Recent Advances in Ultrasonic Imaging

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Ultrasonics has been used for many years to detect flaws in materials by means of a pulse echo or A-scan technique. Ultrasonic images are formed by displaying the echoes in a two dimensional pattern so that the spatial relationships between the interfaces and acoustic impedance discontinuities that give rise to the echoes are maintained. When the echo data is arranged in this way, it is possible for one's eye and brain to serve as a very sophisticated pattern recognition system to detect flaws or defects within an object. This capability is particularly important when one is examining an object that normally has a considerable amount of internal structure. Since most of my experience is with medical applications, I will take the human abdominal region as an example. An ultrasonic image will be able to delineate the more or less known outlines of these normal internal structures. Frequently, however, the purpose of such an examination is to look for some abnormality such as a tumor or cyst and using an ultrasonic image these structures can be differentiated from the normal structures by those who have been trained in this sort of procedure. This can be done because the operator has learned to recognize certain patterns and he is able to employ his eye-brain pattern recognition system when the echo data is presented in the form of an image.

If one were to only look at the pulse-echo pattern along a single line, it would at best be very difficult to separate the normal echoes from the abnormal ones. Once a particular region within this image is identified as being abnormal, it is then possible to intelligently interrogate it using a pulse echo technique to determine the acoustic characteristics more precisely.

For reasons that are not entirely clear, the diversity of imaging systems available for medical applications seems to be far larger than those available for NDE applications. In the past four or five years the field of ultrasonic imaging for medical purposes has undergone a number of significant advances. It seems that some of these advances in imaging techniques could be incorporated into instruments that are designed solely for NDE work.

Basic Imaging Systems

There are two fundamental systems for producing ultrasonic images which are known as the B and C-scan techniques. These systems are reasonably simple in concept, in many cases produce very good images, and most people active in the NDE field are familiar with them. These systems will be used as references for explaining newer advanced systems. A B-scan system is shown in Fig. 1. The transducer, which is illustrated as a focused type, emits pulses of ultrasonic waves that pass through the object. Echoes generated by interfaces or flaws are reflected back to the transducer which receives them and converts them to an r.f. electrical signal. These r.f. pulses are detected
Fig. 1. Diagram of a focused B-scan system.
and used to intensity modulate the cursor of an oscilloscope which moves across the scope face at a constant rate. If the acoustic velocity within the specimen under examination does not vary too much, the system can be calibrated so that distances on the scope face are proportional to distances in the object.

In order to obtain the second dimension of the image, the transducer is scanned along a line (Fig. 1), and the scope cursor moves up or down by an amount proportional to that moved by the transducer. The resulting image is a cross sectional view of the object i.e. one dimension of the image is depth into the object and the second dimension is the lateral dimension along the scan line of the transducer. This is one of the simplest types of B-scan systems. The most widely used systems are called contact B-scanners. In this case, the transducer is located on the end of an articulated arm. Instead of just being able to move the transducer along a line, it is possible to move the transducer within a plane and rotate the transducer as well. When the transducer is both rotated and translated, it is known as compound scanning. When this kind of B scan system is used, the transducer is moved over the surface of the object under examination and is rocked back and forth in order to pick up interfaces that are not oriented parallel to the surface.

