than the electrical side. My intuition tells me that this may give us a cleaner system. Finally, I would suggest that we move away from the flat ends on the array elements and use domed rods. The advantage of the spherical dome is that it would generate a spherically diverging wave at the position of the array and ensure a wide coverage angle from each element. In summary, an array where the phase shift is introduced into the acoustic path consisting of a series of rods placed on a hexagonal grid[11] and with spherical domes at the liquid interface should be investigated. The sketch of Fig. 4 outlines the overall system.

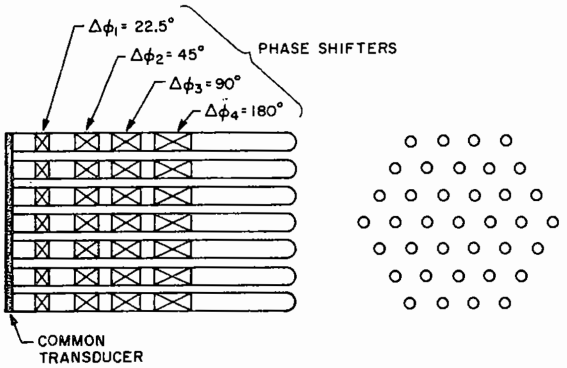


Fig. 4 Proposal for domed hexagonal array with discrete acoustic phase shifters and a common transducer.

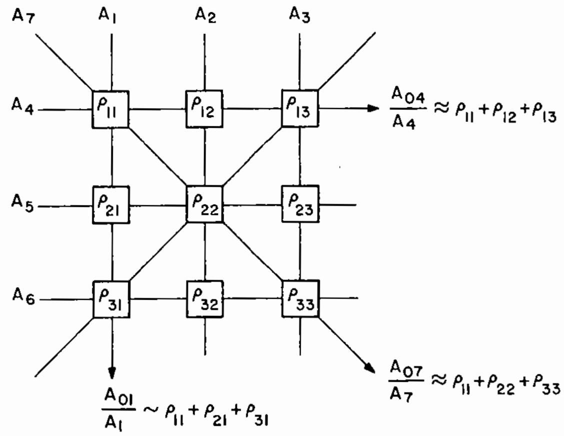


Fig. 5 Sketch of a simple system for tomography. By measuring the A_{01} through A_{on} one can find the individual values of ρ_{nm}.

TOMOGRAPHY

Tomography is a method for reconstructing the image from a series of linear scans. It has been used successfully by Bracewell[12,13] using microwave radiation traveling through outer space and by Hounsfield using X-ray beams in the human body.[3] In both cases the radiation travels in straight lines with refraction. It is used in these two cases to map a single parameter - the emission of microwaves from the region of the sun and the density of material in the human body. In neither case is it possible to focus the radiation and measure these parameters point-by-point. The principle is quite simple and we use a two-dimensional rectangular array to illustrate the process. In Fig. 5 we illustrate a 3 X 3 grid of discrete points with differing densities. The X-ray beam is in the form of a pencil. When it is positioned along the first row it will suffer a change in intensity, ΔR_1, which is proportional to the sum of $\rho_{11} + \rho_{12} + \rho_{13}$. The beam traveling along the second row will undergo a change

$$\Delta R_2 = \rho_{21} + \rho_{22} + \rho_{23}$$

and along the third row

$$\Delta R_3 = \rho_{31} + \rho_{32} + \rho_{33}$$

We next rotate the beam and let it travel along the column to obtain

$$\Delta C_1 = \rho_{11} + \rho_{21} + \rho_{31}$$

$$\Delta C_2 = \rho_{12} + \rho_{22} + \rho_{32}$$

$$\Delta C_3 = \rho_{13} + \rho_{23} + \rho_{33}$$

For a 45^0 degree rotation it travels along the diagonal with a change

$$\Delta D_1 = \rho_{11} + \rho_{22} + \rho_{33}$$

Other rotations will give other sums. It is easy to convince oneself that the separate values of ρ_{i1} through ρ_{33} can be unraveled from all these.

The problem becomes complex for a real imaging problem such as a cross-section of the human head. We don't have nine values of ρ but more like 10,000 or 100,000. For that we need the computer. Hence the name Computer Aided Tomography (CAT). It is a very striking system and it has made an enormous impact on the medical profession.[14] Will it have a similar impact with systems based on other forms of radiation such as ultrasound ? My answer is "No, it will not."

