Sound energy may be reflected, refracted, scattered, absorbed or transmitted while interacting with a material. Reflection takes place in the same way as for light, i.e. angle of incidence equals angle of reflection. At any interface between two media of different acoustic impedances a mismatch occurs causing the major percentage of the wave to be reflected back, the remainder being transmitted. There are two main cases:

Material	**Longitudinal**	**Transverse**
Aluminium	6.32	3.13
Brass	4.28	2.03
Copper	4.66	2.26
Gold	3.24	1.20
Iron	5.90	3.23
Lead	2.16	0.70
Steel	5.89	3.24
Perspex	2.70	1.40
Water	1.43	-
Oil (transformer)	1.39	-
Air	0.33	-

TABLE 3.2 : VELOCITIES OF SOUND IN SOME COMMON MATERIALS

2.1.2.1 Reflection and transmission at normal incidence

The percentage of incident energy reflected from the interface between two materials depends on the ratio of acoustic impedances of the two materials and the angle of incidence. When the angle of incidence is 0 (normal incidence), the reflection coefficient (R), which is the ratio of the reflected beam intensity I_r to the incident beam intensity I;, is given by

$$= I_r/I_i = (Z_2 - Z_1)^2 /((Z_1+Z_2)^2$$

where Z\ is the acoustic impedance of medium 1, and Z2 is the acoustic impedance of medium 2. The remainder of the energy is transmitted across the interface into the second material. The transmission coefficient (T) which is the ratio of the transmitted intensity 'I t ' to the incident intensity 'I;' is given by

$$= I_r / I_i = Z_1,Z_2/(Z_1+Z_2)^2$$

Using the values of characteristic impedances, reflection and transmission coefficients can be calculated for pairs of different materials. The equations show that the transmission coefficient approaches unity and the reflection coefficient tends to zero when Z_1 and Z_2 have approximately similar values. The materials are then said to be well matched or coupled. On the other hand, when the two materials have substantially dissimilar characteristic impedances, e.g. for a solid or liquid in contact with a gas, the transmission and reflection coefficients tend to zero and 100 per cent prospectively. The materials are then said to be mismatched or poorly coupled. It is for this reason that a coupling fluid is commonly used when transmitting or receiving sound waves in solids.

3.6.1.2.2 Reflection and transmission at oblique incidence

When an ultrasonic wave is incident on the boundary of two materials at an angle other than normal, the phenomenon of mode conversion (a change in the nature of the wave motion i.e. longitudinal to transverse and vice versa) must be considered. All possible ultrasonic waves leaving the point of impingement are shown for an incident longitudinal ultrasonic wave in below figure mode conversion can also take place on the reflection side of the interface if material 1 is solid.

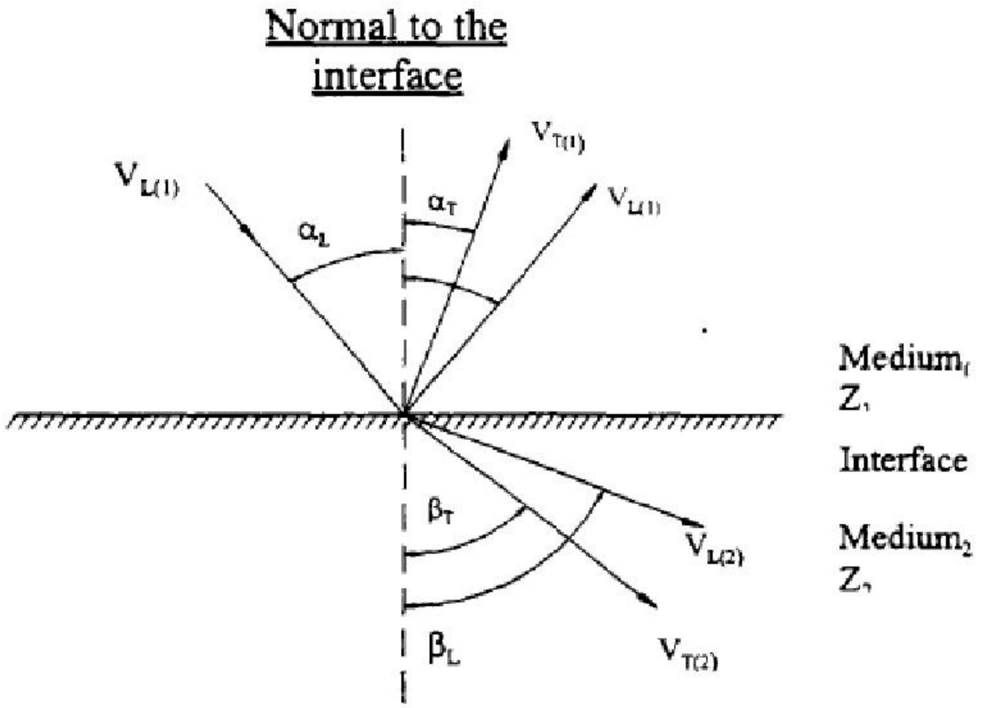
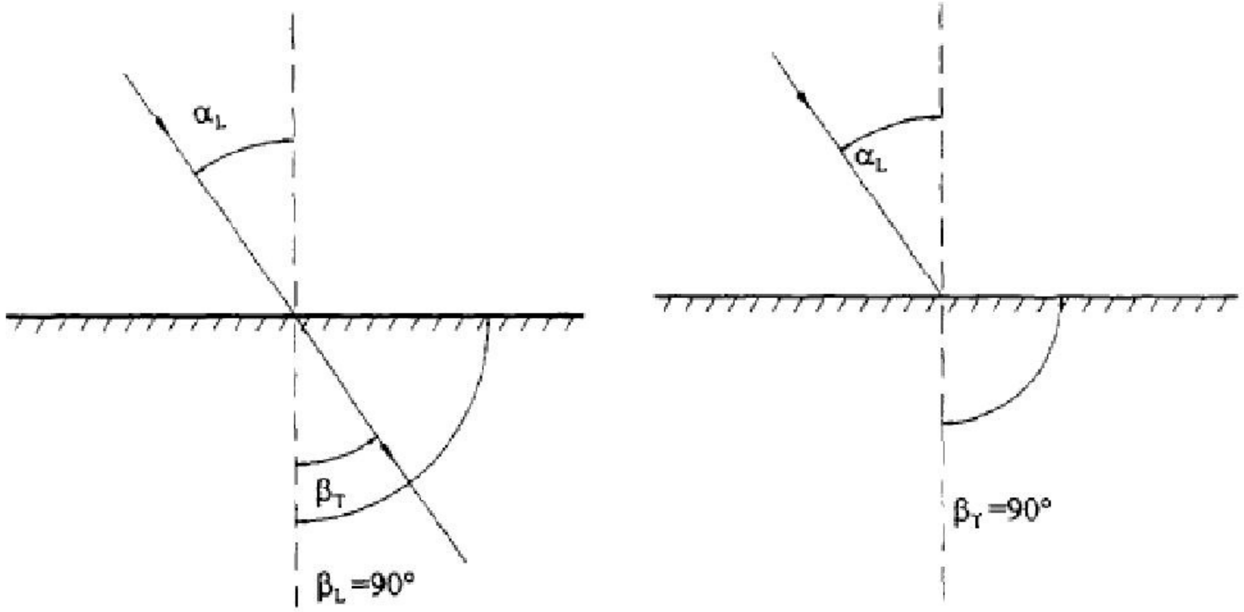


