Nondestructive Evaluation

Gordon S. Kino

We are all familiar with the recent crash of a DC-10 in Chicago and the nuclear reactor incident at Three Mile Island in Pennsylvania. Both accidents were due, in part, to undetected mechanical faults. As mechanical structures become more complex, the need for reliable testing methods becomes more vital. It is important to evaluate the properties of mechanical structures, both during their manufacture and during their operation, in a manner that does not destroy them. Such a test is termed a nondestructive evaluation.

Standard methods of nondestructive evaluation include radiography, eddy current testing, the use of dye penetrants, and ultrasonic testing. Radiographic techniques have some of the same advantages and disadvantages that they have in medicine. They require bulky apparatus, particularly for examining thick metal parts. Furthermore, when large metal parts are being examined, very-high-energy beams must be used, which can necessitate clearing the inspection area (this is a major disadvantage). But just as in medical practice, radiography provides familiar, easily recognizable data, and direct contact with the materials being tested is not required.

Eddy current testing involves the use of a small coil to which a radio-frequency signal is applied to excite currents in a neighboring piece of metal. These currents are interrupted by the presence of a small crack and affect the impedance of the coil. Thus, eddy current testing can be used to determine the presence of a crack and, to some extent, its size.

Acoustic testing techniques stem from Langevin's development of sonar during World War I. An acoustic wave signal of short duration is excited by a piezoelectric transducer at the surface of the material being tested. This acoustic wave beam penetrates the material, is reflected by a flaw, and returns to the exciting transducer. By measuring the transit time of the signal to the flaw and back, its distance from the surface can be determined. By measuring the amplitude of the returned signal and the position of the exciting transducer, some information about the size and location of the flaw can be obtained. The larger the flaw, the larger the amplitude of the return echo. The great advantage of acoustic techniques is that they use elastic waves and tend to measure the elastic properties of the material. Since we are usually interested in mechanical properties of materials, the acoustic measurement technique provides data closely related to a determination of the reliability and useful life of a material.

Summary. Nondestructive evaluation is a technique for determining the presence, type, and size of flaws in mechanical structures without destroying them. A description of various types of nondestructive evaluation methods is given in this article. Particular attention is paid to acoustic wave probing techniques. Major advances have been made in the development of the theory of acoustic wave scattering from flaws and in the development of methods for determining the nature of a flaw from the variation of the scattered acoustic wave amplitude with frequency and angle. Several new types of acoustic imaging methods have been developed; prime examples are the acoustic microscope and electronically focused and scanned acoustic wave imaging systems. New acoustic measurement techniques for determining the fields in materials and predicting their breaking stress are discussed, as is the development of new types of eddy current techniques and electromagnetic transducers.

Most of these methods provide only limited quantitative information on the nature, position, and size of flaws. It was recognized in recent years that a more fundamental scientific approach to the problem was required. It is not enough, for instance, merely to determine the presence of a flaw. It is necessary to know its future effect on the life and strength of a mechanical structure. To do this, knowledge is required about fracture mechanics, material properties, and the relation between the measurement techniques used and the mechanical properties of the structure. It is also necessary to develop sophisticated computer and electronic processing techniques and better acoustic probes. Thus several disciplines, including electrical engineering, physics, materials science, and mechanics, must be brought to bear on the problem.

A few years ago the U.S. Air Force, which was having difficulties in testing military aircraft, realized the need to study nondestructive testing techniques more fundamentally. Michael Buckley of the Air Force Materials Laboratory (AFML) held several conferences to stimulate interest among university and industrial scientists who had the necessary acoustic and related expertise but no previous contact with the field of nondestructive evaluation. This eventually resulted in an interdisciplinary program under the auspices of the Defense Advanced Research Projects Agency (DARPA) and the AFML. This program was inspired and administered by Donald Thompson of Rockwell International Science Center, where basic research work on nondestructive evaluation was already being carried out.

Because of its flexibility and the competence of the researchers administering it, this unusual approach to university research has proved to be highly successful. Approximately eight universities and five industrial research organizations, including Rockwell itself, are working cooperatively on the program. Regular informal meetings are held by the research groups to keep themselves abreast of the progress being made, the difficulties being encountered, and the relationship between their particular research and the overall program.

Interest in this field has increased at several universities—in particular, at Stanford. Stanford now has a very large interdisciplinary nondestructive evaluation research program of its own. Faculty and students in electrical engineering, applied physics, applied mechanics, materials science, aeronautics, and astronautics are involved. Similar programs are being developed at the University of Tennessee and at Iowa State University.

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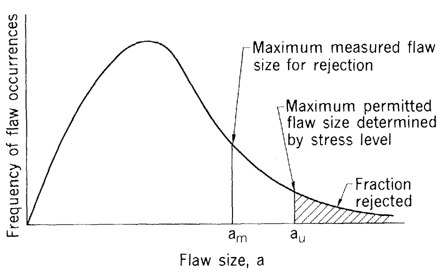
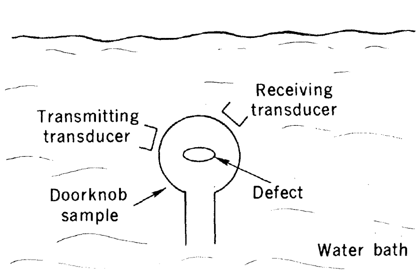
Mechanics of Failure Prediction

The mechanical failure of a structural material usually begins with the formation of a sharp crack at a local inhomogeneity. Once the crack is formed, it will increase in length until failure occurs. The presence of a crack weakens the structure because the stress required for instantaneous failure is smaller the larger the crack. The crack will grow at a rate determined by its initial size and the applied stress. Naturally, the larger the crack is initially, the shorter the time until failure.