The system performance parameters that should be considered in evaluating an ultrasonic imaging system are shown in Table I. The peak value of the transmitted power varies from 10 to 100 watts/cm². The sensitivity is 10⁻⁸ - 10⁻⁹ watts/cm² which is considered to be good. The operating frequencies are typically in the low MHz range for medical applications because of the high acoustic attenuation of biological tissue existing at higher frequencies. The system can be operated at much higher frequencies if the object attenuation is sufficiently low to permit this. The field of view can be very large and is easily adjustable. There is no problem in obtaining a field of view as large as one half meter. The axial resolution, measured along the direction of the acoustic beam can be a couple of wavelengths since very short pulses are ordinarily employed. The lateral resolution is much worse. If a collimated acoustic beam is used, the lateral resolution will be about 30 wavelengths. If it is possible to work in the focal region of a focused transducer, this can be improved. The range is dependent on the operating frequency and the attenuation of the object under study. In medical systems operating at 2 MHz, the range is about 15 cm. The frame rate is about 10 to 30 seconds for these systems which are manually scanned. Although this is a B-scan system, it could easily be operated in the A-mode as well. The dynamic range of these systems has to be very large to accommodate echoes that are being specularly reflected from interfaces as well as those that are diffusely reflected. In addition, the object can be highly attenuating and there could be a 30 dB difference in the amplitude of the echoes depending on whether they are coming from near or far surfaces. It is desirable to have a 60-70 dB dynamic range. Currently available systems have in excess of 100 dB available. Since this is a non-real time system, it is necessary to store each line of data until the frame is completed. Initially bistable storage tubes were used to do this but have been largely abandoned because of the lack of dynamic range. Currently, image converter tubes are used that will accept the data at a slow rate and read it out at TV rates. A regular TV monitor can then be used to display the image. The contact B-scanner is particularly easy to use and certainly in the medical field.
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the current popularity of ultrasonic imaging is due in large part to this aspect of the system.

The final parameter of interest which is often overlooked is the degree of coherence of the system. In most ultrasonic imaging systems, the radiation is very monochromatic and there is a definite phase relationship between all of the wavefronts. If an object is totally irradiated by this coherent radiation, it is found that the diffraction fringes from out of focus structure within the object have as high a contrast in the final image as the structural details that are in focus. This is analogous to the familiar speckle that one is accustomed to seeing when an object is illuminated with a laser. If one is interested in some fine detail of the object under investigation, the presence of this ultrasonic speckle can make it impossible to detect. If the ultrasonic images are being made for pattern recognition purposes then it is desirable to eliminate the speckle by using an incoherent imaging system. There are a number of ways of degrading the coherence of the system, but it is not appropriate to describe them in detail here. A particularly easy way to make the system incoherent is to illuminate the object one point at a time. In this case, the radiation from each point cannot interfere with the other radiation and the speckle disappears. This is what is done with a B-scan system and consequently it is an incoherent imaging system.

A C-scan system is shown in Fig. 2. Although it is shown operating in the transmission mode, it can be operated in the reflection mode as well. The illustrated system utilizes two focused transducers in a confocal geometry. The transmitted signal is chiefly acted upon by the small region at the focal point of the transducer and then is received, detected and displayed as an intensity modulation of a scope or TV monitor. The transducers are synchronously scanned in a two-dimensional raster pattern as indicated in Fig. 2 and the image is built up point by point. It is important to note that an orthographic view is obtained in this case as opposed to the cross-sectional view obtained with the B-scan system.

Reviewing the performance parameters listed in Table I we note that the figures for the first four items are the same as those given for the B-scan system. The C-scan system can have very high lateral resolution as well as axial resolution. The limitation is set by the numerical aperture of the focused transducer. The range is the same as for the B-scan system. The frame rate can be of the order of seconds, but it is more typically of the order of minutes in commercially available C-scan systems. Frame times as long as 30 minutes are not unusual for an image with very high resolution. This system can be easily operated in the A-mode. The dynamic range and the method of image display are similar to those described for the B-scan system. The C-scan system is not as convenient to use as a contact B-scanner because the object has to be immersed or the sound has to be coupled in via some type of water bag arrangement.

The B and C-scan systems are "state-of-the-art" for commercially available systems. If these systems are to be improved, one must consider which performance parameters are most appropriate to improve and what the effects will be on the other parameters. For both of these systems, it is desirable to increase the frame rate. An increased frame rate not only enables
C-SCAN SYSTEM USED IN TRANSMISSION

Fig. 2. Diagram of a focused C-scan system.
one to obtain an image somewhat faster, but if it is increased to the extent that one's eye does not detect a flicker between successive frames, then, the eye-brain system can perform real time image enhancement, correlate various image features, and filter out artifacts. It is also desirable to increase the lateral resolution of the B-scan system. It is important to make these improvements without any undue compromise of the other parameters and without increasing the cost of the overall system too much.

