Inspection using Ultrasonics

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A common application of ultrasound is non-destructive testing (NDT) sometimes called non-destructive evaluation (NDE).

Non-destructive evaluation covers a wide range of applications, such as: testing pressure vessels, testing welded joints, finding delamination flaws in aerospace assemblies, finding faults in silicon wafers, testing railway track for cracks and testing gas turbine engine blades for casting faults. Whilst the range of applications is great rather few different techniques are used. Applications can be classed as either flaw-detection or material property assessment. Transmission testing is commonly used for material property assessment and pulse-echo methods are used predominantly in flaw-detection with A-mode scans. C-scanning is used sometimes on samples that fit into water immersion tanks. Arrays are not used as frequently as in medical imaging. Heterogeneous materials such as austenitic stainless steel, cast iron and concrete are considered particularly difficult to test because these materials can generate random multiplicative noise. It is, however, possible to detect line scatterers in concrete, such as reinforcement bars, at a range of 0.5 m. Other methods that are infrequently used are resonance spectroscopy and acoustic emission . These are mentioned because the principles of operation are significantly different to the pulsed methods otherwise used in non-destructive evaluation.

A. Pulsed methods.

Pulsed ultrasound is used for inspection purposes, including: medical imaging, sonar, acoustic microscopy and non-destructive evaluation. In a pulsed system a transducer is placed in contact with a sample, electrical driving signals are sent to the transducer to make pulses of ultrasonic waves, which enter the sample and echoes from internal scatterers are collected by a receiver, processed and displayed for interpretation (see figure 1).

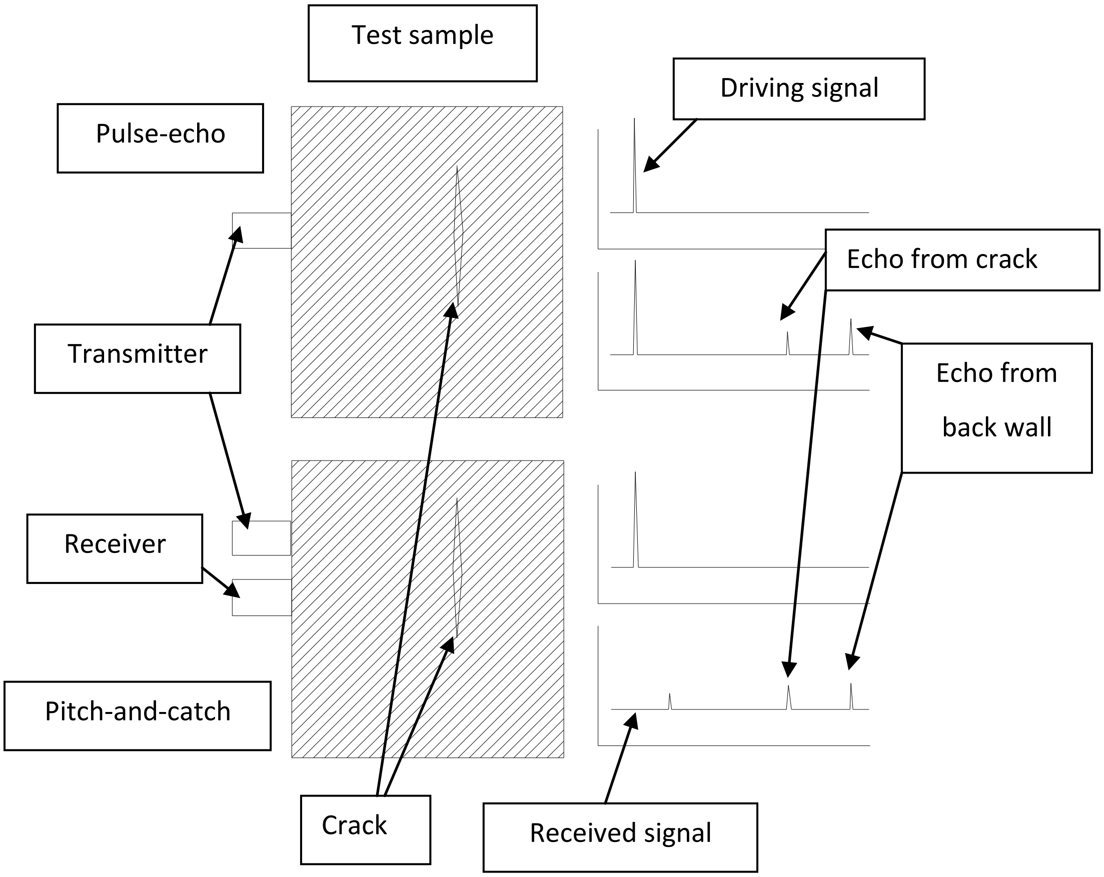


Figure 1

Conventional pulsed methods used for inspecting a test sample, showing impulse drive signals and received signals