Figure: Phenomena of reflection, refraction and mode conversion for an incident wave.

2.1.2.3 First and second critical angles

If the angle of incidence cc_L is small , ultrasonic waves travelling in a medium undergo the phenomena of mode conversion and refraction on encountering a boundary with another medium. This results in the simultaneous propagation of longitudinal and transverse waves at different angles of refraction in the second medium. As the angle of incidence is increased, the angle of refraction also increases. When the refraction angle of a longitudinal wave reaches 90° the wave emerges from the second medium and travels parallel to the boundary. The angle of incidence at which the refracted longitudinal wave emerges is called the first critical angle. If the angle of incidence a_L is further increased the angle of refraction for the transverse wave also approaches 90°. The value of a_L for which the angle of refraction of the transverse wave is exactly 90° is called the second critical, angle At the second critical angle the refracted transverse wave emerges from the medium and travels parallel to the boundary. The transverse wave has thus become a surface or Raleigh wave.



a) First critical angle

b) Second critical angle

Figure : First and second critical angles.

2.2 Equipment for ultrasonic testing

The equipment for ultrasonic testing mainly consists of a flaw detector, transducers and the test or calibration blocks. These are briefly described here. Below figure shows the block diagram for a typical flaw detector. A pulse generator generates pulses of alternating voltages which excite the crystal in the probe to generate specimen by coupling the probe to it. The waves are reflected from the far boundary of the test specimen or from any discontinuities within it and reach the probe again. Here through the reverse piezoelectric effect the ultrasonic waves are converted into voltage pulses and are fed to the y-plates of a cathode ray tube through an amplifier. These then are displayed on the CRT screen as pulses of definite amplitude and can be interpreted as signals from the back wall of the test specimen or from the discontinuity present within it.

