Ultrasonic Testing (UT) - Welds

NDT4

Training and Examination Services
Granta Park, Great Abington
Cambridge CB21 6AL
United Kingdom

Ultrasonic Testing (UT) – Welds – NDT4

Contents

Section	Subject
	Preliminary pages
	Contents
	Standards and Associated Reading
	COSHH, H&S, Cautions and Warnings
	Introduction to NDT Methods
	NDT Certification Schemes
1	**Physical Principles**
1.1	Frequency
1.2	Wavelength
1.3	Resolution
1.4	Signal amplitude
2	**Modes of Sound Energy**
2.1	Compressional waves
2.2	Shear waves
2.3	Rayleigh or surface waves
2.4	Lamb waves
3	**Generating Ultrasound**
3.1	Piezo-electric crystals
3.2	Quartz or silicon oxide (SiO_2)
3.3	Lithium sulphide (Li_2SO_4)
3.4	Barium titanate ($BaTiO_3$)
3.5	Lead metaniobate ($PbNb_2O_6$)
3.6	Lead zirconate titanate ($PbZrO_3$, $PbTiO_3$)
3.7	Electromagnetic acoustic transducers
4	**Pulse Length and Damping**
5	**The Sound Beam**
5.1	Near zone (or near field)
5.2	Far zone
6	**Total Attenuation Loss**
6.1	Attenuation due to beam spread
7	**Acoustic Impedance**
8	**Snell's Law**
8.1	Critical angle calculation
8.2	Mode conversion
9	**Probe Design**
9.1	Compression wave probes
9.2	Angle probes
9.3	Twin crystal probes
9.4	Other probe types

10 Test Techniques
10.1 Pulse echo
10.2 Through-transmission
10.3 Tandem scanning
10.4 Contact scanning
10.5 Gap scanning
10.6 Immersion testing
10.7 Presentation

11 Ultrasonic Flaw Detector
11.1 Principles
11.2 Cathode ray tube
11.3 Pulse generation
11.4 Range control
11.5 Delay
11.6 Calibrated gain/attenuator control
11.7 Reject/suppressor control
11.8 The decibel

12 Calibration and Sensitivity
12.1 Finding the probe index
12.2 Checking the probe angle
12.3 Calibration of shear waves for range

13 Flaw Location

14 Flaw sizing
14.1 The 6dB drop sizing method
14.2 The 20dB drop sizing metho
14.3 Construction of a beam edge plot - 20dB
14.4 Constructing an angle beam plot
14.5 Proving the beam plot
14.6 Modified near zone angle probes
14.7 Horizontal beam plot

15 Sensitivity Setting
15.1 The Institute of Welding (IOW) block
15.2 Distance amplitude correction (DAC) curves
15.3 Flat-bottomed holes (FBH)
15.4 Using noise
15.5 Transfer correction
15.6 The distance gain size (DGS) method
15.7 Signal-to-noise ratio (SNR)

16 Ultrasonic Equipment Checks
16.1 Linearity of time base
16.2 Linearity of equipment gain
16.3 Probe index and beam alignment
16.4 Beam angle
16.5 Sensitivity and signal-to-noise ratio
16.6 Pulse duration
16.7 Resolving power (resolution)

17 **Practical Weld Inspection**
17.1 Identifying flaws in butt welds

18 **Root Flaws**
18.1 Excess penetration
18.2 Root concavity
18.3 Root crack
18.4 Lack of root fusion
18.5 Misalignment

19 **Face and Body Flaws**
19.1 Lack of fusion
19.2 Crack
19.3 Gas pore
19.4 Porosity
19.5 Linear inclusion (slag)

20 **Plate Inspection**

21 **Inspection Procedure**
21.1 Information required prior to testing
21.2 Compression scan
21.3 Root scan
21.4 Weld scan
21.5 Transverse scan
21.6 Double V welds
21.7 Pipes
21.8 Reporting

22 **Ultrasonic Thickness Measurement**
22.1 Measurement modes
22.2 Requirements – test object, instruments, probes and reference blocks

Glossary

Product Technology Notes

Preface

These notes are provided as training reference material and to meet the study requirements for examination on the NDT course to which they relate.