The reasoning is not complicated - tomography serves a grand purpose when the effects of diffraction are absent. Furthermore, X-rays can be collimated and they will travel for a great distance without spreading. For example, with a beam 1 mm in diameter the path length before appreciable spreading takes place, as worked out previously, is D^2/λ. For a 1 mm diameter and a 10 nm wavelength this distance turns out to be

$$10^{-6}/10^{-9} = 10^3 \text{ mtrs} = 1 \text{ Km} .$$

Bracewell[12] worked with diameter D equal to 1000λ and a wavelength of 10 cm. His beam maintained its pencil shape for 100 Km. On the other hand, acoustic beams with a 1 mm wavelength would begin to spread immediately from a source 1 mm in diameter. From a source 1 cm in diameter the acoustic beam would travel only 10 cm before spreading. It is even worse since most objects - such as the human head, or complex materials - have large changes in the acoustic velocity. The media is inhomogenous for sound waves. There the conceptual simplicity of tomography is lost. I doubt that we will ever see an ultrasonic system based on tomography. On the other hand, I would expect a more widespread use for X-ray tomography in NDE. The virtues there will be pointed out by Morris, Kruger and Wecksung at this session.

HOLOGRAPHY AND SPECKLE INTERFEROMETRY

Holography both optical and ultrasonic - preserving as it does both the phase and amplitude of the scattered waves - is so well known that it is not necessary to describe that system here. In any event, it has been done in a recent article by Campbell and McLachlan.[15] Speckle interferometry is important to NDE in that it may find more widespread use than holography. "The speckle pattern, caused by the random interference of light scattered from various depths on the object surface (assumed to be rough) acts as a grid naturally printed on the object surface" (Hung, p. 51).[16] In a sense it thus serves the same purpose as the pattern used in the moire technique. "Speckle photography offers a comparatively easy method of separating the various displacements from a complex distorting structure, simplifying the process as compared with the fringe information of holographic interferometry" (Gregory, p. 184).[17] Interferometers based on speckle are primarily used to monitor vibrations and map nodal lines where the nulls in the vibration modes exist. As such these instruments have been used for crack detection, pressure vessel inspection and composite material inspection. The system holds some advantages over holographic techniques. It does not appear to have found application in ultrasonic systems. Again I suspect that it will turn out to be uniquely suited for coherent optical beams. The working space for such beams can be extended and this permits the inspection of large structures. Further the wavelength near 0.5 micrometers compares favorably with the surface roughness on many objects. Ultrasonic waves with 1 mm wavelength would not enjoy this advantage.

ULTRASONIC MICROSCOPY

We come now to the subject of microscopy. In one sense it can be viewed as a scaled version of imaging as discussed previously. But, there are two characteristics that distinguish it from the imaging at low frequencies and qualify it for inclusion as a separate section. First, the ideal lens consisting of a spherical cavity produces a diffracted limited beam with a beam diameter that is less than one wavelength. The manner in which this can be exploited to form an image with mechanical scanning has been illustrated with the mounts in the poster session. The second, and equally important, is the fact that in reflection imaging with spherically converging waves we encounter the phenomena of total internal reflection (TIR). This is quite unique to acoustic systems. I would hope that it could be used over a much wider front in acoustic systems.

We can begin with some early work of Rollins.[6] He studied the reflection of acoustic waves from a plane surface of copper as a function of the angle of incidence. As the angle increased he encountered the usual critical angles as first the longitudinal wave in the solid moved parallel to the interface. Beyond this he encountered the critical angle for shear waves and near there he found that the excitation of Rayleigh waves along the interface would strongly influence the reflected signal (Fig. 6). Rollins pointed out that the critical angle for Rayleigh waves was sensitive to the parameters of the two materials forming the interface. He also showed that changes in these parameters by whatever means could be monitored by studying the variation in the critical angle as determined by the variations in the reflected signal (Fig. 7). Breazeale[7] in a subsequent article analyzed the reflection of a Gaussian beam incident at the critical angle for Rayleigh waves. He observed that the shape of the reflected beam was dependent upon the nature solid material at the interface - that reflection from a water steel