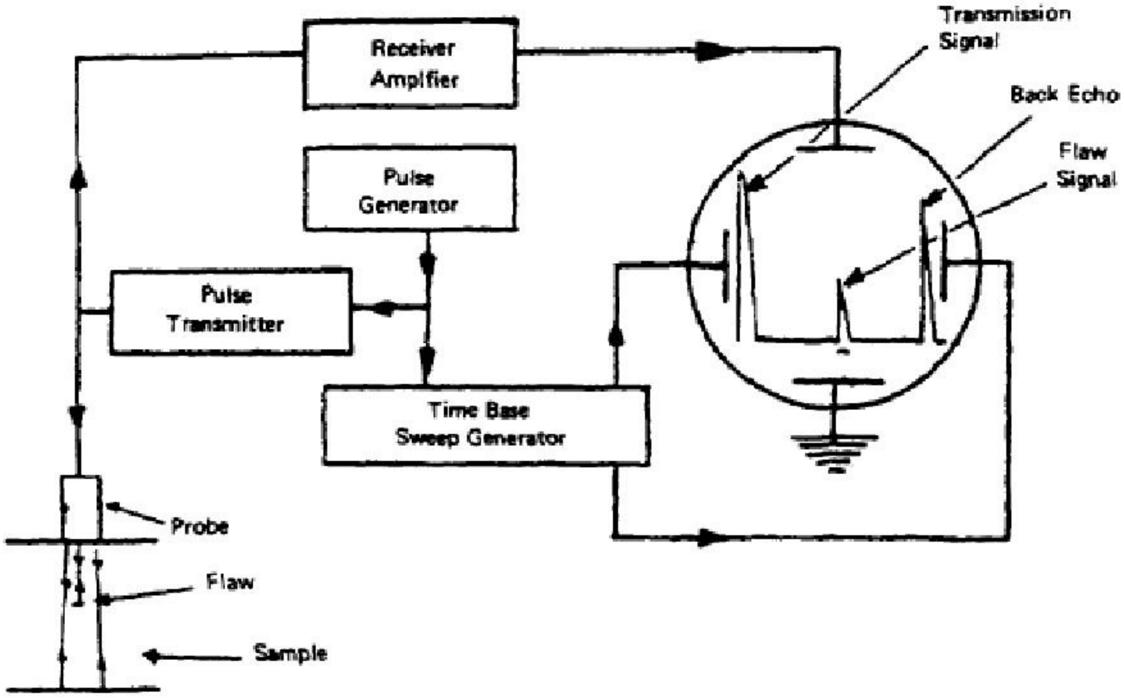


Figure: A typical ultrasonic test unit.

Ultrasound is generated in certain natural and artificially made crystals which show the effect of piezoelectricity i.e. they produce electric charges on being subjected to mechanical stresses and vice versa. Thus on the application of electric pulses of appropriate frequency these crystals produce ultrasonic pulses which are mechanical vibrations. The most commonly used materials are quartz, lithium sulphate, barium titanate and lead metaniobate. The properly cut crystal is contained in a housing, the whole assembly being termed as an ultrasonic probe. The two faces of the crystal are provided with electrical connections. On the front face of the crystal (the face which comes in contact with the test specimen) a perspex piece is provided to avoid wear and tear of the crystal. At the rear of the crystal there is damping material such as a spring or tungsten araldite. This damping material is necessary to reduce the vibration of the crystal after transmitting the ultrasonic pulse so that the crystal can be more efficient as a receiver of sound energy. Damping is necessary therefore to improve the resolution of the probe. A typical probe is shown in Figure 3.19. The probe generates ultrasound of a particular frequency which depends upon the thickness of the piezoelectric crystal. The sound comes out of the probe in the form of a cone-like beam which has two distinct regions namely the near field and the far field. Most of the testing is performed using the far field region of the beam. The probes that send the ultrasonic beams into the test specimen at right angles to the surface are called normal beam probes while those that send beams into the specimen at a certain angle are termed as angle beam probes. In angle beam probes the crystal is mounted on a perspex wedge so that the longitudinal waves fall on the surface of the test specimen obliquely. Then through the phenomenon of mode conversion and choosing a suitable angle of incidence, shear waves can be sent into the test specimen at the desired angle. These angle beam probes are used specially for the inspection of welds whose bead has not been removed.

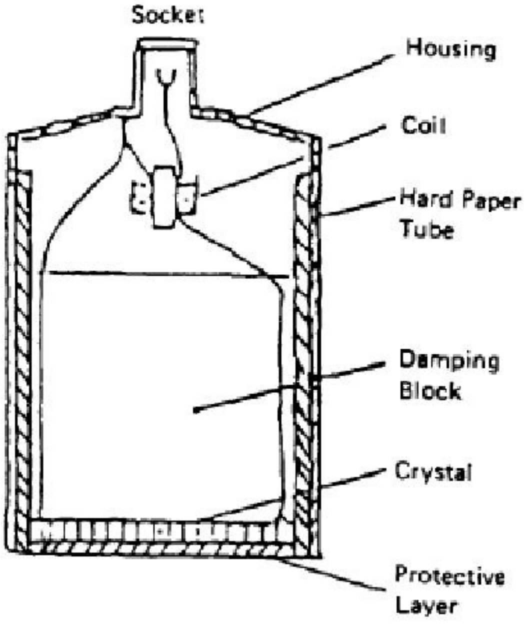


Figure: A typical normal beam single crystal ultrasonic probe.

To draw any meaningful conclusions from the indications of reflected ultrasound the flaw detector-probe system should be properly calibrated using standard calibration blocks. There is a large variety of these blocks which are in use for different types of inspection problems. Some of the most commonly used ones are briefly described here. The I.I.W test block, shown in above Figure , can be used to set test sensitivity, time base calibration, determination of shear wave probe index and angle, checking the amplifier linearity and checking the flaw detector - probe resolving power. The block is sometimes referred to as the VI block.

The V2 test block is mainly used with the miniature angle probes to calibrate the CRT screen. The block is shown in above figure along with the CRT screen appearance when the probe is placed in two different positions on the block.

Some blocks are made having flat bottom holes. These type of test blocks are made from a plate of the same material as the material under test. The ASTM area-amplitude blocks and distance-amplitude blocks are examples of this type of block

These blocks provide known-area reflectors which can be compared to reflections from unknown reflectors. They also enable reproducible levels of sensitivity to be set and therefore to approximate the magnitude of flaws in terms of reflectivity. In addition to the standard test blocks there are a number of other test blocks available. In general a test block should simulate the physical and metallurgical properties of the specimen under test. The variety of test blocks available can be found by consulting the various national standards, e.g. ASME, ASTM, BS, DIN, J1S, etc