They do not form an authoritative document, nor should they be used as a reference for NDT inspection or used as the basis for decision making on NDT matters. The standards listed are correct at time of printing and should be consulted for technical matters.

NOTE: These training notes are not subject to amendment after issue.

Standards and Associated Reading

BS EN ISO 11666	Non-destructive testing of welds – Ultrasonic testing – Acceptance levels
BS EN 1330-1	Non-destructive testing – Terminology – Part 1: List of general terms
BS EN 1330-2	Nondestructive testing – Terminology – Part 2: Terms common to NDT methods
BS EN 1330-4	Non-destructive testing – Terminology – Part 4: Terms used in ultrasonic testing
BS EN ISO 23279	Non-destructive testing of welds – Ultrasonic testing – Characterization of indications in welds
BS EN ISO 17640	Non-destructive testing of welds – Ultrasonic testing – techniques, testing levels and assessment
BS EN ISO-16810	Non-destructive testing – Ultrasonic Testing. General principles
BS EN ISO 16811	Non-destructive testing – Ultrasonic Testing. Sensitivity and range setting
BS EN ISO 16823	Non-destructive testing – Ultrasonic Testing. Transmission technique
BS EN ISO 16826	Non-destructive testing – Ultrasonic Testing. For discontinuities perpendicular to the surface
BS EN ISO 16827	Non-destructive testing – Ultrasonic Testing. Characterization and sizing of discontinuities
BS EN 10160	UT of steel flat product of thickness equal to or greater than 6mm (reflection method)
BS EN 10228-3	Non-destructive testing of steel forgings. Part 3: Ultrasonic testing of ferritic or martensitic steel forgings
BS EN 10228-4	Non-destructive testing of steel forgings. Part 4: Ultrasonic testing of austenitic and austenitic-ferritic stainless steel forgings
BS EN ISO 17635	Non-destructive examination of welds – General rules for metallic materials
BS EN ISO 2400	Non-destructive testing – Ultrasonic Testing Specification for calibration block No.1
BS EN 12668-1	Non-destructive testing – Characterization and verification of ultrasonic examination equipment. Part 1: Instruments
BS EN 12668-2	Non-destructive testing – Characterization and verification of ultrasonic examination equipment. Part 2: Probes

BS EN 12668-3	Non-destructive testing – Characterization and verification of ultrasonic examination equipment. Part 3: Combined equipment
BS EN 12680-1	Founding – Ultrasonic examination. Part 1: Steel castings for general purposes
BS EN ISO 7963	Non-destructive testing – Ultrasonic testing - Specification for calibration block No. 2.
BS M 36	Ultrasonic testing of special forgings by an immersion technique using flat bottomed holes as a reference standard
BS M 38	Guide to compilation of instructions and reports for the in-service non-destructive testing of aerospace products
BS EN 473	Superseded by BS EN ISO 9712
BN EN ISO 9712	Non-destructive testing. Qualification and certification of personnel
BS EN 4179	Aerospace series. Qualification and approval of personnel for non-destructive testing.
ISO 18175	Non-destructive testing. Evaluating performance characteristics of ultrasonic pulse-echo testing systems without the use of electronic measurement instruments - First Edition.
BS EN 14127	Non-destructive testing. Ultrasonic thickness measurement.
BS EN ISO 6520-1	Welding and allied processes — Classification of geometric imperfections in metallic materials — Part 1: Fusion welding

Associated Reading

NDT Ed.org – Introduction to ultrasonic testing
http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/cc_ut_index.htm

Procedures and 'Recommendations for Ultrasonic Testing of Butt Welds' 2nd edition. The Welding Institute

'Ultrasonic Flaw Detection for Technicians' by J C Drury.
Obtainable from the British Institute of Non-Destructive Testing

Mathematics and Formulae in NDT. Edited by Dr. R Halmshaw.
Obtainable from the British Institute of Non-Destructive Testing

COSHH, H&S, Caution and Warnings Relevant to TWI Training & Examination Services

Introduction

The use of chemicals in NDT is regulated by law under the Control of Substances Hazardous to Health (COSHH) Regulations 2005. These regulations require the School to assess and control the risk of health damage from every kind of substance used in training. Students are also required by the law to co-operate with the School's risk management efforts and to comply with the Control Measures adopted.