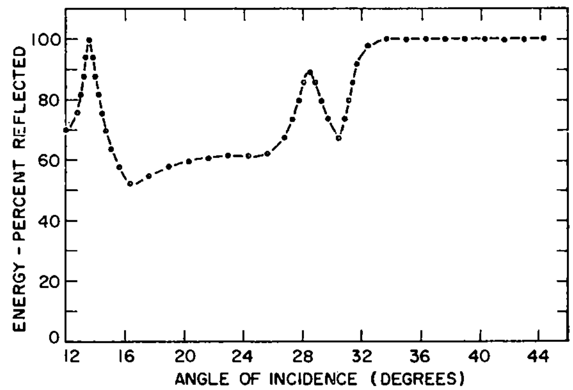


Fig. 6 The reflection versus incident angle from a water aluminum interface. (Rollins[6])

interface generated a reflected beam with a cross-section that differed from that of a beam reflected from a water brass interface. Breazeale was primarily interested in the phenomena of "Schoch" displacement where the reflected beam was actually displaced or translated from the point of contact for the incident beam. The effect is named after Arnold Schoch who first observed it.[18]

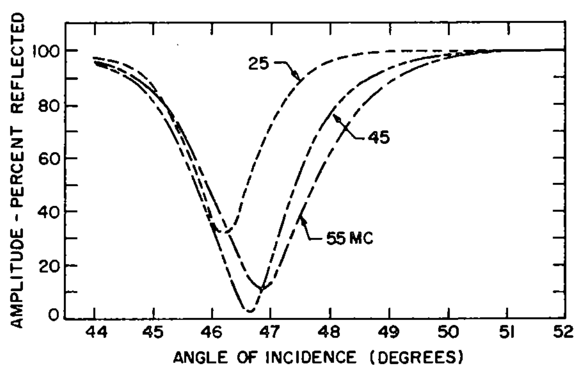


Fig. 7(a) The reflection near the critical angle for electrolytic copper. (Rollins[6])

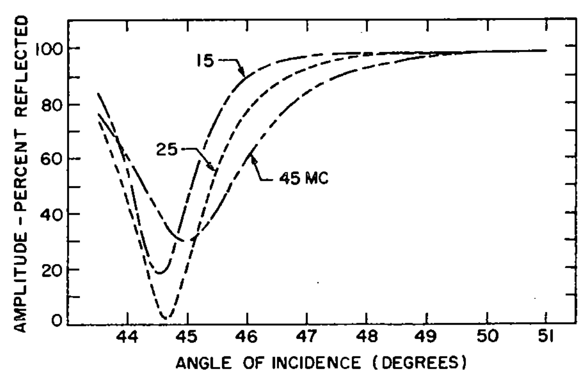


Fig. 7(b) Reflection near the critical angle for the copper of Fig. 7(a) after heat treating (600°F) and quenching in water.

The people at the British Steel Corporation have used this technique to good advantage with a real instrument. Andrews and Keightley[8] have built the apparatus sketched in Fig. 8. It has a source for the incident acoustic beam and a receiver for the reflected beam. The device is made such that the angle of the receiving transducer as measured from the normal is equal to the angle of the incident beam. The transducers are moved in a way that maintains this equal relationship between the two elements as the angle of incidence is varied to accommodate variations in the critical angle for the Rayleigh wave. This variation can arise from either of two causes - a change in the material parameters or a change in the level of stress. The curves of Fig. 9 and Fig. 10 show the quantitative relationship as presented in their paper. They used the technique to monitor levels of stress in sheet steel but there radiography with X-ray appears to be a faster technique. They have found it to be an important instrument for measuring compositional changes and case hardening. In my opinion this system is worthy of a great deal of study.

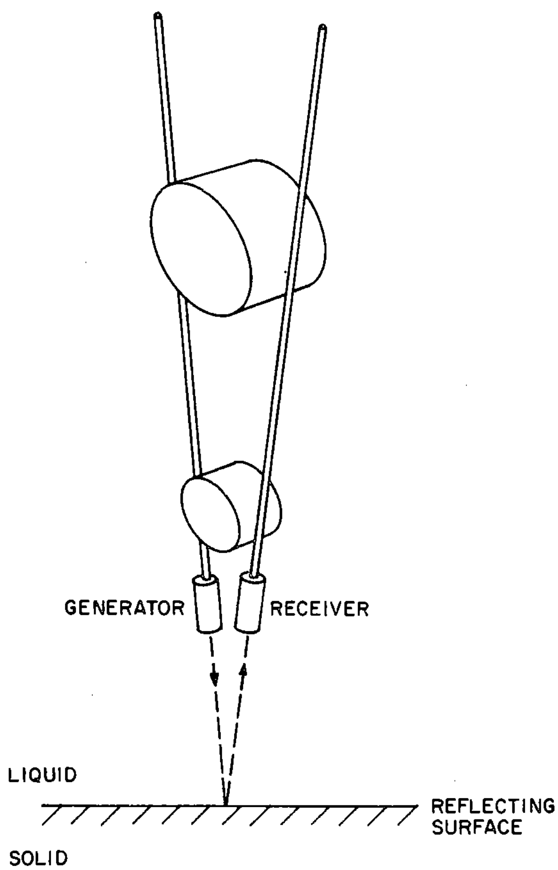


Fig. 8 Critical angle goniometer. (Andrews and Keightley[8])