There may be many very small cracks or microcracks in a particular structural material. Thus, a typical flaw size-frequency distribution would look like the plot shown in Fig. 1. The problem of nondestructive testing is to choose the maximum flaw size, a_u, above which all parts must be rejected. Since the measurement technique has a certain inaccuracy, the maximum measured flaw size for parts that must be rejected is a_m, where $a_m < a_u$. If the chosen measured flaw size for rejection is unnecessarily small, then too many parts will be rejected and the cost will be unnecessarily high. If it is too large, however, too many parts will fail and, again, the cost will be unnecessarily high. (Thus there is an optimum choice of a_m for minimum cost.) Furthermore, if the accuracy of the measurement is greatly in error, safety requires that a_m be fixed at a value far below the optimum value a_u, in which case too many parts tend to be rejected and the cost becomes higher.

It is therefore very important to increase the accuracy of quantitative prediction of flaw size and of the determination of the relationship between flaw size and failure time. This would make it possible to avoid rejecting components unnecessarily while avoiding the risk of accepting components that would fail. Methods to predict the measurement error and relate the errors to accept-reject criteria (in particular for structural ceramic materials) have been developed by Thompson and Evans (*1*).





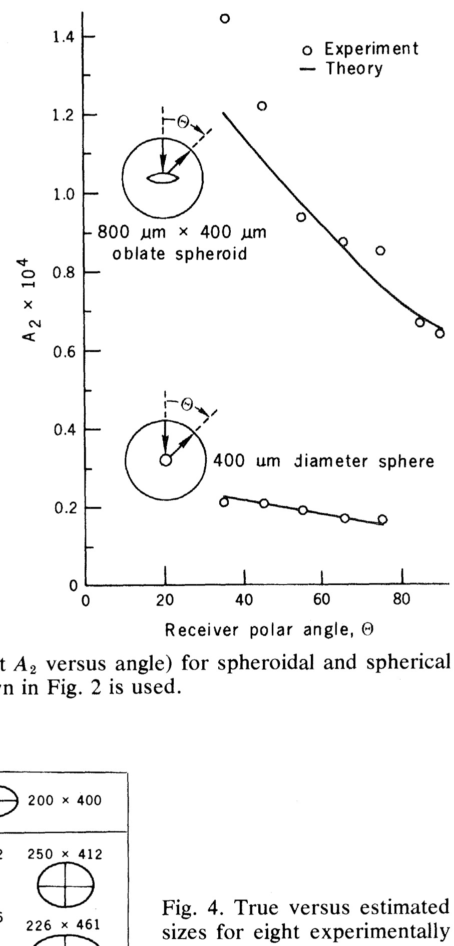


Fig. 1 (top). Flaw size-frequency distribution. Fig. 2 (bottom). Experimental configuration for verification of theory. Fig. 3 (right). Low-frequency scattering (coefficient A_2 versus angle) for spheroidal and spherical voids that occurs when the configuration shown in Fig. 2 is used.

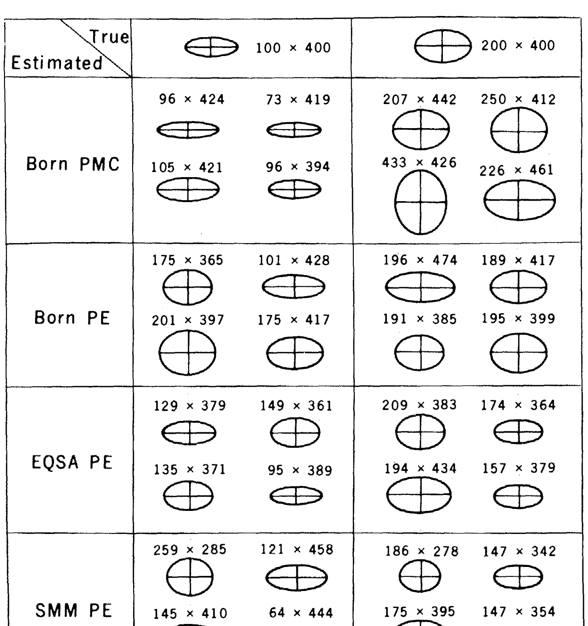


Fig. 4. True versus estimated sizes for eight experimentally recorded oblate spheroid defects (*8*). Four methods were used in computer Adaptive Learning Programs (*ALN*): (i) Born (*3*) pitch-catch (*PMC*), (ii) Born pulse echo (*PE*) (direct reflection) (*3*), (iii) Extended Quasi-Static Approximation (*EQSA*) pulse echo (*4*), and (iv) Scattering Matrix Method (*SMM*) pulse echo (*6*). Sizes are given in microns. Each panel shows four orientations of the spheroidal defect to the transducers (*8*).

Quantitative Measurements of Flaw Size

Table 1 gives typical flaw sizes that cause failure in several common materials (*1*). It can be seen that in some cases the flaws of interest are several centimeters in size; in other cases they measure a few micrometers. This implies that the measurement techniques required may be very different depending on the material that is tested.

Much of the DARPA-AFML-Rockwell program has been devoted to the development of measuring techniques and of theoretical methods for accurately determining the size of flaws. Theories have been developed to predict the amplitude of the scattered acoustic wave from so-called penny-shaped cracks (cracks in the shape of a disk) and surface cracks (which have the shape of a halfpenny extending downward from the surface). Wave scattering from more general spherical and ellipsoidal cavities and inclusions of foreign materials in the host matrix has also been studied. At the same time, it has been considered important to develop techniques for making calibrated defects in metal, glass, and ceramic samples so that the theories can be tested (*2*).

Long-wavelength scattering theory. The problem of determining the scattering of an acoustic wave from a defect in a solid material is closely related to quantum mechanical and electromagnetic scattering theories. Here, because both compressive (longitudinal) waves and shear (transverse) waves can propagate in a solid and because the fields are tensors rather than vectors or scalars, the mathematical difficulties are more severe. It was necessary to reformulate the theory and make extensive use of computers to extract the data from the scattered waves. In compensation, there is much more information available than from equivalent electromagnetic wave-scattering results.