Hazard Data Sheets

The School holds Manufacturers Safety Data Sheets for every substance in use. Copies are readily available for students to read before using any product. The Data Sheets contain information on:

- Trade name of the product; eg Magnaglo, Ardrox, etc.
- Hazardous ingredients of the products.
- Effect of those ingredients on people's health.
- Hazard category of the substance; eg irritant, harmful, corrosive or toxic, etc.
- Special precautions for use; eg the correct personal protective equipment (PPE) to wear.
- Instructions for First Aid.
- Advice on disposal.

EH40 – Occupational Exposure Conditions

- Electrical Hazards include the following
  - Electrical shock and burns from contact with live parts
  - Injury from exposure to arcing or fire from faulty equipment
  - Explosion caused by electrical apparatus (or static electricity)
  - Electric shocks can lead to other types of injury such as falling from ladders or scaffolds.

  It is therefore important that workers know how to use electrical equipment and that it should be properly maintained and switched off when cleaning, adjusting or moving/transporting.
- As is the case with all items of test equipment and safety equipment, national regulations in the country of operation must be adhered to.

What is Exposure?

Exposure to a substance is uptake into the body. The exposure routes are:

- Breathing fume, dust, gas or mist.
- Skin contact.
- Injection into the skin.
- Swallowing.

Many thousands of substances are used at work but only about 500 substances have workplace exposure limits (WELs). Until 2005 it had been normal for HSE to publish a new edition of EH40, or at least an amendment, each year. However, with increasing use of the website facilities, the HSE no longer always publishes a revised hardcopy edition or amendment.

The web-based list applicable from 1 October 2007 can now be found at **http://www.hse.gov.uk/coshh/table1.pdf**

Safety and Environmental Requirements

Ultrasonic testing requires the use of couplant and cleaning fluids, some of which may be hazardous to health. Extended or repeated contact of such materials with the skin or mucous membranes shall be avoided.

Testing materials shall be used in accordance with manufacturer's instructions. National accident prevention, electrical safety handling of dangerous substances and personal and environmental protection regulations shall be observed at all times.

Cautions and Warnings

Some of the test samples used on the ultrasonic courses are heavy and become slippery when covered in couplant. Care should be taken when moving the samples and suitable PPE, particularly safety boots and barrier cream, should be used.

Introduction to Non-Destructive Testing

Non-destructive testing (NDT) is the ability to examine a material (usually for discontinuities) without degrading it or permanently altering the article being tested, as opposed to destructive testing which renders the product virtually useless after testing.

Other advantages of NDT over destructive testing are that every item can be examined with no adverse consequences, materials can be examined for conditions internally and at the surface and, most importantly, parts can be examined whilst in service, giving a good balance between cost effectiveness and quality control. NDT is used in almost every industry with the majority of applications coming from the aerospace, power generation, automotive, rail, oil & gas, petrochemical and pipeline markets, safety being the main priority of these industries. When properly applied, NDT saves money, time, materials and lives. NDT as it is known today has been developing since around the 1920s, with the methods used today taking shape later and vast technological advancements being made during the Second World War. The basic principal methods are:

- Visual testing (VT).
- Penetrant testing (PT).
- Magnetic particle testing (MT).
- Eddy current testing (ET).
- Ultrasonic testing (UT).
- Radiographic testing (RT).

In all NDT methods, the interpretation of results is critical. Much depends on the skill and experience of the technician, although properly formulated test techniques and procedures will improve accuracy and consistency.

Visual testing (VT)

With sufficient lighting and access, visual techniques provide simple, rapid methods of testing whilst also being the least expensive. Close visual testing (CVT) refers to viewing directly with the eye (with or without magnification) whereas remote visual inspection (RVI) refers to the use of optical devices such as the boroscope and the fibrescope.

Visual testing begins with the eye; however, the first boroscopes used a hollow tube and a mirror with a small lamp at the end to investigate the bores of rifles and cannons for problems and discontinuities. In the 1950s, the lamps were replaced by glass fibre bundles which were used to transmit the light. These became known as fibrescopes which were also less rigid, increasing the capabilities of testing. With usage expanding, many users began to suffer from eye fatigue which led to the development of video technology. This was first used in the 1970s and relies on electronics to transmit the images rather than fibreoptics.