With this background, I believe the next logical step is to replace the mechanical scanning goniometer with electronic scanners. The most obvious comes not from arrays, but from Shaw's[19] idea of converting surface waves to traveling bulk waves. The beauty of this system is that the angle can be precisely controlled with the freouency. The elegance, the simplicity of this system, all argue that it will one day come into use as an instrument in NDE. The basic proposal for adapting the Grating Acoustic Scanner for TIR is sketched in Fig. 11. I suspect that EMATS could be designed to

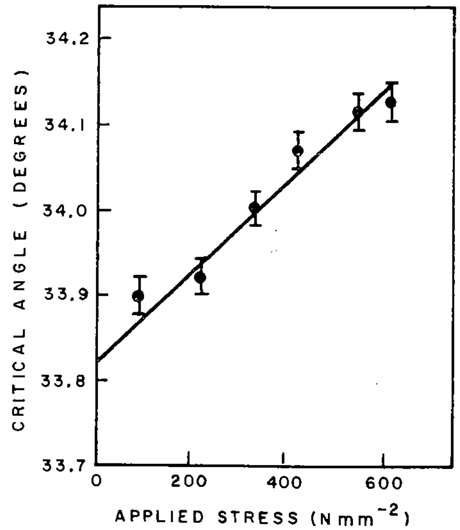


Fig. 9 Variation in critical angle with stress in steel. (Andrews and Keightley[8])

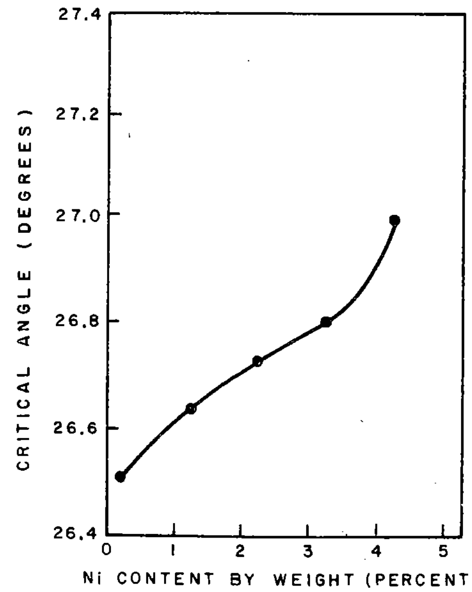


Fig. 10 Variation in critical angle with composition of steel. (Andrews and Keightley[8])

operate in a mode that is quite analogous to this. In any event, it is important to study the phase shifts of the reflected wave when the waves in the solid are changed from propagating waves to evanescent waves.

Total internal reflection is important since it is unique to acoustic radiation. It does not occur in optical systems. The reason is straightforward. In many optical systems the region between the lens and the object is a fast medium and the object itself is a slower medium. The optical ray is refracted toward the normal as it enters the object. The system (with total internal reflection) has been used by McCutchen[20] in a modified optical microscope where the light traveled through oil and a cover slip is common before reaching the object but its use has been limited. We can also simulate the

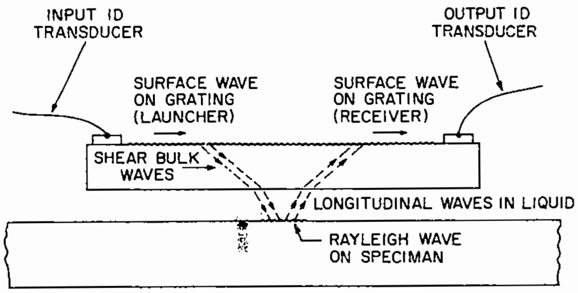


Fig. 11 Proposal for a critical angle acoustic scanner for examining surfaces. It is modelled from the Grating Acoustic Scanner. (Shaw[19])

effect with guided optical waves and Tien has done just that.[21] He used optical beams that were confined to a surface. The surface was coated with a dielectric film of differing thickness such that the wave velocity in one guide is slower than it is in the other. With the input beam incident at the proper angle the translation along the interface is larger than the beam diameter. The reflected beam is well separated from the incident beam as seen in Fig. 12.