Exact scattering theories are only possible for defects in simple shapes such as spheres or cylinders and can be used as a check on an approximate theory. One type of approximation is the assumption that the acoustic wave has a wavelength much larger than the flaw size. This implies that scattering is in the so-called Rayleigh or long-wavelength regime. In this case, the scattered power varies as the fourth power of the acoustic frequency and the sixth power of the diameter of the defect. Remarkably, Rayleigh wave-scattering results can provide information on the shape, size, and type of defects.

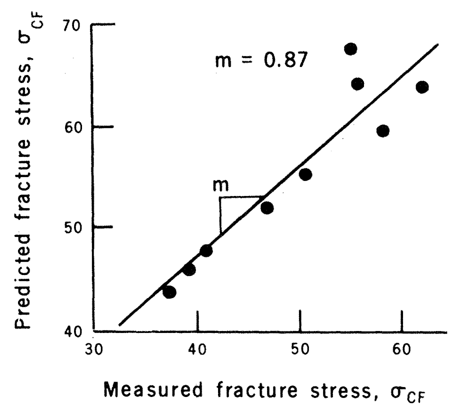
Exact field theories (*3*) for scattering from spherical defects have been compared with several types of long-wavelength approximation theories: (i) the Born approximation, in which it is assumed that the fields in the medium are unperturbed but that the elastic constant and density are perturbed (*4*); (ii) the quasi-static approximation, in which it is assumed that the fields are perturbed in the same way as static applied fields are (*5*); and (iii) the scattering matrix method, which represents the fields at the surface of the flaw in terms of an integral equation that can itself be reduced to a matrix equation which is further simplified by keeping only certain terms (*6*). In this case, the theory can be extended outside the Rayleigh range.

After some idea of the range of validity of the approximation methods had been obtained, they were used to treat problems such as that of an ellipsoidal inclusion, or penny-shaped crack, for which there is no exact field theory solution.

The theories were checked experimentally by measuring scattering as a function of frequency and as a function of the angle between the transmitted acoustic beam and the received acoustic beam (the pitch-catch method). The experiments were conducted with a metal sample in the form of a doorknob, with the transmitting and receiving transducers placed in water baths (Fig. 2). A test sample was made by machining a defect into two matching pieces, which were diffusion-bonded together so that the bond could not be detected acoustically.

The results obtained in the Rayleigh regime for scattering as a function of angle are in excellent agreement with theory (*3, 4*). Figure 3 shows an example of the results obtained by Tittmann and Morris (*7*) for scattering from spherical and spheroidal voids in the low-frequency approximation and a comparison with theory. The agreement between theory and experiment is excellent.

Once it was proved that the theory could be relied upon, the fundamental problem of inversion of the data was addressed by several people in the DARPA program. Would it be possible, they wondered, to determine the shape and size of the spheroidal defect from the scattering as a function of angle? A particularly important method for this purpose is that of Whalen and Mucciardi (*8*), who devised techniques in which a computer is trained with known defects. The computer is then required to pick out defects of the same shape, size, and orientation as the ones it was programmed with. Computers trained with experimental flaw data have shown good success at such tasks. Recently, however, they have been trained with theoretical data. For this purpose, researchers used several different theories and tried to de-



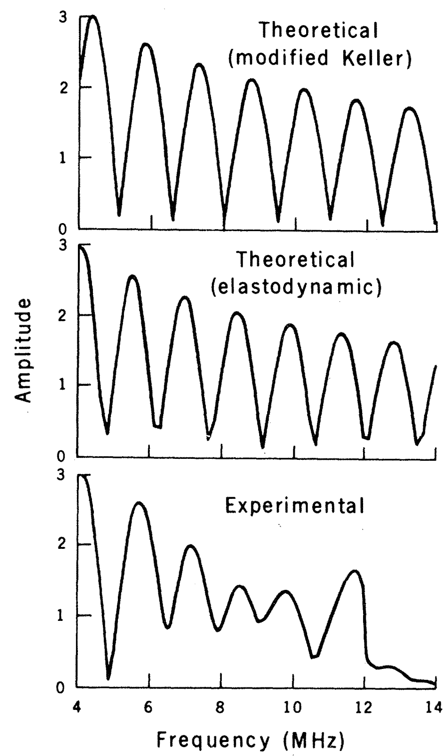
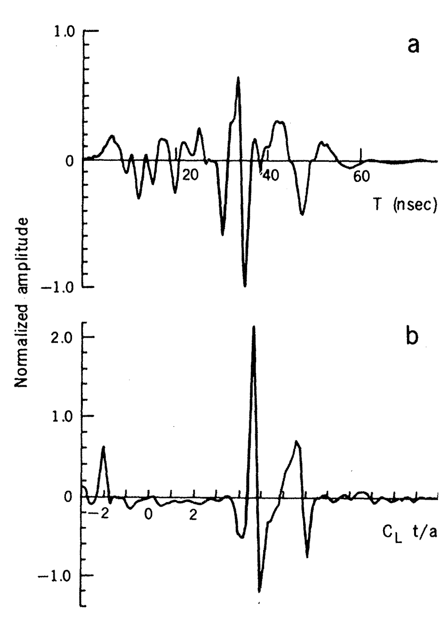


Fig. 5 (left). Actual fracture stress versus fracture stress predicted by the acoustic measurement. The "best fit" straight line relating the two results gave a ratio of 0.87 between them (*10*). Fig. 6 (right). Comparison of experimental data to theory by Keller (*15*) (as modified by Adler) and to the elastodynamic theory by Achenbach and Gantesen (*14*). The wave is incident at an angle 60° to the normal of a penny-shaped crack (2500 μm radius) in titanium.