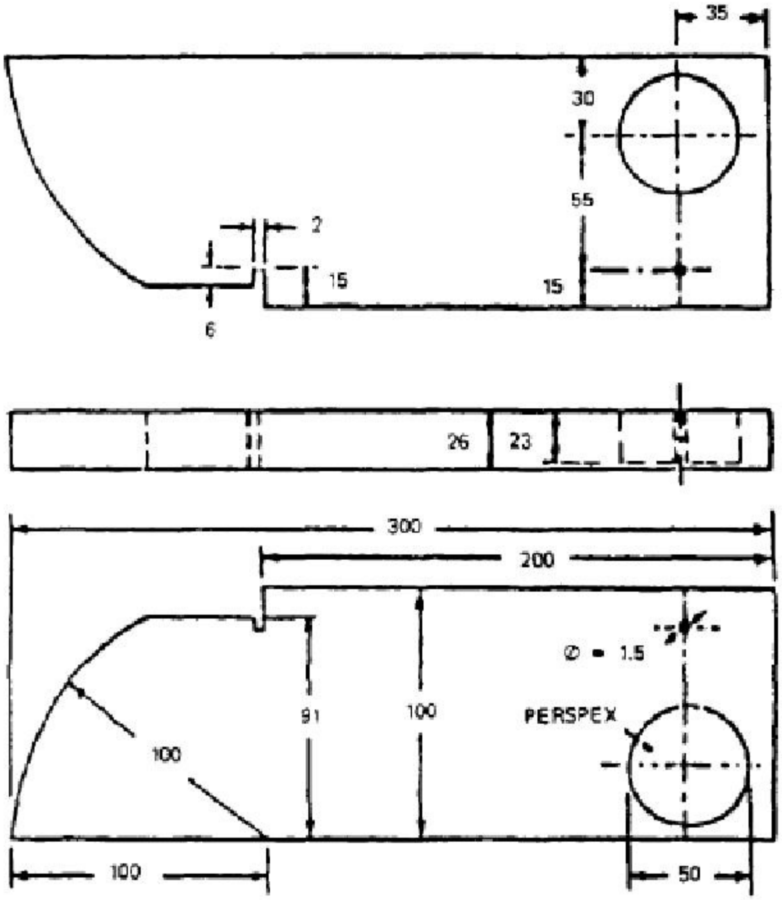


Figure : I.I.W test block.

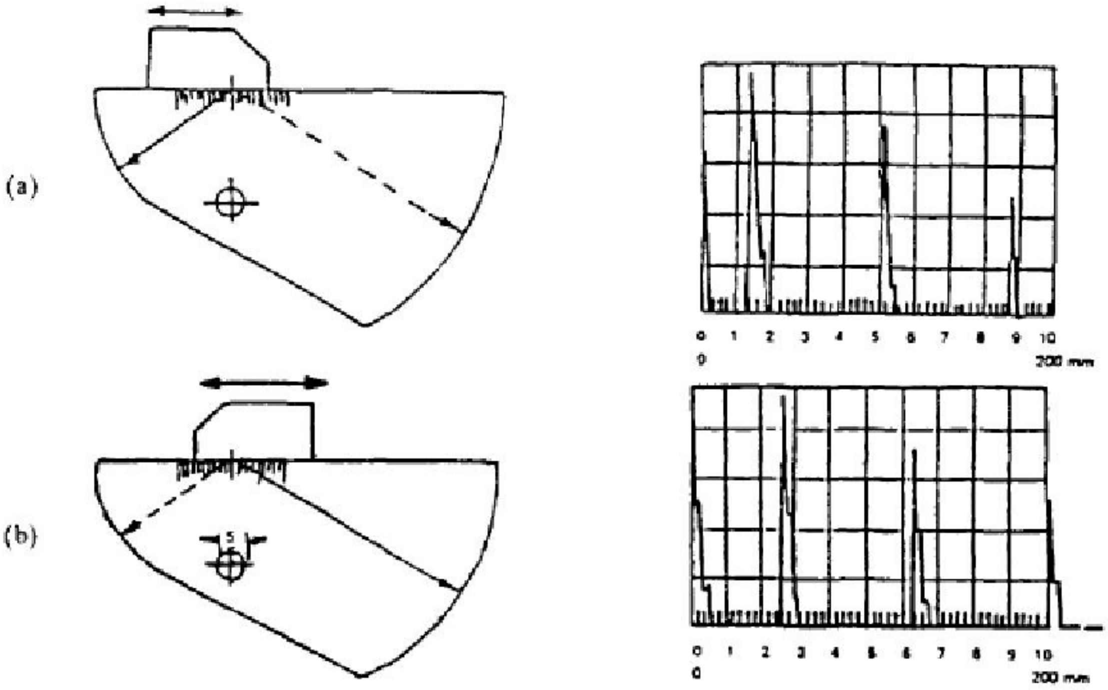


Figure : V2 test block (a) with the probe index at the zero point and directed to the 25 mm radius, (b) with the probe index at the zero point and directed to the 50 mm radius.

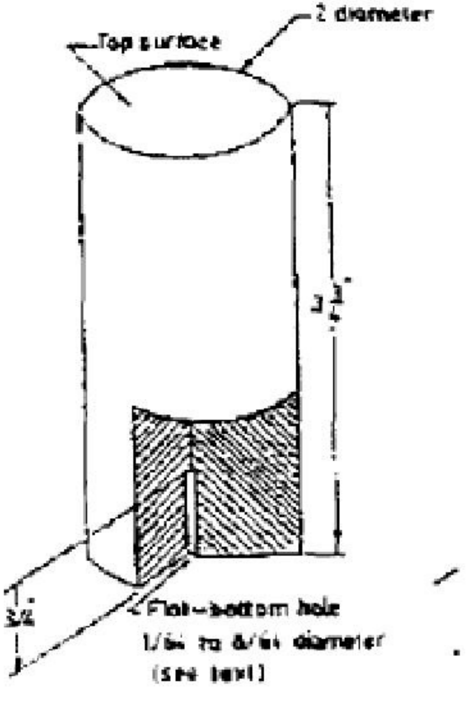


Figure : Flat bottom hole type test block.