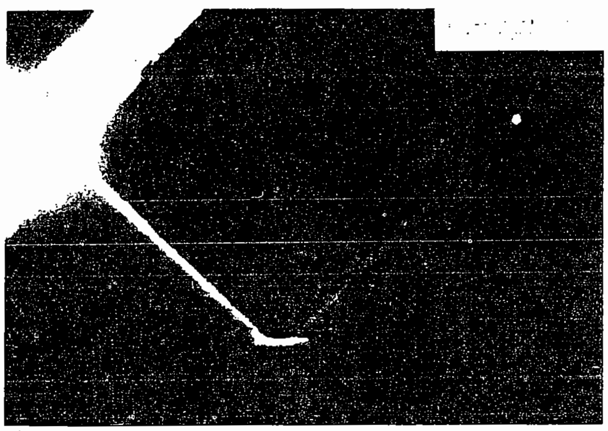


Fig. 12 The remarkable reflection properties of a guided optical beam at the boundary between two dielectric waveguides. (Tien[21])

In acoustic systems we need not resort to these artificial constructions. This phenomena is naturally occurring at a liquid-solid interface when the wave is incident from the liquid. In that situation the wave is bent toward the interface as it enters the solid. The refraction is so strong that the angle between the tilt and the normal for total internal reflection is only 10^o. The conical beam used in the microscope reaches out to 50^o.[22] This means that a large part of the beam undergoes total internal reflection. Important in all of this is the phase shift between that part of the beam inside the critical angle and that part outside of the critical angle. This relative phase shift permits us to monitor variations in the critical angle, for whatever cause, as we scan across the object. The details of how this works can be found in the literature.[4,23,24] Here we can use the results.

The "phase" character of this system of imaging may not be evident in the images themselves as recorded by scanning the object through the transverse coordinates. But it is clear when we study the variation in the reflected signal when the object is moved axially along the beam axis towards the lens. A display of this type is shown in Fig. 13 for three different materials - YAG, YIG and $A\ell_2O_3$. The periodicity of this curve which appears when the object is moved in from the focal point yields information on the elastic coefficients. A plot of this periodicity for various materials has been published by Weglein[24] and analyzed by Atalar[23] with the results of Fig. 14. Another form of this display is shown in Fig. 15 which is a simple object consisting of a chrome strip on glass. Some of you may recognize this as the central component of a mask for integrated circuit technology. The curve of reflectance versus lens-object spacing is here displayed in a two-dimensional plot where the change in periodicity with the addition of the chrome layer is clearly revealed.

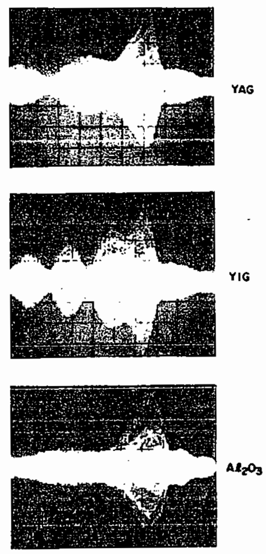


Fig. 13 Long exposure oscilloscope photos of the returning pulses as the distance between the sample and lens is varied. Envelopes show V(Z) curves for different crystals. Horizontal scale 3.75μ/div. (1100 MHz).

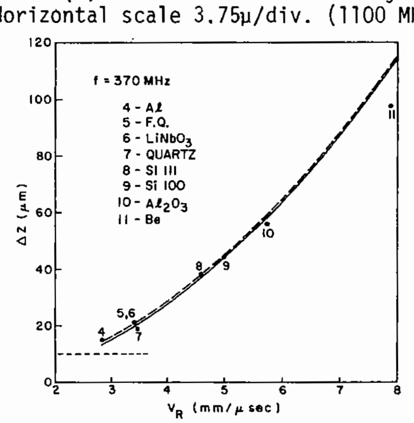


Fig. 14 The periodicity (ΔZ) of the reflectivity (as displayed in the YIG sample of Fig. 13) for different materials. The V_R is the Rayleigh velocity for each material. (Weglein[24])