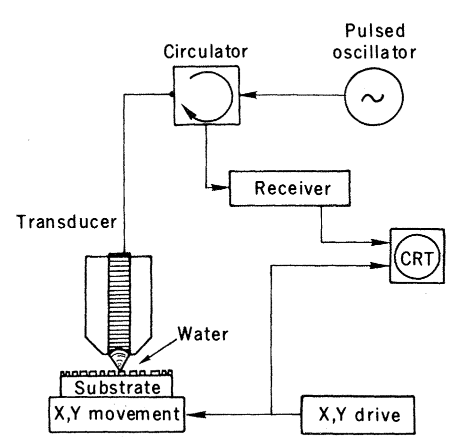


Fig. 7 (left). (a) Impulse response of defect. (b) Theoretical impulse response of a tungsten carbide spherical inclusion in Si_3N_4. C_L, longitudinal wave acoustic velocity; *t*, time; *a*, radius of defect. Fig. 8 (right). A schematic diagram of the Jipson and Quate acoustic microscope operating in the reflection mode (*17*). *CRT*, cathode-ray tube.

termine the shape and size of spheroidal defects from experimental data supplied to them by the Rockwell group (*8*). The results for one set of samples are shown in Fig. 4.

In general, the results are in fairly good agreement with the actual size of the defect. In the pitch-catch method, the transmitting and receiving transducer are at different angles to the major axis of the defect, so experimental accuracy is poor. Figure 4 shows the estimated major and minor axes of ellipses A and B, respectively, for each of the four methods. The computer technique was also able to estimate with reasonable accuracy the polar orientation of the spheroidal defect.

A second set of measurements was made and a theory was devised to address the problem of determining the size of elliptically shaped cracks and relating the results to the breaking stress of a sample that contains a crack. Gubernatis *et al.* (*9*) and Budiansky and Rice (*10*) used the quasi-static approximation; that is, they assumed that the acoustic fields in the neighborhood of the defect are distorted in the same way as applied static fields are. They showed that by measuring the acoustic waves scattered from an elliptical flat crack, it is possible to predict the maximum stress required for fracture.

Auld (*11*) and Kino (*12*) developed scattering theories that could be applied to surface acoustic waves, whose energy is mainly contained near the surface of a substrate. The Budiansky and Rice theory was extended by Resch *et al.* (*13*) to deal with Rayleigh or surface acoustic waves incident to a semielliptical surface crack. The advantage was that it would be relatively simple to carry out experimental tests of the theory by forming the cracks in the surface of a brittle substrate such as glass. After the surface-wave-scattering experiment, the material was stressed until fracture and the predictions of the acoustic theory were checked against actual measurements of fracture stress. Typical crack sizes were 100 to 500 μm. The results, shown in Fig. 5, indicate that there is relatively good agreement between the measured fracture stress and the fracture stress predicted from the acoustic theory. Thus, apparently for the first time, this experiment proved that mechanical properties of materials can be predicted accurately from acoustic measurements.

Short-wavelength scattering theory. Another group of researchers addressed the problem of high-frequency or short-wavelength scattering, in which it is assumed that the length of the acoustic wave is much shorter than the flaw. Achenbach and Gantesen (*14*) extended an electromagnetic theory of Keller (*15*) to an acoustic application and were able to show that when a flat crack is excited by an incident acoustic wave at an angle to the normal, it behaves as if its periphery radiates acoustic waves. Phase interference occurs between the signals radiated from the edges of the crack, resembling the scattering of light from a slit. Thus, the scattered waves exhibit a characteristic interference pattern as a function of both frequency and angle.

Some of the experimental results obtained by Adler (*16*) are compared to Keller's and Achenbach and Gantesen's theories in Fig. 6. The maxima and minima of the scattering pattern are fairly

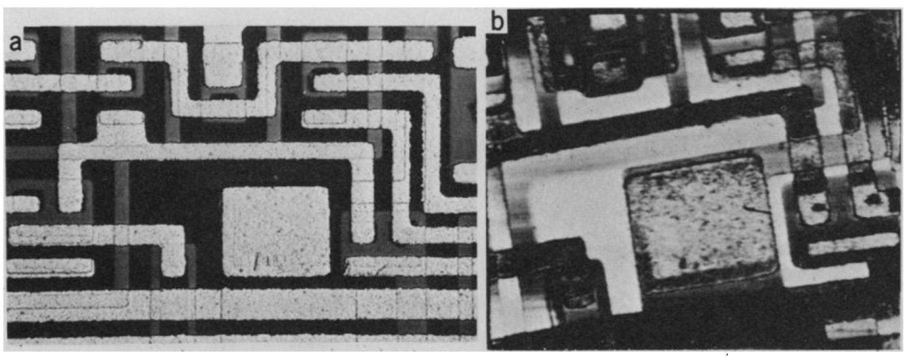


Fig. 9. Comparison of the optical (a) and acoustic (b) images of an integrated circuit. Aluminum line width is about 7 μm.

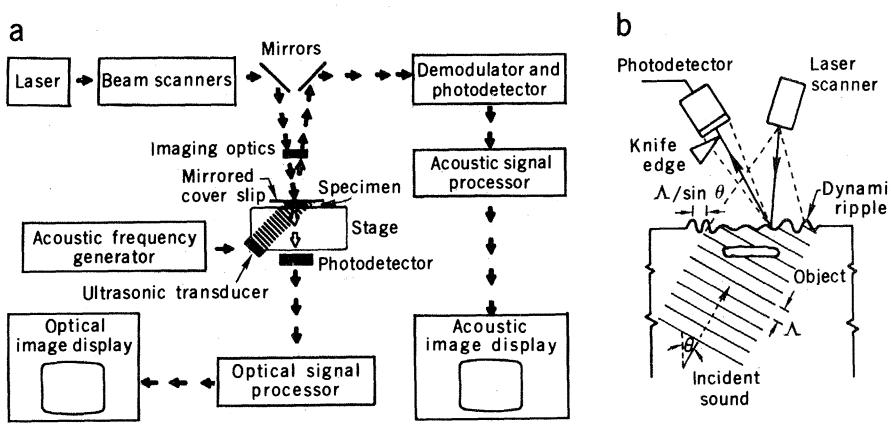


Fig. 10. (a) Diagram of the scanning laser acoustic microscope. (b) Illustration of laser detection of acoustic energy at an interface (*18*). Λ, wavelength.