2.3 General procedure for ultrasonic testing

The most commonly used method of ultrasonic testing is the pulse-echo or reflection method. In this case the transmitter and receiving probes are on the same side of the specimen and the presence of a defect is indicated by the reception of an echo before that of the boundary or backwall signal. The CRT screen shows the separation between the time of arrival of the defect echo compared to that of the natural boundary of the specimen, therefore, location of the defect can be assessed accurately. Usually one probe acts simultaneously as a transmitter and then as a receiver and is referred to as a TR probe. The principle of the pulse echo method is illustrated in above Figure

The time base of the CRT can be calibrated either in units of time or, if the velocity of sound in the material is known, in units of distance. If "1" is the distance from the transducer to the defect and "t" the time taken for waves to travel this distance in both directions then, 1 = vt/2 where v is the sound velocity in the material.

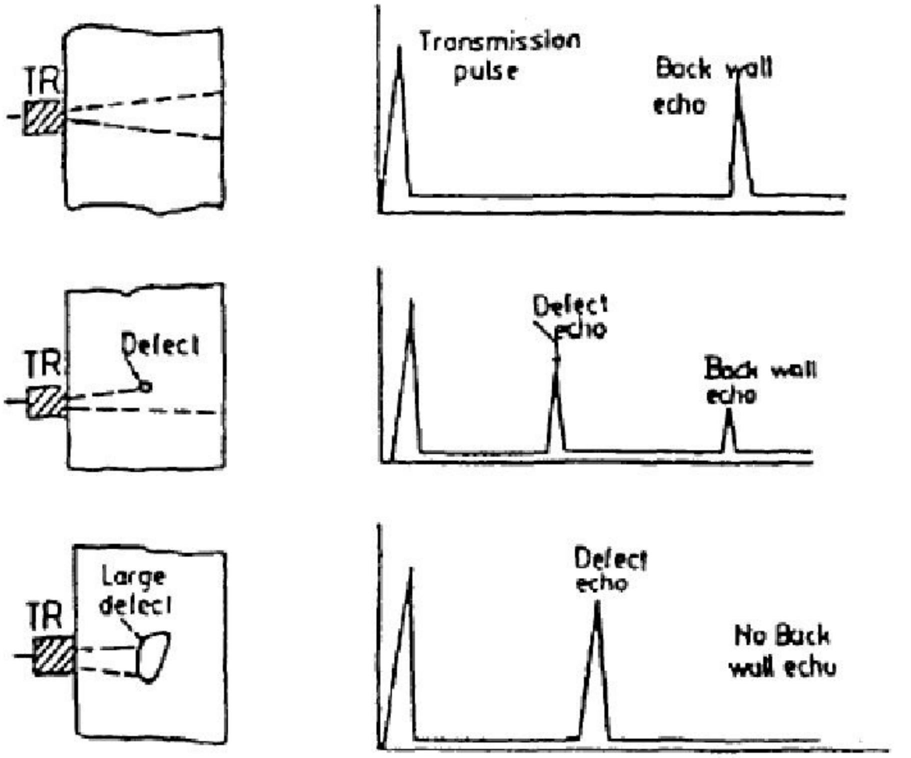


Figure: Principle of pulse echo method of ultrasonic testing (a) defect free specimen (b) specimen with small defect (c) specimen with large defect.

The procedure to conduct an ultrasonic test is influenced by a number of factors. Also the nature of the test problems in industry varies over a wide range. Therefore it is difficult to define a method which is versatile enough to work in all situations. However, it is possible to outline a general procedure which will facilitate the inspection by ultrasonics in most cases.

(i) The test specimen

Specimen characteristics such as the condition and type of surface, the geometry and the microstructure are important. Very rough surfaces may have to be made smooth by grinding, etc. Grease, dirt and loose scale or paint should be removed. The geometry of the specimen should be known since this has a bearing on the reflection of sound inside the specimen. Some reflections due to a complex geometry may be confused with those from genuine defects. The material microstructure or grain structure affects the degree of penetration of sound through it. For a fixed frequency the penetration is more in fine grained materials than in coarse grained materials.

(ii) Types of probes and equipment

The quality of ultrasonic trace depends on the probes and equipment which in turn determine the resolving power, the dead zone and the amount of sound penetration. It is difficult to construct a probe which will provide good detection and resolution qualities and at the same time provide deep penetration. For this reason, a variety of probes exist some of which are designed for special purposes. For the examination of large surface areas it is best to use probes with large transducers in order to reduce the time taken for the test. However the wide beam from such a probe will not detect a given size of flaw as easily as a narrower one. The probability of detecting flaws close to the surface depends on the type of equipment and probes used. The dead zone can be decreased in size by suitably designing the probe and also shortening the pulse length. The selection of the test frequency must depend upon previous experience or on preliminary experimental tests or on code requirements. The finer the grain structure is, the greater is the homogeneity of the material and the higher is the frequency which can be applied. The smaller the defects being looked for the higher the frequency used. Low frequencies are selected for coarse grained materials such as castings, etc. After the selection of the probe and the equipment has been finalized, its characteristics should be checked with the help of test blocks.