Further enhancements to video technology include pan, tilt and zoom lenses, and mounting cameras to platforms and wheels, all allowing more parts to be tested and better images for improved inspection. Video devices also allow recordings of inspections to be taken, meaning permanent records can be kept. This has a number of advantages such as enabling other inspectors to observe the test as it was performed and allowing further review and evaluation.

Penetrant testing (PT)

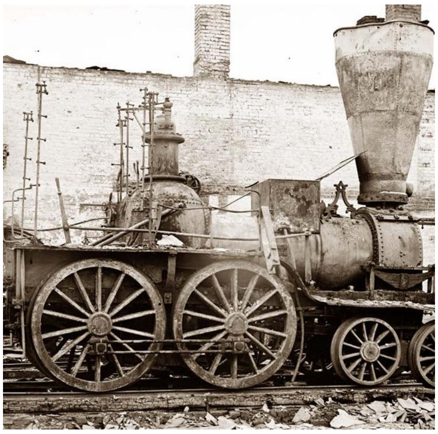
Penetrant testing locates surface-breaking discontinuities by covering the item with a penetrating liquid, which is drawn into the discontinuity by capillary action. After removal of excess penetrant, the indication is made visible by application of a developer. Colour contrast or fluorescent systems may be used.

Advantages	Disadvantages
Applicable to non-ferromagnetics	Only detects defects open to the surface
Able to test large parts with a portable kit	Careful surface preparation required
Batch testing	Not applicable to porous materials
Applicable to small parts with complex geometry	Temperature dependent
Simple, cheap, easy to interpret	Cannot retest indefinitely
Sensitivity	Compatibility of chemicals

History of penetrant testing

A very early surface inspection technique involved the rubbing of carbon black on glazed pottery. The carbon black would settle in surface cracks, rendering them visible. Later, it became the practice in railway workshops to examine iron and steel components by the oil and whiting method. In this method, heavy oil, commonly available in railway workshops, was diluted with kerosene in large tanks so that locomotive parts such as wheels could be submerged. After removal and careful cleaning, the surface was then coated with a fine suspension of chalk in alcohol so that a white surface layer was formed once the alcohol had evaporated. The object was then vibrated by being struck with a hammer, causing the residual oil in any surface cracks to seep out and stain the white coating. This method was in use from the latter part of the 19th century to approximately 1940, when the magnetic particle method was introduced and found to be more sensitive for ferromagnetic iron and steels.

A different (though related) method was introduced in the 1940s. The surface under examination was coated with a lacquer, and after drying, the sample was caused to vibrate by the tap of a hammer. The vibration causes the brittle lacquer layer to crack generally around surface defects. The brittle lacquer (stress coat) has been used primarily to show the distribution of stresses in a part and not for finding defects.



Many of these early developments were carried out by Magnaflux in Chicago, IL, USA in association with Switzer Bros, Cleveland, OH, USA. More effective penetrating oils containing highly visible (usually red) dyes were developed by Magnaflux to enhance flaw detection capability. This method, known as the visible or colour contrast dye penetrant method, is still used quite extensively today. In the 1940s, Magnaflux introduced the Zyglo system of penetrant inspection where fluorescent dyes were added to the liquid penetrant. These dyes would then fluoresce when exposed to ultraviolet light (sometimes referred to as black light), rendering indications from cracks and other surface flaws more readily visible to inspectors. UV lights have become increasingly portable with hand held UV torches now readily available.

Magnetic particle testing (MT)

Magnetic particle testing is used to locate surface and slightly sub-surface discontinuities in ferromagnetic materials by introducing a magnetic flux into the material.

Advantages	Disadvantages
Will detect some sub-surface defects	Ferromagnetic materials only
Rapid and simple to understand	Requirement to test in two directions
Pre-cleaning not as critical as with dye penetrant testing (PT)	Demagnetisation may be required
Will work through thin coatings	Oddly-shaped parts difficult to test
Cheap equipment	Not suited to batch testing
Direct test method	Can damage the component under test

History of magnetic particle testing

The origins of MT can be traced to the 1860s when cannon barrels were tested for defects by first magnetising the barrel and then running a compass down the length of the barrel. By monitoring the needle of the compass, defects within the barrel could be detected.