**Types of Imaging Systems**

There are a considerable number of imaging systems that currently exist in either a laboratory or prototype state that seek to improve upon the performance parameters of the conventional B and C-scan systems. In order to describe them and point out how they differ, it is helpful to group them into the various categories listed in Table II. The first group includes the B and C-scan systems as well as a mechanical sector scanner. The mechanical sector scanner which is shown in Fig. 3 was developed by Henry & Griffith at NIH. It is a B-scan system with a motor connected to the transducer so that it can be oscillated back and forth. The ultrasonic beam swings through an arc in the object under investigation. The device is used as a contact scanner with the space between the transducer and the object filled with a gel. The frame rate of the scanner is 30-40 frames/sec making a real time system. Before describing the details of this system, it is appropriate to consider several of the systems in the next group.

All of the systems in group II use multiple transducers which are arranged in different kinds of arrays. The first type is known as a sequenced linear array. It was developed by Bom and is shown in Fig. 4. It consists of a row of 20 transducers, each one is sequentially used to send out an ultrasonic beam and receive the returning echoes.

The electronically phased arrays make up the next group. In these systems all of the transducers are pulsed simultaneously but the relative phases of the r.f. signals sent to the transducers are varied so that the direction and focus of the ultrasonic beam emanating from the array can be changed electronically. In the simplest of these systems, the beam is left unfocused and is scanned through a sector. In more sophisticated versions, the beam is focused while it is scanned and the focus can be dynamically varied while the array is receiving echoes.

All of these systems are used for a single application which is to visualize the heart. Since they are looking at a moving object, it is necessary that the frame rate be in excess of 30 frames/sec. To achieve this goal, all of these systems sacrifice resolution and image quality. The line density in a frame is very low and it is difficult to get useful information from a single frame. The imaging systems are useful because the rapid frame rate makes it possible for the eye/brain system to perform real time image enhancement.

A sequenced array system that can produce images with high resolution has been developed at SRI and is shown in Fig. 5. This system works best in transmission but can also be used in reflection. The object is irradiated by ultrasound and an ultrasonic lens is used to image the object onto the array.

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Table II. Types of Ultrasonic Imaging Systems

I. Single & Double Transducer Systems
   A. Single Transducer (A,B,C, Scan; Reflection Mode)
   B. Double Transducer (C Scan; Transmission Mode)
   C. Mechanical Sector Scan Systems

II. Multiple Transducer Systems
   A. Sequenced Linear Array
   B. Electronically Phased Linear Array
   C. Two-Dimensional Array (NXN)
   D. Thinned Arrays

III. Systems Using Optical Diffraction or Reflection
   A. Laser Illuminated Liquid-Air Interface
   B. Bragg-Diffraction Imaging
   C. Laser Illuminated Membrane
   D. Laser Scanned Solid Surface
Fig. 3. Mechanical sector scanner developed by Griffith and Henry.\textsuperscript{6}
MULTISCAN ECHOCARDIOGRAPHY

transducer
piezo-electric
elements

echo
formation

transmission
direction

line height corresponding
to element position

tissue cavity

echo return time

Fig. 4. Sequenced array developed by Bom. 7
Fig. 5. Real time ultrasonic imaging system developed at Stanford Research Institute. (Courtesy of P. S. Green)
The linear array which is composed of 192 elements is able to read out one line of the image. In order to obtain the remaining lines, there is a clever arrangement consisting of two counter-rotating prisms which cause the image to scan up and down across the array. The resulting frame rate is 15 per second. One of the features of this array is that each element has a separate preamplifier and signal processing channel including a signal storage element. The commutation between elements takes place at high signal levels and thus some of the cross-talk problems encountered in arrays that commutate at low signal levels are avoided.