If the transmitter is used as a receiver the method is known as pulse-echo but if a second transducer is used as a receiver then the method is known as pitch-and-catch. The times of arrival of echoes can be measured and converted into distance using the appropriate value for the speed of sound in the sample and other factors depending on the geometry of the test (division by two in this case). As well as having echoes from cracks in the sample the received signal may also have echoes from surfaces, such as the back-wall echo shown in figure 8, to add to the difficulty of interpretation. Further complications arise with parallel-sided, objects with high Q factors that reverberate, generating relatively long series of exponentially damped pulses (see figure 3B).

A. Axial and lateral resolution

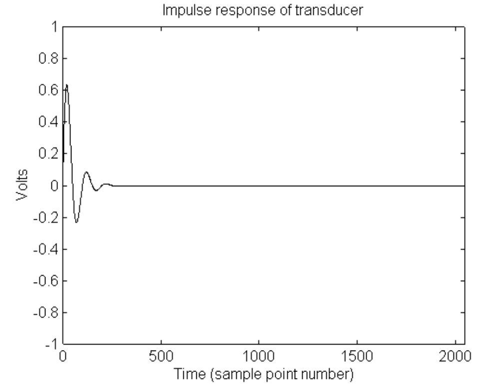
The value of the axial resolution is equal to the spatial extent of the pulse in the test material and is equal to the pulse duration multiplied by the wave speed. Two scatterers can be resolved as distinct along the acoustic axis if they are separated by more than the axial resolution therefore a short ultrasonic pulse gives better resolution than a long pulse. Transducers with higher centre frequencies emit shorter pulses and are used when finer axial resolution is required. Two scatterers can be resolved as distinct perpendicular to the acoustic axis if they are separated by more than the beam width. Lateral resolution is determined mainly by the transducer aperture size for collimated transducers. A diverging beam has a lateral resolution that increases with range and a focussed beam has the smallest lateral resolution in the vicinity of the focus - after the focus the beam diverges.

B. Driving signals and processing

A chirp signal is a burst of waves that can be synthesised (referred to here as controlled chirps) or otherwise created and processed. However, chirps are frequently used inadvertently in pulsed ultrasonic and acoustic systems because all transducers respond with a chirp of some description when driven electrically, irrespective of the drive signal. Many systems do little to process the chirp automatically. The commonest and least effective signal processing of chirps is human interpretation of a displayed signal; the alternative is automatic processing by computer. Matched filtering, which is a form of linear pattern detection, converts a long chirp into a short impulse (compression) and can only be done quickly by computer. Compression improves the axial resolution and this is the main benefit of matched filtering. Matched filtering is closely connected with deconvolution (see Geophysical exploration).

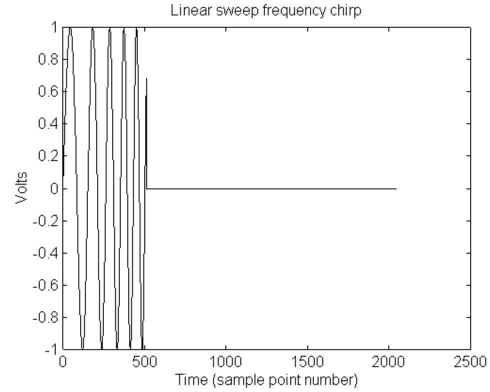
Figure 2 follows two chirps, a controlled chirp and an *inadvertent* chirp (impulse drive), through typical stages of processing. Two signals were synthesised by: convoluting the transducer’s response with each of the two electrical drive signals, convoluting the result with a perfect echo at 1000 time samples and adding white noise. At this stage signals represent typical received signals. The next stage processed the inadvertent chirp in two ways, the first being typical of many conventional, non-destructive test systems was rectification followed by level detection; the second way was applying deconvolution, namely, matched filtering followed by envelope detection. The controlled chirp was only processed by deconvolution. The match filter was the time-reversed recording of the output of the transducer. Figure 2 C shows a typical received signal. Figure 2 D shows the signal presented for interpretation by a conventional non-destructive ultrasonic test showing three peaks from one echo, the peaks come from the inadvertently formed chirp (due to the impulse response of the transducer). Figure 2 E shows the conventional test with deconvolution, there is now only one main peak instead of three.