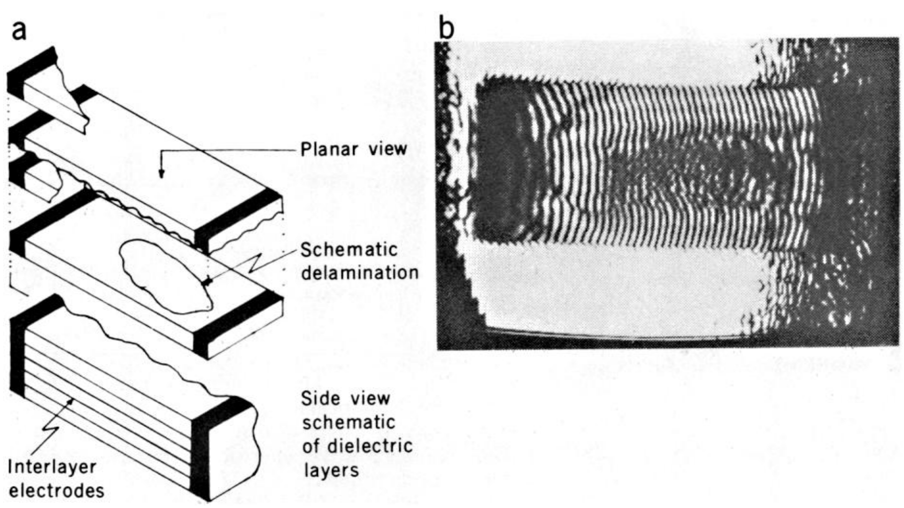


Fig. 11. (a) Ceramic chip capacitor with interlayer delamination. (b) Acoustic interferogram at 100 MHz with the scanning laser acoustic microscope.

Table 1. Order-of-magnitude estimates of critical flaw sizes for common materials.

Material	Type	Critical flaw size (mm)
Steels	4340	1.5
	D6AC	1.0
	Marage 250	5.0
	9Ni4Co 20C	18.0
Aluminum alloys	2014-T6S1	4.5
	2024-T3511	25.0
Titanium alloys	6A1-4V	2.5
	8A1-1Mo-IV(β)	14.5
Silicon nitrides	Hot-pressed	0.05
	Reaction-sintered	0.02
Glasses	Soda lime	0.001
	Silica	0.003

closely predicted by their theories and can be used for picking out the size of the penny-shaped crack. The results for scattering as a function of angle are in still better agreement with the theory. Very accurate results of this type have been obtained by Tittmann (*17*), who used surface acoustic waves incident to surface cracks.

Another important set of problems concerns testing structural ceramics such as silicon nitride and silicon carbide. Several research groups around the world are attempting to construct automobile turbines with these materials because of their strength, the easy availability of the raw materials from which they are made, and the high temperature at which they can operate. This could lead to a small, clean, highly efficient engine. The basic problem is that flaws as small as 10 to 25 μm can cause the brittle turbine blades (which are themselves only a few centimeters long) to break. Because of the smallness of the flaws that must be detected, Murakami *et al.* (*18*) have developed new high-frequency nondestructive testing techniques that make use of a thin-film transducer of zinc oxide deposited on a sapphire rod that is placed against the ceramic material and operated with pulse lengths of 2 nanoseconds at frequencies of 100 to 500 megahertz. These frequencies are one order of magnitude higher than those used previously in nondestructive evaluation. Murakami *et al.* carried out sophisticated signal processing with a computer to compensate for the frequency response of the transducer and the diffraction and attenuation in the sample, which varies with frequency. By this means it is possible to compare with experimental results the exact field theory for scattering of a signal from a spherical defect in ceramic material.

Using calculations by Richardson and Cohen (*19*) at Rockwell, it is possible to predict scattering as a function of frequency from various types of spherical defects in materials such as tungsten carbide and silicon when introduced into a matrix of silicon nitride. Since the frequency response of the scattered signal is extremely complicated, it would be easier to look at scattering as a function of time rather than frequency; that is, as a function of the time response of the scatterer when excited by a short acoustic pulse. One would expect, for instance, that a spherical cavity excited by a short acoustic pulse would give rise to a single pulse reflected from its front surface. An inclusion would give rise to at least two reflected pulses, one from the front surface and one from the back surface somewhat later. The latter is often large in amplitude because of the focusing caused by the spherical reflector.

Figure 7 shows the results for a tungsten carbide inclusion in a matrix of silicon nitride. The exact theoretical response curve shows a short pulse that is followed by a series of later pulses. The experimental curve shows a similar pattern, except that additional signals arrived between the two main sets of pulses. This was because the inclusion was not pure tungsten carbide, but a two-phase mixture of tungsten disilicide and silicon carbide. A good measure of the diameter of the defect can be obtained, and such techniques show very clearly (by means of a single or double pulse) the difference between a vacancy and an inclusion.

Acoustic Imaging

The acoustic microscope. An important development in recent years has been the use of imaging techniques to locate and find the shape of defects in materials. For example, Jipson and Quate (*20*) and Kessler and Yukas (*21*) have constructed two very different types of scanning acoustic microscopes for observing tiny flaws near surfaces.

Jipson and Quate's microscope (Fig. 8) operates in the frequency range between 100 MHz and a few gigahertz. It uses a thin-film zinc oxide transducer deposited on a sapphire substrate in which a spherical lens is machined. The contact to the sample is made through a thin layer of water. The lens focuses an acoustic beam to a point close to its center of curvature, with a definition a little better than an acoustic wavelength. With a water immersion medium, the definition is approximately 4000 angstroms at 3 GHz.