(iii) Nature of defects

Defect characteristics which include the type, size and location, differ in different types of materials. They are a function of the design, manufacturing process and the service conditions of the material. The detection and evaluation of large defects is not normally a difficult problem. The outline of a defect can be obtained approximately by moving the probe over the surface of the test specimen. The flaw echo increases from zero to a maximum value as the probe is moved from a region free from defects to a point where it is closest to a defect. Information as to the character of a defect can be obtained from the shape of the defect echo. For small defects, the size of the defect is estimated by comparing the flaw reflectivity with the reflectivity of standard reflectors. If the standard reflector is of the same shape and size as the unknown flaw, the reflectivity will be the same at the same beam path length. Unfortunately this is seldom the case since reference reflectors are generally flat bottomed holes or side drilled holes and have no real equivalence to real flaws. Theoretically it is possible under favourable conditions to detect flaws having dimensions of the order of half a wavelength. Indications obtained with an ultrasonic flaw detector depend to a great extent on the orientation of the defect in the material. Using the single probe method, the largest echoes are obtained when the beam strikes the surface of the specimen at right angles. On a properly calibrated time base the position of the echo from a defect indicates its location within the specimen. The determination of the type, size and location of defects which are not at right angles to the sound beam is complicated and needs deep understanding and considerable experience.

(iv) Selection of couplant

The couplant provides impedance matching between the probe and the test specimen. The degree of acoustic coupling depends on the roughness of the surface and the type of couplant used. In general the smoother the surface the better the conditions for the penetration of ultrasonic waves into the material under test. Commonly used couplants are water, oils of varying degrees of viscosity, grease, glycerine and a mixture of 1 part glycerine to 2 parts water. Special pastes such as Polycell mixed with water are also used.

(v) Test standards

Standards are used to check the performance of the flaw detector probe system. There are mainly two types of these standards. The first type of standard is used to control such parameters as amplifier gain, pulse power and time base marking and to ensure that they remain constant for the whole of the test. They are also used to verify the angle of incidence and to find the point where the beam emerges in angle probes. Another purpose of this group of standards is to calibrate the time base of the oscilloscope. The second group of standards contains those used for special purposes. They are normally used for tests which are largely dependent on the properties of the examined material and, if possible, they are made of the same materials and have the same shapes as the examined objects. These standards allow for the setting of the minimum permissible defect as well as the location of defects.

(vi) Scanning procedure

Before undertaking an ultrasonic examination, the scanning procedure should be laid down. For longitudinal probes this is simple but care must be taken with angle or shear wave probes. For instance in the inspection of welds using an angle probe scanning begins with the probe at either the half skip or full skip positions and continues with the probe being moved in a zigzag manner between the half skip and full skip positions. There are in general four scanning movements in manual scanning, rotational, orbital, lateral and traversing. The half skip position is recommended for critical flaw assessment and size estimation whenever possible. In some special applications the gap scanning method is employed. Here, an irrigated probe is held slightly away from the material surface by housing it in a recess made in a contact scanning head. Probe wear can be avoided by interposing a free running endless belt of plastic ribbon between the probe and the test surface. Acoustical coupling is obtained by enclosing the probe in an oil filled rotating cylinder in which case only the surface requires irrigation. Immersion scanning, which is most commonly used in automatic inspection, is done by holding the probe under water in a mechanical or electronic manipulator, the movement of which controls the movement of the probe.

(vii) Defect sizing

After the flaws in the test specimen have been detected it is important to evaluate them in terms of their type, size and location. Whereas the type and location of the flaw may be inferred directly from the echo on the CRT screen; the size of the flaw has to be determined. The commonly used methods for flaw sizing in ultrasonic testing are 6 dB drop method, 20 dB drop method, maximum amplitude method and the DGS diagram method. The basic assumption in the 6 dB drop method is that the echo height displayed when the probe is positioned for maximum response from the flaw will fall by one half (i.e. by 6 dB and hence the name) when the axis of the beam is brought in line with the edge of the flaw. The method only works if the ultrasonic response from the flaw is essentially uniform over the whole reflecting surface. If the reflectivity of the flaw varies considerably the probe is moved until the last significant echo peak is observed just before the echo drops off rapidly. This peak is brought to full screen height and then the probe is moved to the 6 dB point as before. A similar procedure is followed for the other end of the flaw. The 6 dB drop method is suitable for the sizing of flaws which have sizes of the same order or greater than that of the ultrasonic beam width but will give inaccurate results with flaws of smaller sizes than the ultrasonic beam. It is therefore generally used to determine flaw length but not flaw height. The 20 dB drop method utilizes for the determination of flaw size, the edge of the ultrasonic beam where the intensity falls to 10% (i.e. 20 dB) of the intensity at the central axis of the beam. The 20 dB drop method gives more accurate results than the 6 dB drop method because of the greater control one has on the manipulation of the ultrasonic beam. However, size estimation using either the 6 dB or 20 dB drop method have inherent difficulties which must be considered. The main problem is that the amplitude may drop for reasons other than the beam scanning past the end of the defect due to any of the following reasons:

(a) The defect may taper in section giving a reduction in cross sectional area within the beam. If this is enough to drop the signal 20 dB or 6 dB the defect may be reported as finished while it in fact continues for an additional distance.