Figure 2 F shows deconvolution of the controlled chirp with only one peak and low background noise.



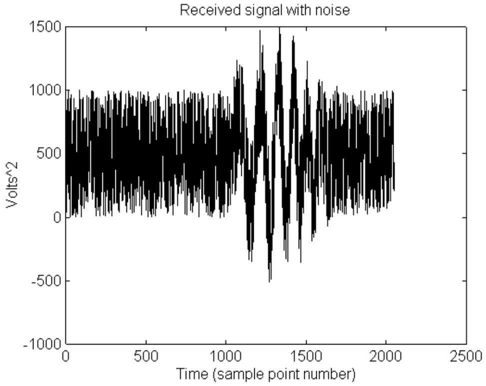
A

A chirp formed inadvertently



B

A controlled chirp



C

A chirp in noise

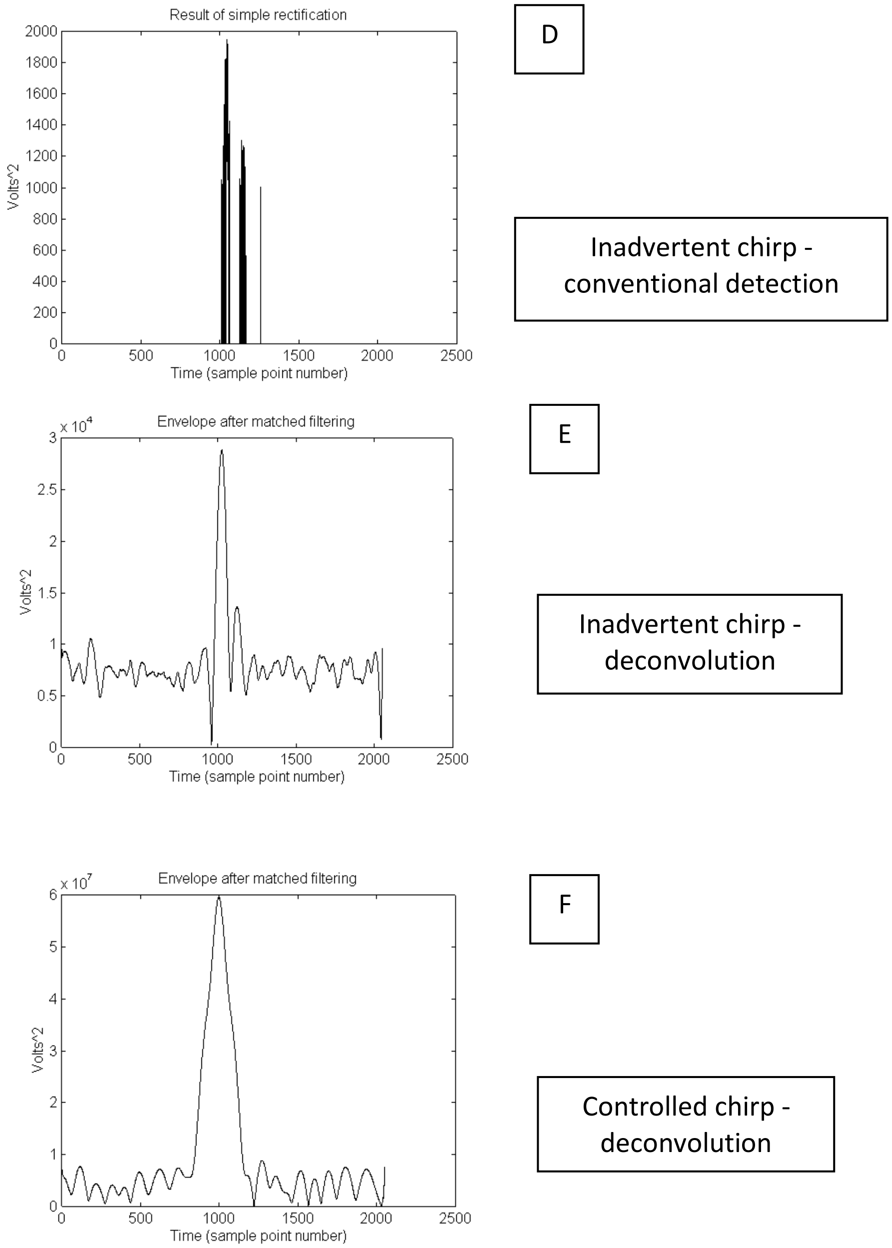


Figure 2

Comparison of the signals used in a conventional, pulsed inspection system (inadvertently formed chirps) and a system using controlled chirps with deconvolution.