This is a type of C-scan system that has been modified to achieve real time operation and a field of view of 6 inches. In doing this, the system has become a coherent one and there are some problems with speckle when thick objects are imaged. The trade off is reasonable since the real time images will enable one to filter out some of the speckle. An image of a printed circuit board is shown in Fig. 6. Note that it is possible to see the weave of the fiberglass.

Another system that comes under the category of phased arrays is being developed at Stanford University under the direction of Gordon Kino. This system has much higher resolution than the other phased array systems. The technique that is used to phase the elements of the array is rather elegant and is described in the paper by Kino appearing in the Proceedings of this meeting. It uses an analog technique rather than the digital or electrically controlled delay lines used by the other systems.

The resulting scan format is rectilinear rather than being a sector scan. The active elements are phased so that they are focused along a line 25 cm from the array. This line focus then moves along a line parallel to the array. The object is irradiated by a line source parallel to the array. Currently, the second dimension of the image is obtained by mechanically moving the object up and down resulting in a frame time of one second. An image of a crescent wrench obtained with this system is shown in Fig. 7.

This is a type of C-scan system operating in the transmission mode. The incoherent nature of a C-scan imager has been maintained to a large extent in this system. The frame time is much faster for this system then a conventional C-scan system but there is some degradation of the resolution and the dynamic range.

It should be noted that it is very difficult to make an array of small transducers and have them matched in phase and amplitude. Some progress is being made but a number of engineering problems have to be solved before they can be manufactured economically.

The next category of systems listed in Table II are those using two-dimensional arrays. There are several existing efforts in this area, although only two will be described. One project is under the direction of James Mielnik at Stanford University and the other is under the direction of Henry Rochal at General Electric. In neither case are the elements of the array required to be matched in phase i.e., these are incoherent arrays. For
Fig. 6. Ultrasonic Image of a printed circuit board.
(Courtesy of P. S. Green)
Fig. 7. Ultrasonic image of a wrench.
(Courtesy of G. Kino)
an incoherent array that is used to produce an orthographic projection of
the object, the number of elements in the array has to equal the number of
image elements in the ultrasonic image. Considering that a TV picture has
about 10^6 image elements, it seems reasonable to assume that a minimal quality
image would require about 10^4 image elements in each dimension.

There are significant differences between the two approaches relating
to the techniques for processing the signals from the piezoelectric array
elements. The General Electric imager uses hybrid circuitry to fabricate
an entire signal processing channel for each image element. At the end of
the channel is a storage element for holding the signal until it is read out.
The Stanford imager has an integrated transmit receive switch following each
array element but uses a row-column addressing scheme to commutate between
the elements so that only one signal processing channel is required. At
the present time, the largest array built by each group contains 100 elements.
The array built by the Stanford group is shown in Fig. 8.

Since it is very difficult to construct a two-dimensional array with an
adequate number of elements, consideration has been given to "thinned arrays".16
This synthetic aperture approach requires that both the phase and amplitude
characteristics of each array element be matched. This is a rather stringent
requirement for the current transducer technology and, in general, the results
from these types of arrays have not been too promising. There is not too
much activity in this area at the present time.

The next group of systems use either optical diffraction or reflection
to convert the ultrasonic image into a visible image. For particular applications
some of these systems have proven to be very useful but, in general, they
are not as sensitive as those systems using a piezoelectric transducer. The
first system listed in Table II uses a liquid-air interface to form an ultrasonic ripple pattern. This system was developed a number of years ago by
Byron Brenden17 who is now with Holosonics. It was one of the first ultrasonics imaging systems to produce recognizable images in that time. A diagram
of the system is shown in Fig. 9. The laser beam that is incident on the
liquid surface is diffracted by the ripple pattern. The diffracted beam is
modulated by the ripple pattern and contains an image of the ripple pattern.
This optical image can be viewed directly or it can be focused onto a vidicon
and displayed on a T.V. monitor. The chief drawback to this technique is that
it is a highly coherent imaging system. The numerous diffraction fringes
and specularity appearing in the image prevent any quantitative image analysis.
The sensitivity and dynamic range of the system are also less than is desired.