(b) The orientation of the defect may change so that the probe angle is no longer giving maximum response, another probe may have to be used.

(c) The defect may change its direction.

(d) The probe may be twisted inadvertently.

(e) The surface roughness may change.

The maximum amplitude method takes into account the fact that most defects which occur do not present a single, polished reflecting surface, but in fact take a rather ragged path through the material with some facets of the defect surface suitably oriented to the beam and some unfavorably oriented. As the beam is scanned across the surface of the defect, the beam centre will sweep each facet in turn. As it does, the echo from that facet will reach a maximum and then begin to fall, even though the main envelope may at any instant, be rising or falling in echo amplitude. The stand-off and range of the maximum echo of each facet is noted and plotted on the flaw location slide. This results in a series of points which trace out the extent of the defect. The gain is increased to follow the series of maximum echoes until the beam sweeps the last facet.

The DGS method makes use of the so called DGS diagram, developed by Krautkramer in 1958 by comparing the echoes from small reflectors, namely different diameter flat bottom holes located at various distances from the probe, with the echo of a large reflector, a back wall reflector, also at different distances from the probe (Section 7.2.4). For normal probes it relates the distance D from the probe (i.e. along the beam) in near field units, thus compensating for probes of different sizes and frequencies, to the gain G in dB for a flat bottom hole compared to a particular back wall reflector and the size S of the flat bottom hole as a proportion of the probe crystal diameter.

Since in the case of angle beam probes some of the near field length is contained within the perspex path length and this varies for different designs and sizes of probe, individual DGS diagrams are drawn for each design, size and frequency of angle beam probe. For this reason the scale used in the D-scale is calibrated in beam path lengths, the G-scale in decibels as before and the S-scale representing flat bottom hole or disc shaped reflector diameters in mm.

(viii) Test report

In order that the results of the ultrasonic examination may be fully assessed it is necessary for the tester's findings to be systematically recorded. The report should contain details of the work under inspection, the code used, the equipment used and the calibration and scanning procedures. Also the probe angles, probe positions, flaw ranges and amplitude should be recorded in case the inspection needs to be repeated. The principle is that all the information necessary to duplicate the inspection has to be recorded.

Applications of ultrasonic testing

Thickness measurements

Thickness measurements using ultrasonics can be applied using either the pulse echo or resonance techniques. Some typical applications are:

(i) Wall thickness measurement in pressure vessels, pipelines, gas holders, storage tanks for chemicals and accurate estimate of the effect of wear and corrosion without having to dismantle the plant.

(ii) Measurement of the thickness of ship hulls for corrosion control.

(iii) Control of machining operations, such as final grinding of hollow propellers.

(iv) Ultrasonic thickness gauging of materials during manufacture.

(v) Measurement of wall thickness of hollow aluminium extrusions.

(vi) Measurement of the thickness of lead sheath and insulating material extruded over a core of wire. Inspection of heat exchanger tubing in nuclear reactors. wire. Inspection of heat exchanger tubing in nuclear reactors
(viii) Measurement of the wall thickness of small bore tubing including the canning tubes for reactor fuel elements.

Flaw detection

Typical flaws encountered in industrial materials are cracks, porosity, laminations, inclusions, lack of root penetration, lack of fusion, cavities, laps, seams, corrosion, etc. Some examples of the detection of these defects are as follows:

- Examination of welded joints in pressure vessels, containers for industrial liquids and gases, pipelines, steel bridges, pipelines, steel or aluminium columns, frames and roofs (during manufacturing, pre-service and in-service).
- Inspection of steel, aluminium and other castings,
- Inspection of rolled billets, bars and sections.
- Inspection of small bore tubes including the canning tubes for nuclear fuel elements.
- Ultrasonic testing of alloy steel forgings for large turbine rotors,
- Testing of turbine rotors and blades for aircraft engines.

- Early stage inspection in the production of steel and aluminium blocks and slabs, plates, bar sections, tubes, sheets and wires.
- Detection of unbonded surfaces in ceramics, refractories, rubber, plastics and laminates.
- Detection of honeycomb bond in the aircraft industry.
- Inspection of jet engine rotors.
- Detection of caustic embrittlement failure in riveted boiler drums in the power generation industry.
- Detection of cracks in the fish plate holes in railway lines and in locomotive and bogey axles.
- Detection of hydrogen cracks in roller bearings resulting from improper heat treatment.
- In service automatic monitoring of fatigue crack growth.
- Detection of stress corrosion cracking.
- Detection of fatigue cracks in parts working under fluctuating stress.
- Inspection of fine quality wire.
- Testing of wooden components such as utility poles.
- Application of ultrasonics to monitor material characteristics in the space environment.
- Determination of lack of bonding in clad fuel elements,
- Detection of flaws in grinding wheels.
- Varieties of glass which are not sufficiently transparent to allow optical inspection can be tested ultrasonically.
- Quality control in the manufacture of rubber tyres by locating voids, etc.

- Inspection of engine crankshafts.