This form of NDT became much more common after the First World War, in the 1920s, when William Hoke discovered that flaws in magnetised materials created distortions in the magnetic field. When a fine ferromagnetic powder was applied to the parts, it was observed that they built up around the defects, providing a visible indication of their location.

Magnetic particle testing superseded the oil and chalk method in the 1930s as it proved far more sensitive to surface breaking flaws. Today it is still preferred to the penetrant method on ferromagnetic material and much of the equipment being used then is very similar to that of today, with the only advances coming in the form of fluorescent coating to increase the visibility of indications and more portable devices being used. In the early days, battery packs and direct current were the norm and it was some years before alternating current proved acceptable.

Magnetism

The phenomenon called magnetism is said to have been discovered in the ancient Greek city of Magnesia, where naturally occurring magnets were found to attract iron.

The use of magnets in navigation goes back to Viking times or maybe earlier, where it was found that rods of magnetised material, when freely suspended, would always point in a north-south direction. The end of the rod which pointed towards the North Pole star became known as the North Pole and consequently the other end became the South Pole.

Hans Christian Oersted (1777-1851) discovered the connection between electricity and magnetism, followed by Michael Faraday (1791-1867), whose experiments revealed that magnetic and electrical energy could be interchanged.

Historical perspective

Electromagnetic testing – the interaction of magnetic fields with circulating electrical currents - had its origin in 1831 when Michael Faraday discovered electromagnetic induction. He induced current flow in a secondary coil by switching a battery on and off. D E Hughes performed the first recorded eddy current test in 1879. He was able to distinguish between different metals by noting a change in excitation frequency resulting from effects of test material resistivity and magnetic permeability.

Introduction to electromagnetic testing

Many electromagnetic induction or eddy current comparators were patented in the period from 1952. Innumerable examples of comparator tests were reported in the literature and in patents. Many involved simple comparator coils into which round bars or other test objects were placed, producing simple changes in the amplitudes of test signals, or unbalancing simple bridge circuits. In nearly all cases, particularly where ferromagnetic test materials were involved, no quantitative analyses of test objects dimensions, properties, or discontinuities were possible with such instruments. Often, difficulties were encountered in reproducing test results. Some test circuits were adjusted or balanced to optimise signal differences between a known good test object and a known defective test object for each group of objects to be tested. Little or no correlation could then be obtained between various types of specimens, each type having been compared to an arbitrarily selected specimen of the same specific type.

Developments in electromagnetic induction tests

Rapid technological developments in many fields before and during the Second World War (1939-45) contributed both to the demand for NDT and to the development of advanced test methods. Radar and sonar systems allowed the viewing of test data on the screens of cathode-ray tubes or oscilloscopes. Developments in electronic instrumentation and magnetic sensors used both for degaussing ships and for actuating magnetic mines brought a resurgence of activity.

Eddy current testing (ET)

Eddy current testing is based on inducing electrical currents in the material being inspected and observing the interaction between those currents and the material. Eddy currents are generated by coils in the test probe and monitored simultaneously by measuring the coils electrical impedance. As it is an electromagnetic induction process, direct electrical contact with the sample is not required; however, the material must be an electrical conductor.

Advantages	Disadvantages
Sensitive to surface defects	Very susceptible to permeability changes
Can detect through several layers	Only on conductive materials
Can detect through surface coatings	Will not detect defects parallel to surface
Accurate conductivity measurements	Not suitable for large areas and/or complex geometries
Can be automated	Signal interpretation required
Little pre-cleaning required	No permanent record (unless automated)
Portability	

History of eddy current testing

The principles of eddy currents arose in 1831 with Faraday's discovery of electromagnetic induction; eddy current testing methods have their origins in a period just after the First World War, when materials with a high magnetic permeability were being developed for electrical power transformer cores and motor armatures. Eddy currents are a considerable nuisance in electrical engineering – they dissipate heat and efforts to reduce their effect led to a discovery that they could be used to detect material changes and cracks in magnetic materials. The first eddy current testing devices for NDT were in 1879 by Hughes, who used the principles of eddy currents to conduct metallurgical sorting tests and the stray flux tube and bar tests.