In summary, many commercial, pulsed inspection systems are used successfully with inadvertently formed chirps but there are some advantages to be gained in using controlled chirps and deconvolution when axial resolution is important.

B. Multiplicative and additive noise

Multiplicative noise is due to random scattering in the material under test and it is coherent with the driving signal to a varying degree. Averaging of signals collected at several locations (spatial averaging) within a few wavelengths distance is effective in improving the detection of extended targets in the presence of multiplicative noise. Averaging of signals collected at different times (time averaging) is effective in improving the signal-to-noise when additive, non-coherent noise is present. The improvement in additive signal-to-noise is proportional to $\sqrt{N}$, where N is the number of signals averaged.

C. Common ways of using pulsed-ultrasound

Some common classes of pulsed inspection methods are known as: A-scans (amplitude or A-mode), B-scans (brightness B-mode), compound B-mode scans and C-scans (two dimensional scanning). The terminology is virtually the same in medical scanning and non-destructive evaluation. Pulse-echo is commonly used in all three scanning methods. In an A-mode scan the received signal is displayed on a cathode ray tube (CRT) with time as the x-axis and amplitude the y-axis (see figure 2). B-mode is similar to A-mode but there is no y-axis deflection on the CRT, just a straight line whose brightness at any time is controlled by the amplitude of the ultrasonic signal. A compound B-mode scanned image is built-up of many B-mode scans, with the transducer scanning the test sample. Each B-mode line on the CRT is displaced from the others in such a way as to represent the physical scanning of the beam. The compound B-mode scan provides a two-dimensional image, commonly slicing through the sample. C-scanning also creates a two-dimensional image but one in which the image-plane is perpendicular to the acoustic axis, requiring two-dimensional scanning by the transducer of the sample. There are two popular embodiments of C-scanning, both use water coupling between the transducer and test sample: the acoustic microscope (scanning typically 1 mm x 1 mm area) and the water immersion tank (scanning typically 100 mm x 100 mm area). The latter can take several minutes to form an image. A transducer is generally focussed on the test sample in a C-scan and the amplitude of the focussed portion of the received signals controls the brightness of the CRT for each point in the scan.

D. Quality assurance using resonance spectroscopy.

A single continuous wave (CW) is, in theory, a wave of infinite duration and is inherently incapable of providing axial resolution for imaging purposes. For this reason CW is never used for imaging and is seldom used for non-destructive evaluation.

Resonance spectroscopy is a low power, CW application used for quality inspection. It is used to test the quality of mass-produced components because it is fast and the cost per test is low. A test sample is injected with CW ultrasound or sound at one transducer and the response at a second transducer is measured. A spectrum is built-up by stepping over many frequencies. CW excitation fills the sample under test with ultrasound, allowing waves from relatively distant parts of the sample to reach the receiver and contribute to the spectrum. A whole sample can be tested without any scanning and interpretation is done automatically by computer, typically using a trained artificial neural network, resulting in short testing times. The time to complete a full test of, say, 100 test frequencies on an automotive component could be as short as one second so that more than 1,000 parts/hour can be tested. Resonance spectroscopy is suitable for 100% quality assurance of mass-produced parts.

E. Measurements using phase

The phase of the received signal can be measured relative to the transmitted CW signal in a pitch-and-catch test, instead of using pulses. Small changes in the time of flight can be measured this way, which can form the basis of a useful quality test. The disadvantage is that phase measurements become ambiguous if the phase change is greater than one whole cycle (2π).

F. Medical imaging

Applications of both pulsed and continuous (CW) ultrasound are to be found in medicine. Pulsed ultrasound is used for diagnostic imaging and CW is used for therapy purposes, for stimulating the healing of soft-tissues. One exception is a therapy instrument, using focussed, pulsed ultrasound of high intensity to break stones in the body, for example kidney stones. Frame-speeds of at least 10 frames/second are desirable for medical imaging to give the impression of a moving image. High speed scanning is best achieved using electronic beam steering from arrays. One-dimensional arrays (1 x 128 transducers) or one and a half-dimensional arrays (6 x 128 transducers) and two-dimensional arrays (64 x 64 transducers) are used. The one-dimensional arrays are only capable of generating a single sector scan, a slice centerd on the array. A two-dimensional array can scan a reasonable volume in real-time, for example the heart or a foetus. It can provide data for an image plane of arbitrary orientation or for reconstructing a three-dimensional image.