2.4.3 Miscellaneous applications

In addition to the applications already mentioned there are numerous others. Notable among these are those based on the measurement of acoustic velocity and the attenuation of acoustic energy in materials. Some of these applications are as follows:

1. Assessment of the density and tensile strength of ceramic products such as high tension porcelain insulators.
2. Determination of the difference between various types of alloys.
3. Detection of grain growth due to excessive heating.
4. Estimation of the values of the elastic moduli of metals over a wide range of temperature and stress.
5. Tensile strength of high grade cast iron can be estimated by measuring its coefficient of acoustical damping.
6. Crushing strength of concrete can be measured from the transit time of an ultrasonic pulse.
7. Quarrying can be made more efficient by the measurement of pulse velocity or attenuation in rock strata.
8. To find the nature of formations in geophysical surveys without having to undertake boring operations.
9. Detection of bore hole eccentricity in the exploration for mineral ores and oil.
10. Study of press fits.
11. Metallurgical structure analysis and control of case depth and hardness, precipitation of alloy constituents and grain refinement.
12. Determination of intensity and direction of residual stresses in structural metal components.

13. Detection of honeycomb debonds and the regions in which the adhesive fails to develop its nominal strength in the aerospace industry.

14. Measurement of liquid level of industrial liquids in containers.

3.6.5 Range and limitations of ultrasonic testing

Advantages

The principal advantages of ultrasonic inspection as compared to other methods for non-destructive inspection of metal parts are:

1. Superior penetrating power which allows the detection of flaws deep in the part. Ultrasonic inspection is done routinely to depths of about 20 ft in the inspection of parts such as long steel shafts and rotor forgings.

2. High sensitivity permitting the detection of extremely small flaws.

3. Greater accuracy than other non-destructive methods in determining the position of internal flaws, estimating their size and characterizing their orientation, shape and nature.

4. Only one surface needs to be accessible.

5. Operation is electronic, which provides almost instantaneous indications of flaws. This makes the method suitable for immediate interpretation, automation, rapid scanning, on-line production monitoring and process control. With most systems, a permanent record of inspection results can be made for future reference.

6. Volumetric scanning ability, enabling inspection of a volume of metal extending from the front surface to the back surface of a part.

7. Is not hazardous to operators or to nearby personnel, and has no effect on equipment and materials in the vicinity.

    a. Portability.

8. Disadvantages

9. Manual operation requires careful attention by experienced technicians.

10. Extensive technical knowledge is required for the development of inspection procedures.

11. Parts that are rough, irregular in shape, very small or thin, or not homogeneous are difficult to inspect.

12. Discontinuities that are present in a shallow layer immediately beneath the surface may not be detectable.

13. Couplants are needed to provide effective transfer of ultrasonic wave energy between transducers and parts being inspected.

14. Reference standards are needed, both for calibrating the equipment and for characterizing flaws.

UNIT III
RADIOGRAPHIC TESTING

RADIOGRAPHIC TESTING

Fundamental principles

The method of radiographic testing

The method of radiographic testing involves the use of a source of radiation from which the radiations hit the test specimen, pass through it and are detected by a suitable radiation detector placed on the side opposite to that of the source. This is schematically shown in the Figure 3.11. While passing through the test specimen the radiations are absorbed in accordance with the thickness, physical density and the internal defects of the specimen and the detector system therefore receives the differential radiations from different parts of a defective specimen which are recorded onto the detector.

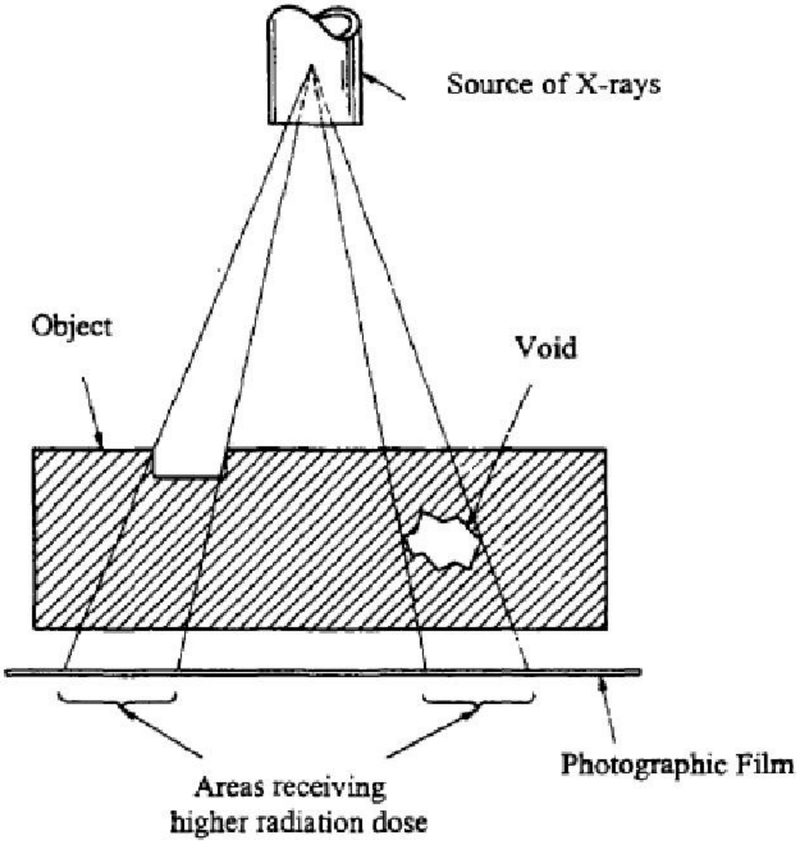


Figure : Arrangement of source, specimen and film in a typical radiographic set up