It was left to Dr Friedrich Förster in the late 1940s to develop the modern day eddy current testing equipment and formulate the theories which govern their use. The introduction by Förster of sophisticated, stable, quantitative test equipment and of practical methods for analysis of quantitative test signals on the complex plane was by far the most important factor contributing to the rapid development and acceptance of electromagnetic induction and eddy current testing. Förster is rightly identified as the father of modern eddy current testing.

By 1950, he had developed a precise theory for many basic types of eddy current tests, including both absolute and differential or comparator test systems and probe or fork coil systems used with thin sheets and extended surfaces.

Continued advances in research and development, advanced electronics and digital equipment have led to eddy currents becoming one of the most versatile of the surface methods of inspection. Eddy current methods have developed into a wide range of uses and are recognised as being the forerunner of NDT techniques today. From the mid-1980s, microprocessor-based eddy current testing instruments were developed which had many advantages for inspectors. Modern electronics have made instruments more user friendly, providing reduced noise levels which made certain test applications very difficult, but also improving methods of signal presentation and recording capabilities.

Applications for microcomputer chips abound, from giving lift-off suppression in simple crack detection to providing signal processing for immediate analysis of condenser tube inspection. As with other testing methods, improvements to the equipment have been made to increase its portability and computer-based systems now allow easy data manipulation and signal processing. Eddy current testing is now a widely used and understood inspection method for flaw detection as well as for thickness and conductivity measurements.

Ultrasonic testing (UT)

Ultrasonic testing measures the time for high frequency (0.5-50MHz) pulses of ultrasound to travel through the inspection material. If a discontinuity is present, the ultrasound will return to the probe in a time period other than that expected of a fault-free specimen.

Advantages	Disadvantages
Sensitive to cracks at various orientations	No permanent record (unless automated)
Portability	Not easily applied to complex geometries and rough surfaces
Safety	Unsuited to coarse grained materials
Able to penetrate thick sections	Reliant upon defect orientation
Measures depth and through-wall extent	

History of ultrasonic testing

In Medieval times craftsmen casting bells for churches were aware that a properly cast bell rang true when struck and that a bell with flaws would give out a false note. This principle was used by wheel-tappers inspecting rolling stock on the railways; they struck wheels with a hammer and listened to the note given out. A loose tyre sounded wrong.

The origin of modern ultrasonic testing (UT) is the discovery by the Curie brothers in 1880 that quartz crystals cut in a certain way produce an electric potential when subjected to pressure - the piezo-electric effect, from the Greek *piedzein* (to press or strike). In 1881 Lippman theorised that the effect might work in reverse, and that quartz crystals might change shape if an electric current was applied to them. He found that this was so and experimented further. Crystals of quartz vibrate when alternating currents are applied to them. Crystal microphones in a modern stereo rely on this principle.

When the Titanic sank in 1912, the Admiralty tried to find a way of locating icebergs by sending out sound waves and listening for an echo. They experimented further with sound to detect submarines during the First World War. Between the wars, marine echo sounding was developed and in the Second World War ASDIC (Anti-Submarine Detection Investigation Committee) was extensively used in the Battle of the Atlantic against the U-boats.

In 1929, the Russian physicist Sokolov experimented with through-transmission techniques, passing vibrations through metals to find flaws; this work was taken up by the Germans. In the 1930s the cathode ray tube was developed and miniaturised in the Second World War to fit small airborne radar sets into aircraft. It made the UT set as we know it possible. Around 1931 Mulhauser obtained a patent for a system using two probes to detect flaws in solids and following this Firestone (1940) and Simons (1945) developed pulsed UT using a pulse-echo technique.

In the years after the Second World War, researchers in Japan began to experiment on the use of ultrasound for medical diagnostic purposes. Working largely in isolation until the 1950s, the Japanese developed techniques for the detection of gallstones, breast masses, and tumours. Japan was also the first country to apply Doppler ultrasound, an application of ultrasound that detects internal moving objects such as blood coursing through the heart for cardiovascular investigation.

The first flaw detector was made by Sproule in 1942 while he was working for the Scottish firm Kelvin & Hughes. Similar work was carried out by Firestone in the USA and by German physicists. Sproule went on to develop the shear-wave probe.