Medical imaging equipment typically operates at center frequencies in the range 1 MHz to 5 MHz. The transducers are damped and create short pulses of between 1½ and 2½ cycles, with axial resolution is in the range 5 mm to 0.5 mm. Higher frequency (10 MHz) transducers have been developed to detect abnormalities of the skin. Contrast in an ultrasound scan is due primarily to reflection of waves. Soft tissue and bone have different values of acoustic impedance therefore bones show up clearly in an ultrasound scan. A foetal skeleton, for example, has a high contrast allowing simple checks can be made on its growth and development during pregnancy.

Material	**Wave speed ($m\ s^{-1}$)**	**Acoustic impedance ($kg\ m^{-2}\ s^{-1}$)**	**Attenuation ($dB\ m^{-1}$)**
Air	330	400	1200
Blood	1600	1.6×10^6	180
Bone	4100	7.8×10^6	2000
Brain	1600	1.6×10^6	850
Fat	1500	1.4×10^6	630
Kidney	1600	1.6×10^6	100
Liver	1600	1.7×10^6	940
Water	1500	1.5×10^6	22

Table VI

Material properties for various types of human tissue.

The intensity of ultrasound used on foetuses must be carefully controlled. High intensity can cause tissue damage by cavitation (see Processing technologies and Sonochemistry) and by heating. Non-linear effects in water cause ultrasonic pulses to become sharper as they travel, increasing the intensity at the leading-edge of a pulse and another area of concern is that most imaging systems use arrays to focus the ultrasound - further increasing the intensity. Transmitter drive levels are kept low for safety. A transducer should be tested and certified before it is approved for use on foetuses. During testing its ultrasonic output is measured using a receiver which has a traceable calibration to a standard. An exceptionally small receiver (1 mm diameter) is needed, which is capable of working over an exceptionally wide range of frequencies (up to 100 MHz); one popular receiver satisfying these requirements is called a membrane hydrophone because it is made from a thin membrane of ferroelectric polymer (PvDF). Photographic methods are used to print fine electrode patterns onto the membrane and the size of these printed electrodes (0.1 mm to 1.0 mm) defines the lateral resolution of the hydrophone. The membrane is typically 0.1 mm thick, which defines the axial resolution.

G. Transducer arrays.

An array is a collection of two or more transducer elements working in concert. An array can be used by transmitting the same signal from the elements but with different time delays that change the direction of propagation of the transmitted wavefront or focus it. Arrays offer considerable flexibility in beam-forming, with no moving parts and high speed scanning.

Figure 3 shows groups of single wavefronts emerging from a linear array of elements. Where the wavefronts overlap with the same phase there is constructive interference but elsewhere the interference is destructive (not shown in the figure). It is common to space elements periodically, with a distance between centers of $\lambda/2$. This gives a good balance between source strength and beam quality. If elements are separated by more than $\lambda/2$ then there will be aliasing, called grating-lobes in this instance, in any wavefronts focussed down as small as λ, meaning that the full potential for axial and lateral resolution available at the operating frequency is not achieved.