The Bragg-Diffraction imaging techniques18,19 depend on an interaction
between a laser beam and an ultrasonic beam in the bulk of a liquid (Fig. 10). The
acoustic wavefronts in the liquid cause compressions and rarefactions. The
resulting changes in index of refraction of the liquid cause the incident
laser beam to be partially diffracted. The diffracted laser beam is modulated
with the acoustic image information. The drawbacks of this system are its
low sensitivity and the specularity of the images.

The next system which utilizes a laser and a thin membrane or pellicle
was developed by Rubin Mezrich at RCA20. A diagram of the system is shown
in Fig. 11. The pellicle is placed in a water tank and couples to the ultra-
Fig. 8. 10x10, 2-dimensional array. (Courtesy of M. G. Maginness)
Fig. 9. Diagram of ultrasonic imaging system developed by B. B. Brenden.17
Fig. 10. Bragg diffraction imaging system developed by Keyani, et al.19
Fig. 11. Diagram of ultrasonic imaging system developed at RCA.
(Courtesy of R. Mezrich)
sonic image onto the pellicle, the amplitude of the motion of the Pellicle at each image point will be very nearly the same as the amplitude of the molecular motion of the water. The pellicle is made highly reflecting by a gold coating and serves as one mirror of a Twyman-Green interferometer. The laser beam enters the interferometer and the beam splitter sends part of the beam to a reference mirror and part through a beam deflector to the pellicle. The two beams are reflected and recombined in a photodiode. The amplitude of the difference signal obtained will be proportional to the image displacement amplitude of the pellicle. The beam defector scans the laser beam over the entire pellicle in a raster pattern and the ultrasonic image is reproduced in this way. The reference mirror is vibrated to stabilize the system against ambient room vibrations. This system is capable of very accurately measuring the displacement amplitude of the pellicle and consequently the absolute value of the ultrasonic intensity at a point.

This property makes the instrument useful for measuring the radiation pattern from a transducer and determining the absolute intensity of the ultrasonic beam. In Fig. 12 the radiation patterns from a transducer at several distances from the transducer are shown. This transducer had a delaminated cover plate which produced the very non-uniform beam pattern near the transducer.

In the past several years, the frequencies at which it is possible to obtain good images has been extended upward until now images can be obtained at frequencies as high as a gigahertz with a resolution approaching one micron. Two acoustic microscope systems, as these are termed, are currently being developed that together span the frequency range from 100 MHz to 1 GHz. The unit that operates over the lower portion of the frequency range was first described by A. Korpe1 et. al. and serves as an example of the last category of systems listed in Table II. A diagram of the system, which is available from Sonoscan, is shown in Fig. 13. The 100 MHz acoustic signal is applied to a specimen which is placed upon the microscope stage. The energy transmitted through the sample creates a ripple pattern at the surface. A laser beam is focused onto this ripple pattern and as the ripple moves under the focused spot, the reflected beam wiggles and is partially intercepted by a knife edge. The beam reaching the photodetector is thus modulated by the acoustic signal. The output of the photodetector consists of two signals; one signal depends upon visual features of the specimen and the other signal depends on the acoustic features of the specimen.

The laser beam is rapidly scanned over the field of interest in a raster pattern and the resulting signals are processed and displayed on the T.V. monitors as optical and acoustic images. One of the specimens that has been examined is a disk of AISI 4140 steel. An acoustic micrograph of this specimen is shown in Fig. 14. The images made in this way are shadowgrams and contain speckle because it is a coherent imaging system.