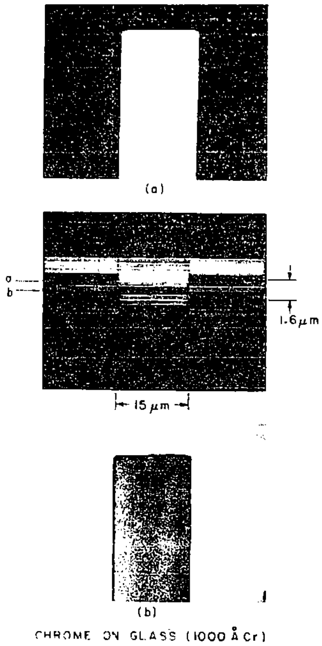


Fig. 15 Acoustic images of a chrome strip on glass. (a) and (b) are images in the x-y plane for two focal positions. Central image is a single scan line (horizontal) as a function of the lens sample spacing.

The type of periodicity, or interference if you will, can be explained by the phase shift that takes place across the critical angle. But there are interference lines of a much finer structure in some of these displays. This comes from a separate source - the energy that moves back and forth between the transducer and the lens. It is a result of residual reflection at the lens surface and its phase does not vary as the object spacing is varied. Although it is small it can be equal to the signal from the object. With this strong interference fringes can be recorded. The optical and acoustic images of Fig. 16 and Fig. 17 clearly show this. The optical image was taken with an interference reflection microscope. Again, this is to be distinguished from the phase shifts associated with the critical angle. Those permit us to record twin boundaries and grain boundaries in the acoustic images - boundaries that are not evident optically. In the illustration of Fig. 18 this effect can be seen in a surface of polished copper.

SUMMARY

Imaging with acoustic waves is unique in many ways. We should concentrate more effort in these areas where it is unique. The EMT transducers is a clear example.[25] The scanned arrays and the conversion to surface waves at a liquid-solid boundary is another.[19] The photoacoustic scanning of surfaces is a third.[26] We should focus more effort on complex shapes - the turbine blades - the holes that are covered with rivet heads. There I think we can progress. In more simple geometry such as the inspection of flat steel plates we will probably lose out to radiography with X-rays as in the example cited with the British Steel Corporation. Tomography with X-rays should be exploited on a

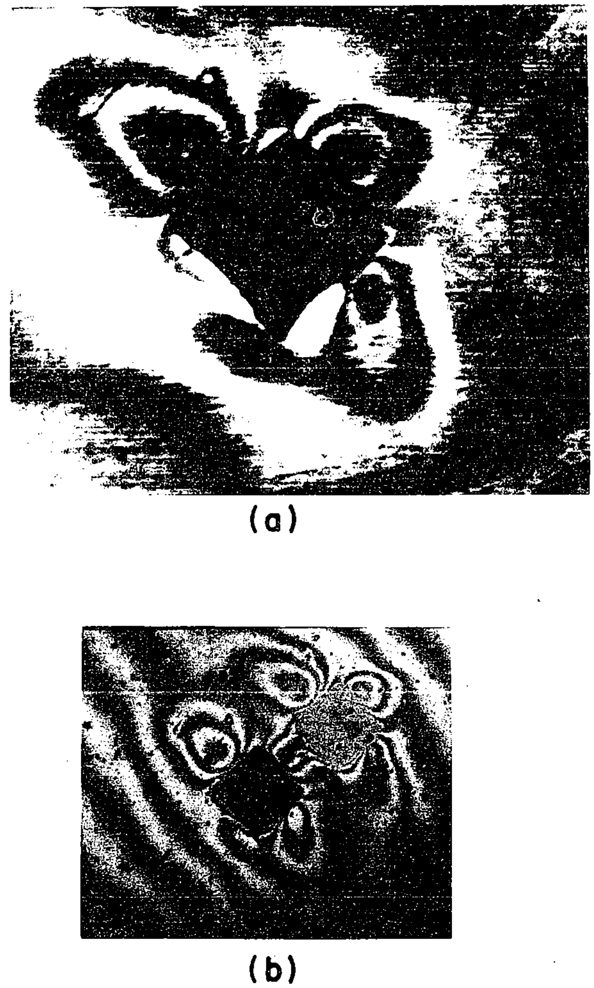


Fig. 16 Acoustic (a) and optical (b) interference patterns for a sample of brass. This is a result of surface contour near the diamond indent.