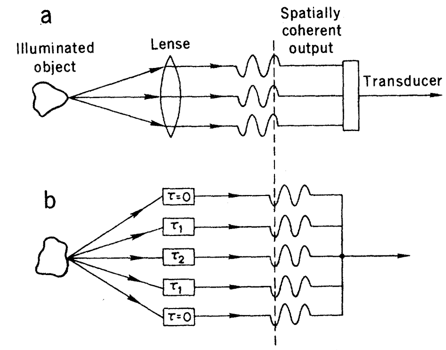


Fig. 12. (a) Diagram of rays passing through a physical lens to a plane transducer (*19*). (b) Diagram of a time-delay system for focusing.

The beam reflected from the substrate of interest is received by the same transducer and the output signal is used to modulate the intensity of a cathode-ray tube (CRT). The sample is scanned by means of a loudspeaker movement in one direction and by means of a hydraulic piston in the perpendicular direction. By coupling this movement to the deflection of the spot on the CRT face, a scanned, TV-like image is obtained.

Figure 9 shows a picture of an integrated circuit taken with the microscope operating in a reflection mode at a frequency of 2.4 GHz. The wavelength is approximately 6000 Å. This picture illustrates a very important property of acoustic waves—their ability to penetrate an optically opaque object and measure subsurface characteristics. In this case, the aluminum gates of the Metal Oxide Semiconductor Floating Electrode Transistor (MOSFET) deposited on the substrate have a layer of silicon dioxide approximately 1000 Å thick between the aluminum and the silicon; this region shows as a bright spot. When no oxide is present, the picture of the gate is dark.

Kessler and Yukas's microscope (Fig. 10) makes use of the ripple of a solid surface caused by an acoustic wave. The ripple deflects a laser beam, and a photodetector measures the deflection (*18*). By passing the focused laser beam past a knife-edge, it is possible to change this deflection to an amplitude modulation that can be displayed as an intensity modulation on the CRT. By scanning the laser beam across the sample (which can be done at normal TV frame rates), an acoustic image of the surface of the sample can be displayed simultaneously. Furthermore, because the system is basically an optical one, it is possible to obtain optical images of the same region at the same time for comparison. Figure 11 shows an interferogram of a ceramic chip capacitor taken at 100 MHz with a Kessler and Yukas microscope. Interlayer delamination can clearly be seen.

The Jipson and Quate microscope has demonstrated definitions as good as 4000 Å—comparable to the best optical microscopes. The Kessler and Yukas microscope has a poorer definition and operates at considerably lower frequencies (100 to 500 MHz); however, it has the advantages of real-time imaging, an optical as well as an acoustic display, and a larger field of view on nonplanar samples.

Electronic scanning and focusing. An important development is the use of electronically scanned imaging systems. As we have indicated, nondestructive evaluation research seeks a firmer quantitative basis and a basic understanding of the criteria for structural failure. But the evaluation techniques are nearly worthless if the time spent evaluating the flaws is more costly than replacing the part. Therefore, a considerable effort has been made to replace the simple acoustic probe an operator uses to manually scan along a structure in search of flaws. This technique requires skill but becomes boring and tends to be very slow. Thus there is an obvious advantage in quickly displaying an easily recognizable image of a flawed region.

The ideal characteristics of acoustic imaging techniques suitable for examining large structures are (i) a rapid process that uses electronic rather than mechanical scanning and (ii) acoustic beams that are focused so that good transverse definition and range resolution through the depth of a thick sample can be obtained. The problem with focusing an acoustic beam is that the physical lens usually required must be immersed in a medium that can propagate acoustic waves. For low-frequency imaging systems operating in a megahertz range, the propagation path may therefore be 10 cm or more. Thus, the imaging system tends to be very bulky and heavy. To obtain good range definition and transverse resolution, a lens is needed whose focal length can be varied as the acoustic pulse travels outward from the transmitting transducer. This is a difficult problem because of the speed required and implies the use of electronically variable focusing techniques rather than a physical lens.

In order to understand why certain components are needed for an electronically focused and scanned system, consider the action of a physical lens that focuses the signal received from one point on an object onto the plane of a large-area transducer (Fig. 12a) (*22*). The physical lens delays the rays passing through it so that all rays reaching the transducer from the focal point suffer the same phase and time delays. To perform the equivalent process electronically, the signals are received by an array of small transducers. The signal arriving at each array element (shown in Fig. 12b) must be delayed in such a way that they are in phase and can be added to each other. Conceptually, the simplest way to do this is to connect electrical delay lines to

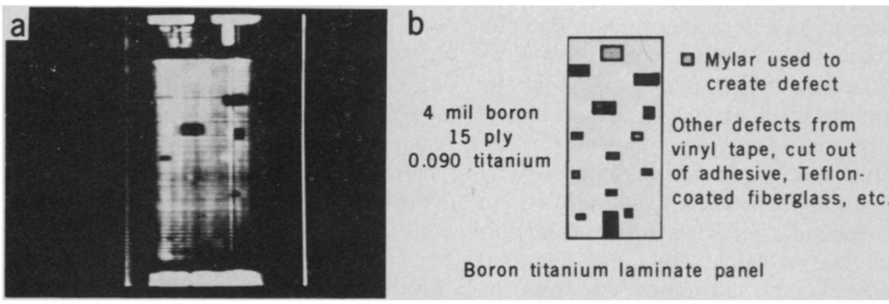
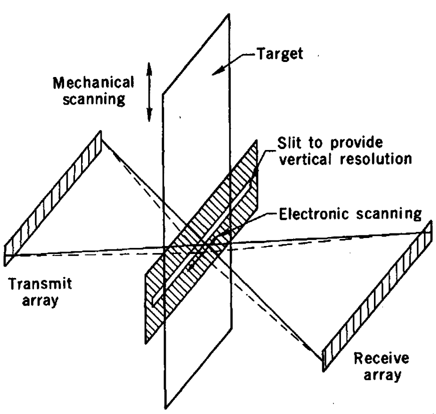


Fig. 13. Transmission image (a) of boron and titanium panel taken at 2.2 MHz using the system diagrammed in (b).