The other acoustic microscope system was developed at Stanford University by C. F. Quate and R. A. Lemons. In principle, it is the same as a C-scan system using focused transducers shown in Fig. 2. In this case, the specimen is scanned rather than the transducers. A diagram of the system is shown in
Fig. 12. Ultrasonic images of transducer radiation patterns. (Courtesy of R. Mezrich)
Fig. 13. Diagram of Sonoscan acoustic microscope.
(Courtesy of L. W. Kessler)
Fig. 14. Acoustic micrograph of a disc of AISI 4140 steel, 3/4" diameter and 0.057" thick. The area shown is 3x4 mm and reveals the grain boundary structures within the material.22 (Courtesy of L. W. Kessler)
Fig. 15. Diagram of acoustic microscope developed by Lemons and Quate.23
Fig. 16. Acoustic micrograph (600 MHz) of normal human breast tissue unstained.24 (Courtesy of Lemons and Quate)
Fig. 15. The transducers are located on the ends of sapphire crystals which contain small acoustic lenses at the opposite ends. The sapphire rods are then placed opposite one another in a confocal geometry and a drop of water is placed between them. The specimen is mounted on a thin membrane which is placed in the acoustic focus and mechanically scanned in a raster pattern. The technique requires several seconds to obtain a single frame. The transmitted or reflected signal is processed and displayed on a T.V. monitor. One of the acoustic micrographs produced in this way is shown in Fig. 16. This is an image of a standard 5 \(\mu\)m thick section of normal human breast tissue made at a frequency of 600 MHz.

Conclusion

An attempt has been made to survey the many varieties of ultrasonic imaging systems that are currently being developed and to categorize them according to the function they serve best. Furthermore, a uniform set of criteria has been used to evaluate the performance of these systems in terms of commercially available B and C scan systems.

References


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DISCUSSION

DR. THOMAS SZABO (AF Cambridge Research Lab): I noticed in your talk you omitted acoustical holography as an imaging type of system and I wonder if you would comment on that at the present time, because it seems to me a hologram could contain information about all the structures inside a solid.

DR. ADDISON: It is true that a hologram contains information about all of the structures within a solid. It is also a highly coherent system and the problems with speckle are significant. One can conceive of special situations where it would be advantageous to use a holographic technique for viewing an object. In general, if the image is being obtained for the purposes of pattern recognition, it is better to use an incoherent system.

Furthermore, acoustic holography systems using multiple receiving elements require all of the elements to be matched with regard to both their amplitude and phase response. This is a difficult requirement to meet. The images that I have seen that were made with acoustic holographic imaging systems are not as good as those made with other systems.

DR. GERRY GARDNER (Southwest Research Institute): A slight question of principle. I suspect that I misunderstood you, but I'll ask the question anyhow. Did you intend to imply, as I understood you, that the number of resolution elements in an image created by an n-by-n-array is equal, in fact, to the number of elements in that array?

DR. ADDISON: There is a factor which you can throw in and reduce the number of image elements in the actual image from that in the array. Is that the nature of your question? Do I understand what you are asking?

DR. GARDNER: Suppose you employ a phased array consisting of n-by-n elements which are not simply a matrix to receive a picture, but in fact, as a device for focusing and steering a beam which you can then scan back and forth across some image plane. Then, are you stating that the number of resolvable elements in the image plane is, in fact, n-by-n?

DR. ADDISON: I was considering only the case of incoherent arrays where the phase information was not being used.

DR. GARDNER: But you do agree, do you not, that the number of resolvable elements in the image plane in a focused and steered beam created by a phased array, although there is a relationship, obviously, that it is not limited to n-by-n elements? Consider the case of two.

DR. ADDISON: Yes. Gordon, you've looked into this more than I have.
PROF. GORDON KINO (Stanford University): It is limited. You're saying, "Consider the case of two," and granted, you get good resolution with two, but you get side lobes off to the side, very close. If you are just talking about the distance between the side lobes divided by the resolution distance, you find after you are all through you come out with about n-by-n.

DR. GARDNER: About n-by-n?

PROF. KINO: Right. Now, if you pulse the system and you do tricks you can increase this by maybe a factor of two or three. And, of course, if you use a sparse system where you use n there and n there, i.e., n plus n, you get n times n, the result of the square.

DR. GARDNER: Okay. That's the point. There are all kinds of ways.

PROF. KINO: Yes. There are all kinds of ways of playing tricks.

DR. ADDISON: Currently there is a problem in trying to build thinned arrays where it is essential to detect the phase of the incoming wavefront.