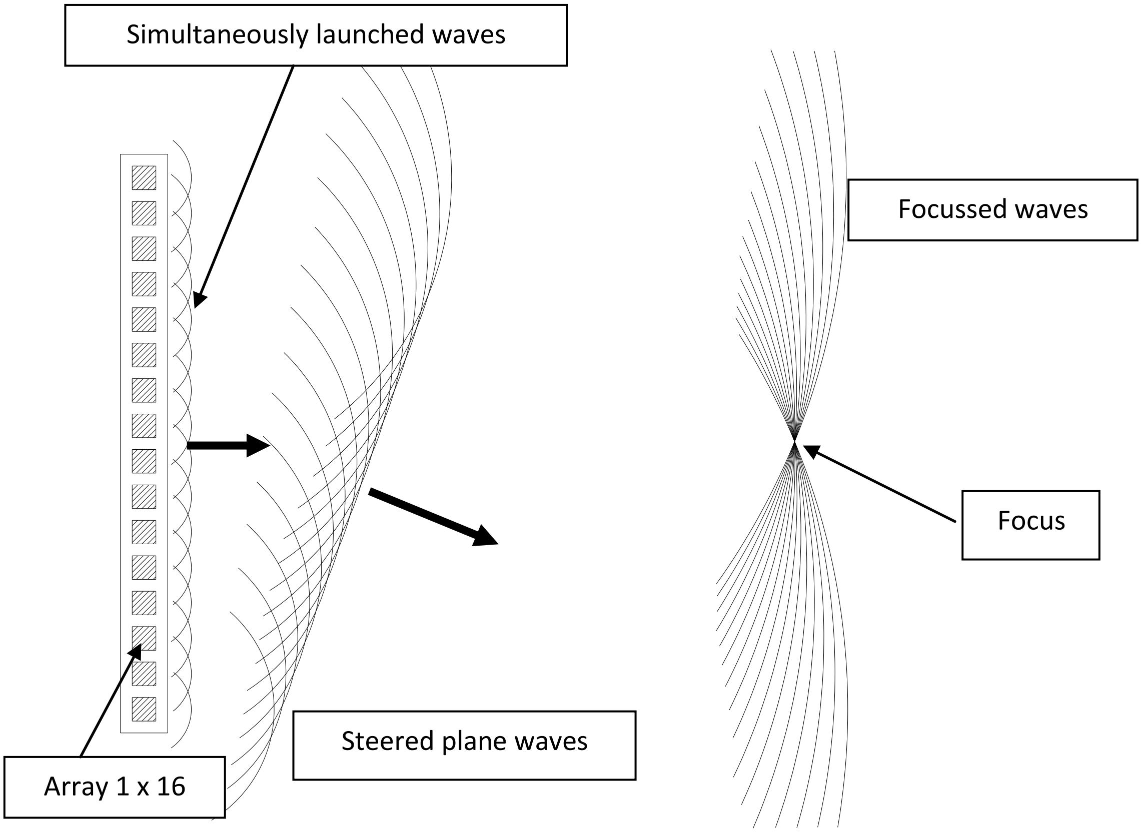


Figure 3

Sketch to illustrate how an ultrasonic beam can be steered and focussed using an array of transmitters.

The same principles, of successive time delays and superposition of signals, can be applied to signals received by the array. A disadvantage is that a considerable amount of signal processing must be done. Beam-forming of received signals can be used to simulate the effect of an ultrasonic lens and beam-forming can provide better quality images than a lens, which is a further benefit of using arrays.

H. Time-reversal mirrors

Arrays can also be used in a self-adaptive imaging mode called time-reversal mirrors. Firstly, a single impulse is transmitted simultaneously from all the elements in an array and the same elements are used for receiving. Then the received signals are simply time-reversed and re-transmitted from the same elements. The elements are used again to collect a second set of signals, which is used for making a compound B-mode scan or C-mode scan. Time-reversal mirroring automatically adapts the transmitted signals to the test sample, providing an image of any scatterers there.

I. Two dimensional arrays

An array with elements distributed over two dimensions gives beam control in three dimensions. Arrays with 64 x 64 (4096) elements have been built but it is not feasible to transmit and receive from all the elements, instead only 128 receivers and 128 transmitters might typically be used in what is known as a sparse array. Since there are more than 256 elements available it is possible to use different elements as transmitter and receivers but there are a very large number of ways of choosing the elements, too many for all of them to be evaluated in a reasonable time. Computer simulations can select configurations that give good performance. Two dimensional arrays allow arbitrary cross-sectional images to be created rapidly, giving better performance for medical imaging.

J. Detecting and sizing flaws

Flaws are detected because they reflect ultrasonic wave energy and positions can be located relatively easily provided an echo can be detected and resolved from other echoes. Improved measurement of the flaw size can be made using waves diffracted from the tips of flaws. Figure 4 shows ultrasonic waves in glass passing, reflecting and diffracting from a narrow slit viewed parallel to its plane. Compression waves are partially converted into shear waves, whose existence can be used to detect flaws. The aim of the experiment is to model flaw detection.