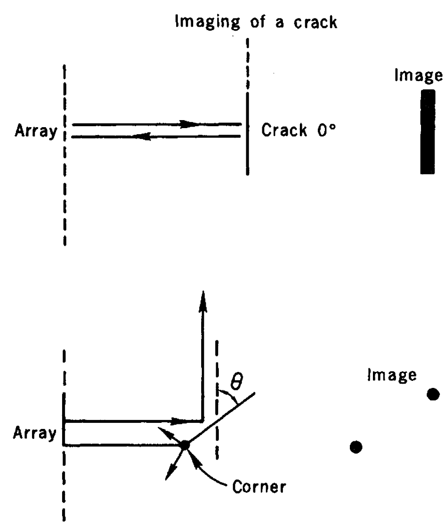


Fig. 14 (left). A transmission imaging system with electronically scanned focused arrays. The mechanical scan provides scanning in the second dimension. Fig. 15 (right). Illustration of scattering from a crack head-on (a) and at an angle Θ to a transducer array (b).

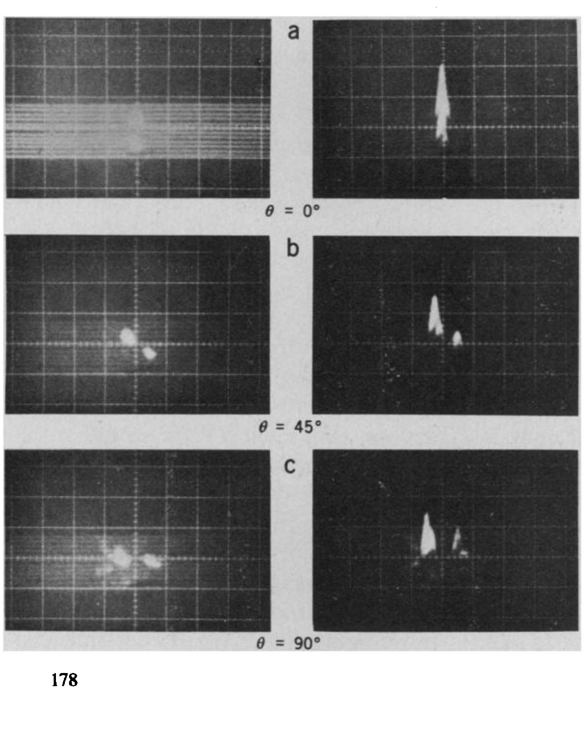


Fig. 16. Photographs of a surface crack taken in the gated mode with the crack facing the array (0°) at 45° and 90° to the array.

each element of the array; a pulsed radio-frequency signal emitted from a point on the object will then arrive at the receiver transducers at different times. The signals from these elements of the array are appropriately delayed to arrive simultaneously at the output of the delay lines and can be added together (Fig. 12b). Therefore there will be a strong response from that particular point, but the signals arriving from some other point would arrive at different times and be out of phase. By changing the delay times of the individual delay lines, the focal point of the acoustic beam can be changed at will.

Various implementations of electronically scanned and focused systems have been demonstrated by Kino (*22*). One example, shown in Fig. 13, is a transmission image made at 2.2 MHz of a boron-reinforced epoxy sample on a titanium backing, a material used in aircraft construction. One of the problems with it is that the layers can become debonded. The system used for transmission imaging is shown in Fig. 14. Mechanical scanning is carried out in one direction and electronic scanning of both a transmitter and receiver array in the perpendicular direction. Flaws in the sample are clearly visible.

A second system has been used for imaging cracks in a surface. We pointed out earlier that the results of Keller (*15*), Achenbach and Gantesen (*14*), and Adler (*16*) demonstrate that a crack behaves as if its edges radiate acoustic waves independently. A physical illustration of this phenomenon can clearly be seen by using imaging. As shown in Fig. 15, an array is placed opposite the crack and the acoustic beam emitted from the array illuminates the crack. When the crack plane is parallel to the array, signals emitted from the array are specularly reflected by the crack back to the array, and an image of the crack is displayed. On the other hand, if the crack is at an angle to the incident beam, the specularly reflected signals do not return to the array. The only signals returning to the array are now emitted from the two ends of the thin crack, which appear as bright spots. Photographs of the displayed image from the crack are shown in Fig. 16.

Imaging systems are now being used in many ways (*22*). The systems for examining the human body are beginning to be adapted to the nondestructive testing field. Other systems using digital processing techniques are being developed by Kino and his co-workers, by Anderson at Varian Associates, by J. Posakony and his co-workers at Battelle Northwest Memorial Institute, and by others. It is expected that imaging methods will be even more widely used in the future.

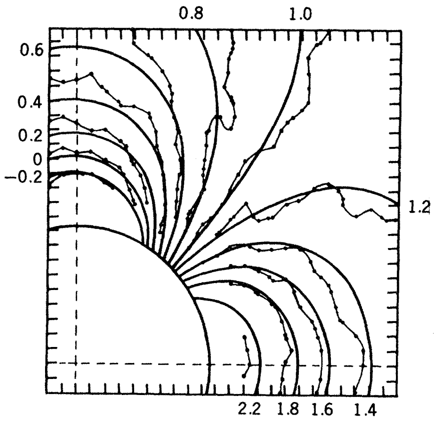


Fig. 17. Experimental (knobbed lines) and theoretical (smooth lines) stress contour plots for a 6061-T6 aluminum panel with a central circular hole.