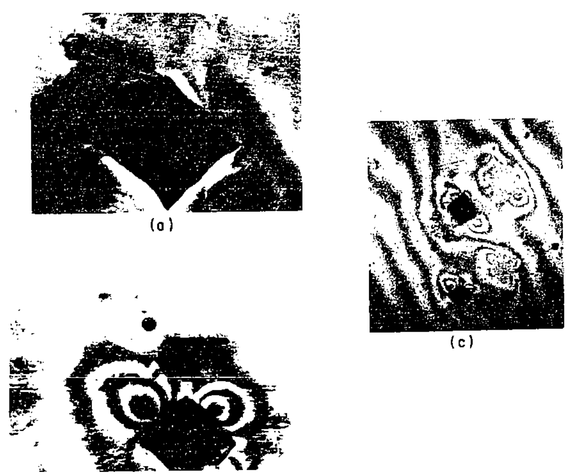
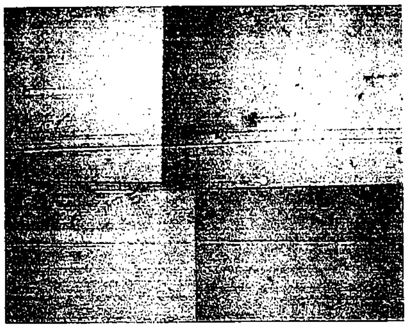
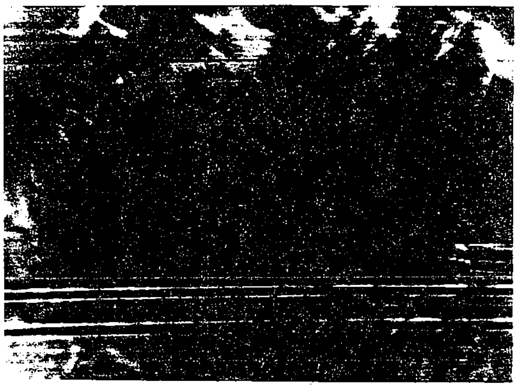


Fig. 17 Acoustic (a) and (b) and optical (c) interference patterns for a sample of brass. It is similar to Fig. 16.



(a)



(b)

Fig. 18 (a) Optical and (b) acoustic (1100 MHz) images of a copper surface.

much wider base. It is uniquely suited to X-radiation which travels without refraction and is sensitive to one and only one parameter - mass density. We should not try to adapt this system to ultrasound. There are much more profitable areas to study. Holography is ideal for optical waves - it is fast - large areas can be explored - stop-action images can be easily recorded. This permits us to study minute changes that take place between successive shots.[15] Holography is not a mode well suited for ultrasound. We should carefully limit our work there. Primarily because there are important areas that need more and still more effort. Surface wave effects, total internal reflection with evanescent waves, and the combination found in photoacoustics are areas where acoustic radiation is superior.

ACKNOWLEDGEMENT

This work was supported by the Advanced Research Projects Agency of the Department of Defense and monitored by the Air Force Office of Scientific Research under Contract No. F49620-78-C-0098.