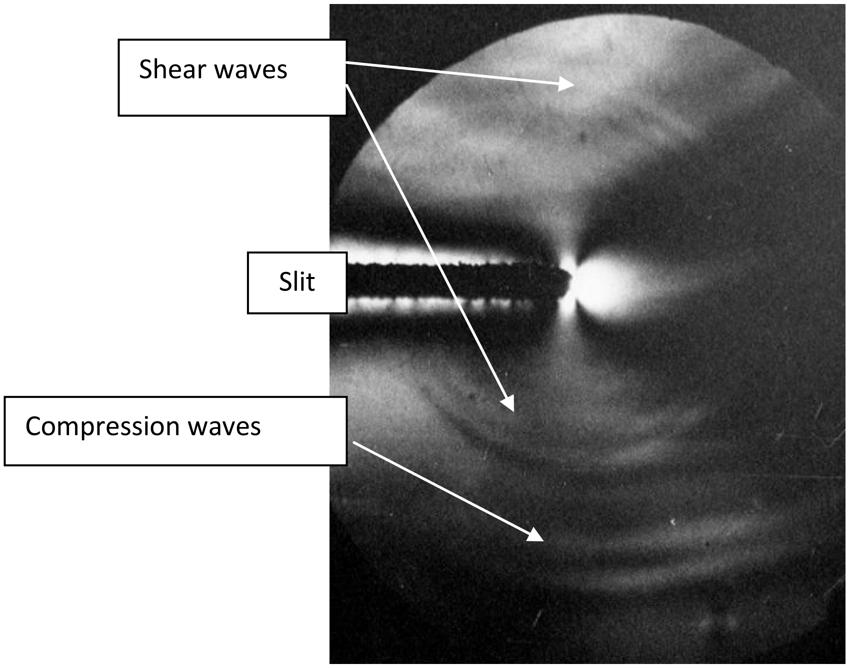


Figure 4

Planar compression waves (1 MHz) travelling from top to bottom in a glass block have been rendered visible passing a planar slit. The tip of the slit acts as a source of cylindrical shear waves, which travel more slowly than the compression waves.

K. Measuring material properties

Empirical relationships have been developed between material properties, such as attenuation and the speed of sound. Typical properties of interest include: crushing strength (concrete), porosity (ceramics) and grain size (austenitic steel and cast iron). Experiments are nearly all performed in transmission, using pitch-and-catch, through a known distance in the test material. Many of these materials are heterogeneous, for which attenuation measurements can be unreliable .

L. Acoustic emission

Acoustic emission is a passive monitoring system used to give a warning of significant structural or material change. It is commonly used for monitoring machinery and structures during normal operations, over long periods of time. There are no transmitters of ultrasound in an acoustic emission system, only receivers. The source of sound is the machinery or structure under test. Ultrasound is created as a crack expands or as wearing progresses and the presence of ultrasound indicates that the material has been degraded. The location of the source can often be identified either from one receiver out of several or from cross-correlation and triangulation. It is also sometimes possible to interpret the acoustic signal as the signature of a particular part wearing. Acoustic emission can be sensitive to environmental noise, for example, acoustic emission has been tried in a pilot scheme to monitor offshore oil production structures but it proved difficult or impossible to separate material emissions from the noise made by sea waves washing against the structure. However, acoustic emission works well for testing components by exploiting the correlation between loading and cracking activity, for example in testing turbine blades for gas-turbine engines, by loading the blades whilst simultaneously monitoring their acoustic emission it is possible to detect the presence of flaws - quiet blades pass the test but noisy blades fail.

M. Geophysical exploration.

The aim of geophysical exploration is to produce cross-sectional images of the Earth showing the rock strata so that promising locations for drilling test wells can be identified. Pulsed sonic methods are used over the frequency range 0.1 Hz to 100 Hz, with a single point source as a transmitter and a linear array of receivers. In a typical test a small explosive charge, or *shot*, is used as the source of sound with about 50 receivers or geophones. A narrow bore-hole is drilled about 100 m down into the underlying rock, into which is put the shot. The geophones are usually spaced 10 m apart or more and buried along a straight line (the *profile*). Recording equipment stores the signals from the geophones. A full analysis is done using computers to process the signals.

The basis of much of the interpretation assumes that the Earth is a layered material, with each layer having its own material properties. The different layers reflect waves back to the surface, reverberate and guide the waves. The main objective of processing the signals is to produce an image of the strata based upon the reflected data only. Other objectives are to compensate for amplitude reduction with range, to compensate for attenuation losses and to compensate for dispersion. Signals are displayed as either compound A-mode (or a variant of it known as VAR) or compound B-mode. The disadvantage of A-mode is that the image is difficult to understand and in B-mode phase information is lost. In VAR one half of the phase is blackened and this gives an image that is more easily understood. Many of the approaches used to process the signals are essentially the same as methods used elsewhere in the field of ultrasonics and acoustics. One example of this is stacking the signals from certain geophones. Stacking is used partly to average signals, thereby improving the signal-to-noise ratio, partly to perform spatial compounding, to help suppress the multiplicative noise created by random scatterers in the rock and partly for focussing (Common Depth Point, CDP, and Common Reflection Point, CRP) and is therefore related to synthetic-aperture focussing used in sonar and radar. Deconvolution of the sonic pulse is also frequently applied (see Pulsed methods). Controlled chirp signals are sometimes used as an alternative to an explosive shot, when large motorised vehicles carrying heavy vibration units are used to transmit low-frequency, linear, sweep frequency chirps (0.1 Hz to 10 Hz) into the ground. Another approach to interpreting seismic profiles is to predict a synthetic seismogram, using a model of the rock formations as a starting point. A computer program, much like a finite element program, then models the propagation of the sonic pulse through the rock strata. Where the predicted and experimental seismograms disagree it is possible to modify the model and re-predict the synthetic seismogram until the degree of disagreement is acceptably low.