Conclusion

In this article I have discussed many new approaches to the problem of nondestructive evaluation. These include a considerable development of scattering theory along with experiments to check it, and the development of new types of microscopic and macroscopic imaging systems. At the same time, much research has been carried out on the problem of relating acoustic measurement methods to quantitative predictions of fracture and of the useful life span of mechanical structures.

We have not dealt with the whole range of basic research now being carried on in the field of nondestructive testing. An example of the progress being made involves the direct determination of stress near a crack by measuring the change in the acoustic velocity of a wave caused by the presence of the stress (*23*). By using a mechanically scanned transducer, this technique has made it possible to measure the stress fields around the crack and should lead to measurements of the effect of welding and fatigue on the residual stress fields in structures. An illustration of stress fields around a hole in aluminum, measured by this technique and compared with results based on theory, is shown in Fig. 17. Good agreement is obtained between the two sets of results.

Another large subset of experiments in the nondestructive testing field has involved the development of better acoustoelectric and acoustomagnetic transducers. For this, reproducible, broad-frequency band transducers with high efficiency are obviously required. New types of transducers that can excite the different types of relevant waves are needed. For imaging systems, the problems of the development of arrays of transducers is extremely severe, whereas for very-high-frequency operation still other types of transducers are required. Therefore, along with the development of the nondestructive testing field there has been a considerable development of transducer technology (*24, 25*).

A particularly important example of progress in transducer technology is the use of magnetic techniques to excite acoustic waves. A small coil is placed near a metallic sample in the presence of a static magnetic field produced by a magnet. When a radio-frequency current is passed through this coil it induces currents in the neighboring metal sample that in turn interact with the applied static magnetic field to vibrate the sample and thus excite acoustic waves. The advantage of such a method is that the transducer need not make contact with the sample. As a result, acoustic waves can be directed against and received from rough pipes of the type used in gas lines. The technique is, therefore, proving useful for carrying out acoustic measurements in difficult samples (*26*).

Finally, there has been considerable development of the standard eddy current techniques. By using new theoretical developments and modern microwave methods, Auld *et al.* (*27*) and the group at Rockwell have shown that it is possible to make use of the ferromagnetic resonances of small ferrite spheres. Such spheres are resonant at a microwave frequency determined by an applied static magnetic field. If a ferrite sphere is placed near a metal object, the resonant frequency will be perturbed. In the presence of a crack, the perturbation will be different. Therefore, by using a sphere about 1 millimeter in diameter and moving it over the surface of a sample, very small cracks can be easily detected and their sizes determined. By this means, an entirely new method of measurement of surface cracks has been demonstrated.

A wide range of research on acoustic emission techniques, nonlinear acoustics for measuring fatigue cracks, holographic techniques, and acoustic tomography is being carried out in laboratories throughout the world. Research in this field can decrease manufacturing costs and increase the useful life of mechanical structures. Most important, it can safeguard human lives. Nondestructive evaluation research programs should therefore be expanded and their results used in operational systems.

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Radar Measurement of the Upper Atmosphere

James C. G. Walker

In 1958 William E. Gordon suggested that radars then in existence had the power and sensitivity to detect the Thomson scattering of electromagnetic radiation by free electrons in the ionosphere (*1*). That this suggestion was correct was shown almost immediately by Bowles (*2*), who used a powerful radar in Illinois that was originally constructed by the Smithsonian Astrophysical Observatory for the study of the ionized trails produced by meteors in the upper atmosphere. Radar measurement of Thomson scattering offered a means of determining the profile of electron density as a function of height in the ionosphere, and had many advantages over other techniques available at the time. Accordingly, work was begun on facilities specifically designed to exploit the new technique. Gordon led the team that built the Arecibo Ionospheric Observatory (now the National Astronomy and Ionosphere Center) in Puerto Rico, while Bowles led the team that built the Jicamarca Radar Observatory in Peru (*3*).

Summary. In the last two decades large radars have proved to be powerful instruments for the measurement of the properties of the upper atmosphere. These radars were used initially to measure properties of the ionosphere by the Thomson scattering technique at heights above 100 kilometers. Careful interpretation of the power and spectrum of radar echoes yielded data on electron and ion densities and temperatures as well as on bulk motion of the ionospheric plasma, all as functions of height and time. More recent developments have made it possible to measure wind speeds and the structure of turbulence in the stratosphere and mesosphere at altitudes below 100 kilometers.

The first observations of Thomson scattering from the ionosphere were surprising, however. The measured spectrum of the scattered radiation was very much narrower, and therefore much easier to detect in the presence of noise, than Gordon had predicted. Because of this original misunderstanding of the theory of the phenomenon, the instruments constructed at both Arecibo and Jicamarca were considerably more powerful than they needed to be in order to carry out their original missions. Successful measurements of ionospheric properties by the Thomson scattering technique (now called incoherent scatter) have since been made by much smaller radars in France, England, Massachusetts, Canada, and Alaska (*4*). The power of the original incoherent scatter radars at Arecibo and Jicamarca has not been wasted, however, as these instruments have been used as test-beds for the development of new techniques for the measurement of a range of properties of the upper atmosphere wider by far than anyone could have imagined in 1958.

The first extension of the capabilities of incoherent scatter radar was soon realized as theoretical plasma physicists explained the difference between the measured and predicted spectral width of the scattered radiation (*5*). Electrostatic forces between negatively charged electrons and positively charged ions in the ionospheric plasma couple the motions of the electrons to those of the more massive ions. Although it is electrons and not ions that scatter electromagnetic radiation, their motions and therefore the Doppler shift they cause in scattered radiation are constrained by the ions. The spectrum of the scattered radiation has a width that is characteristic of the mean thermal motion of the ions. The shape of the spectrum depends strongly on the ratio of the temperature of the electrons to that of the ions in the plasma that is scattering the radiation, and there is an additional weak dependence of the shape on the proportions of

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