REFERENCES

1. E. N. Leith and J. Upatnieks, "Wavefront Reconstruction with Continuous-Tone Objects", J. Opt. Soc. Am. 53, 1377-1381 (December 1963).
2. H. Jensen, L. C. Graham, L. J. Porcello and E. N. Leith, "Side-Looking Airborne Radar", Sci. Am. 237, 84-95 (October 1977).
3. G. N. Hounsfield, "Computerized Transverse Axial Scanning (Tomography): Part 1. Description of System", Brit. J. Radiol. 46, 1016-1022 (November 1973).
4. A. Atalar, C. F. Quate and H. K. Wickramasinghe, "Phase Imaging in Reflection with the Acoustic Microscope", Appl. Phys. Lett. 31, 791-793 (15 December 1977).
5. J. Padawer, "The Nomarski Interference Contrast Microscope", Royal Microscopical Soc. 88, 305-316 (June 1968).
6. F. R. Rollins, Jr., "Ultrasonic Reflectivity at a Liquid-Solid Interface near the Angle of Incidence for Total Reflection", Appl. Phys. Lett. 7, 212-214 (15 October 1965).
7. M. A. Breazeale, L. Adler and G. W. Scott, "Interaction of Ultrasonic Waves Incident at the Rayleigh Angle onto a Liquid-Solid Interface", J. Appl. Phys. 48, 530-537 (February 1977).
8. K. W. Andrews and R. L. Keightley, "An Ultrasonic Goniometer for Surface Stress Measurements", Ultrasonics, 16, 205-209 (September 1978).
9. B. P. Hildebrand and F. L. Becker, "Ultrasonic Holography at the Critical Angle", J. Acoust. Soc. Am. 56, 459-462 (August 1974).
10. D. O. Reudink and Y. S. Yeh, "A Scanning Spot-Beam Satellite System", Bell Sys. Tech. J. 56, 1549-1560 (October 1977), also, B. Glance, "A Fast Low-Loss Microstrip p-i-n Phase Shifter", IEEE Trans. Microwave Theory Tech. MTT-27, 14-16 (January 1979).
11. R. M. Mersereau, "The Processing of Hexagonally Sampled Two-Dimensional Signals", Proc. IEEE, 67, 930-949 (June 1979).
12. R. N. Bracewell and A. C. Riddle, "Inversion of Fan-Beam Scans in Radio Astronomy", Astrophys. J. 150, 427-434 (November 1967).
13. R. N. Bracewell, "Strip Integration in Radioastronomy", Aust. J. Phys. 9, 198-217 (1956).
14. R. Gordon, G. T. Herman and S. A. Johnson, "Image Reconstruction from Projections", Sci. Am. 233, 56-68 (October 1975).
15. J. M. Campbell and E. H. McLachlan, "Holographic Non-Destructive Testing", Brit. J. Non-Destructive Testing, 21, 71-75 (March 1979).
16. Y. Y. Hung, Speckle Metrology, R. K. Erf, Editor, Academic Press, New York (1978), Chap. 4.
17. D. A. Gregory, Speckle Metrology, R. K. Erf, Editor, Academic Press, New York (1978), Chap. 8.

18. L. M. Brekhovskikh, Waves in Layered Media, R. T. Beyer, Editor, Academic Press, New York (1960), p. 107.

19. A. Ronnekleiv, H. J. Shaw and J. Souquet, "Grating Acoustic Scanners", Appl. Phys. Lett. 28, 361-362 (1 April 1976).

20. C. W. McCutchen, "Optical Systems for Observing Surface Topography by Frustrated Total Internal Reflection and by Interference", Rev. Sci. Instr. 35, 1340-1345 (October 1964).

21. P. K. Tien, "Integrated Optics and New Wave Phenomena in Optical Waveguides", Rev. Mod. Phys. 49, 361-420 (April 1977).

22. V. Jipson and C. F. Quate, "Acoustic Microscopy at Optical Wavelengths", Appl. Phys. Lett. 32, 789-791 (15 June 1978).

23. A. Atalar, "An Angular-Spectrum Approach to Contrast in Reflection Acoustic Microscopy", J. Appl. Phys. 49, 5130-5139 (October 1978).

24. R. D. Weglein, "A Model for Predicting Acoustic Material Signatures", Appl. Phys. Lett. 34, 179-181 (1 February 1979).

25. R. B. Thompson, "A Model for the Electromagnetic Generation of Ultrasonic Guided Waves in Ferromagnetic Metal Polycrystals", IEEE Trans. Sonics and Ultrasonics SU-25, 7-15 (January 1978).

26. H. K. Wickramasinghe, R. C. Bray, V. Jipson, C. F. Quate and J. R. Salcedo, "Photoacoustics on a Microscopic Scale", Appl. Phys. Lett. 33, 923-925 (1 December 1978).

SUMMARY DISCUSSION
(C. Quate)

Bob Addison (Rockwell Science Center): You indicated you could say something about the adhesion of the chrome by that technique. Can you say any more about that?

C. Quate: We have been given chrome that has four enduring layers, and this periodicity changes, the contrast will change as the adhesion changes. So, the reflection, the critical angle depends very much on how you adhere the film to the substrate. It's very easy to measure, correlate your search.

B. Hildebrand (Spectron): I would like to remark that the paper Larry Becker and and I did was in 1972. We did exactly that kind of imaging using the 180-phase clip, and we measured differences in hardness, and we drilled a hole up through within one radio wavelength of the surface, and it worked real well.

C. Quate: That's beautiful. Where is it? Why hasn't it gone on?

B. Hildebrand: It's in the Journal of Acoustical Society of America. Not much interest was shown.

C. Quate: Why not?

B. Hildebrand: I don't know.

C. Quate: Do you still think it's important?

B. Hildebrand: Yes, I do.

C. Quate: I do too. I apologize for missing that reference.

# #