N. Marine sonar and sonar in animals.

Sonar systems can be classed as either active or passive. In active sonar an ultrasonic or acoustic pulse is transmitted and echoes are detected. In active marine sonar echoes are displayed in A-mode or B-mode. In a passive marine sonar no signal is transmitted, instead the noise emitted by a target is monitored at several receivers, with which it is possible to measure differences in the times of arrival and calculate the bearing and range. It is common in the field of marine sonar to refer all pressure measurements to the level of 1 μPa with a corresponding reference intensity of 0.67 x 10^{-18} W m^{-2} in water.

$$Intensity = (mean)\ pressure^2 / impedance$$

O. Marine sonar

Marine sonar can be used for warfare, sea bottom sounding, mapping the sea bottom and locating shoals of fish. Complications arise when working in deep oceans because the water temperature changes with depth, causing ultrasonic waves to be reflected. If a vessel moves slowly in a straight line, periodically collecting side-scan sonar signals it is possible to combine them into a compound B-mode image. The signals used in forming this image can then be processed using an algorithm called synthetic aperture focussing, which improves the quality of the image by synthesizing a large aperture lens to focus the image. Common working frequencies for side-scan sonar are in the range 100 kHz to 1 MHz. Sonar used by warships makes use of passive and active array methods: transducer panels are attached to the hulls of ships, long linear arrays are towed behind ships and helicopters lower sonar systems into the water whilst hovering. The return signal contains information about the target that can help identify it because all structures, including ships and submarines, respond to active sonar by resonating and re-radiating ultrasound (see figure 3B). Passive signals can be similarly analysed. Passive counter-measures have the objective of making the submarine quiet and difficult to detect, for example: quiet propellers and engines, streamlined hulls and surface treatments giving low ultrasonic reflection. Active counter-measures aim to confuse the location and identification of the target, for example, jamming sonar. Sonar systems used in warfare must detect targets at a reasonable distance and this constrains the working frequency range to about 1 kHz to 100 kHz, with a typical wavelength of 1.5 m to 1.5 cm. At the lower frequencies the greatest range is achieved but it is then difficult to create a narrow beam because large transducer arrays are required (between 10 m and 100 m). An interesting solution is to make use of non-linear effects in the water. A parametric source is created in this way by driving a sonar transmitter at high power at two frequencies, f_1 and f_2. The non-linear effects create two new waves, one of which is at the difference frequency ($f_1 - f_2$). Sources of difference frequency waves are created at many places in a long, periodic, linear array (a parametric array) in the water ahead of the ship. The beam is exceptionally narrow and points in the direction of the main sonar beam. The difference frequency is typically 10 kHz but it can be changed considerably by making relatively small changes to the two frequencies of the main sonar (approximately 100 kHz), so a parametric source is capable of considerable frequency agility, which is an advantage in view of the complexity of counter-measures used in military sonar systems.

P. Animal sonar

Animals with particularly effective sonar systems include: bats, whales, dolphins and porpoises. These mammals have auditory systems similar to humans, with vocal chords to launch waves and two ears capable of phase discrimination so that the direction of a sound can be estimated. Some bats have sonar systems that work at frequencies up to 100 kHz. All bats use controlled chirp signals when hunting. A relatively short chirp with a wide bandwidth is employed when looking for prey, giving good spatial resolution. Once the bat has detected an echo it increases the repetition frequency of transmission and changes to a longer chirp with a narrower bandwidth, which is good for detecting a Doppler signal. Perhaps the bat can determine the relative speed and direction of its prey or perhaps it can identify the prey using this kind of chirp. As the bat approaches to catch its prey short, large bandwidth chirps are used again at the highest repetition rate for precise spatial information.

Mammals using sonar in the sea get information about the skeletal mass of the peers in their social groups. This is because the reflection coefficient from water to soft tissue is about 0.1% whereas the value for water to bone is almost 50%, so the skeleton generates the strongest echo signals. It is not known if the information is registered as an image in their brains; a close analogy, however, would be foetal imaging. Dolphins and porpoises use their sonar to find fish and they also use it to stun the fish, by emitting an intense burst of waves. Whales and dolphins use frequencies from about 1 Hz up to about 30 kHz for their sonar.

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