Initially UT was limited to testing aircraft, but in the 1950s it was extensively used in the building of power stations in Britain for examining thick steel components safely and cheaply. UT was found to have several advantages over radiography in heavy industrial applications:

- No health hazards were associated with radiography, and a UT technician could work next to welders and other employees without endangering them of holding up work.
- It was efficient in detecting toe cracks in boilers – a major cause of explosions and lack of fusion in boiler tubes.
- It could find planar defects, like laminations, which were sometimes missed by radiography.
- A UT check on a thick component took no more time than a similar check on a thin component as opposed to long exposure times in radiography.

Over the next twenty years, improvements focused on accurate detection and sizing of the flaws with limited success, until 1977 when Silk first discovered an accurate measurement and display of the top and bottom edges of a discontinuity with the time-of-flight diffraction (TOFD) technique. Advances in computing technology have now expanded the use of TOFD as real time analyses of results are now available.

It was also during the 1970s that industries focused on reducing the size and weight of ultrasonic flaw detectors and making them more portable. This was achieved by using semiconductor technology and during the 1990s microchips were introduced into the devices to allow calibration parameters and signal traces to be stored. LCD display panels and digital technology have also contributed to reducing the size and weight of ultrasonic flaw detectors. With the development of ultrasonic phased array and increased computing power, the future for ultrasonic inspection is very exciting.

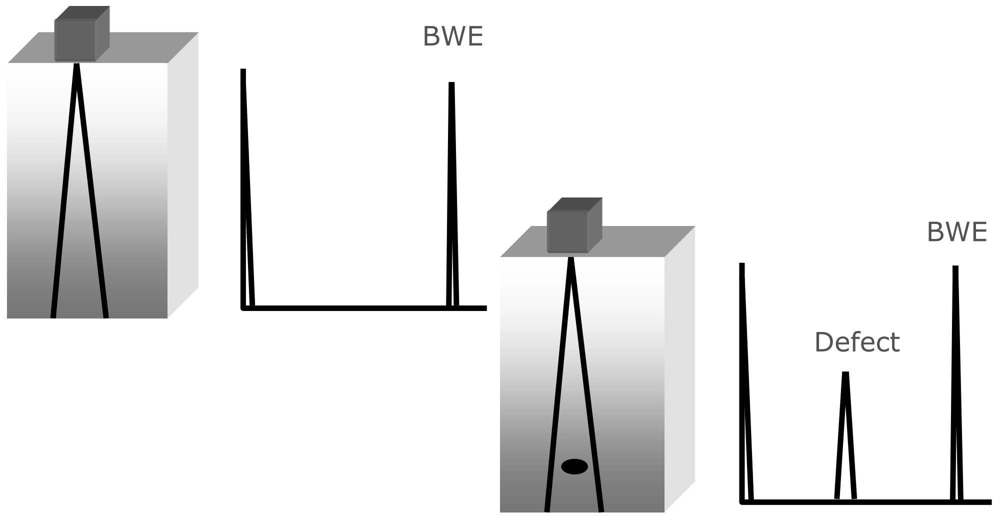
Ultrasound used for testing

The main use of ultrasonic inspection in the human and the animal world is for detecting objects and measuring distance. A pulse of ultrasound (a squeak from a bat or a pulse from an ultrasonic source) hits an object and is reflected back to its source like an echo. From the time it takes to travel to the object and back, the distance of the object from the sound source can be calculated. That is how bats fly in the dark and how dolphins navigate through water. It is also how warships detected and attacked submarines in the Second World War. Wearing a blindfold, you can determine if you are in a very large hall or an ordinary room by clapping your hands sharply; a large hall will give back a distinct echo, but an ordinary room will not. A bat's echo location is more precise: the bat gives out and can sense short wavelengths of ultrasound and these give a sharper echo than we can detect.

In UT a sound pulse is sent into a solid object and an echo returns from any flaws in that object or from the other side of the object. An echo is returned from a solid-air interface or any solid-non-solid interface in the object being examined. We can send ultrasonic pulses into material by making a piezo-electric crystal vibrate in a probe. The pulses can travel in a compression, shear or transverse mode. This is the basis of ultrasonic testing. However, the information from the returning echoes must be presented for interpretation. It is for this purpose that the UT set, or flaw detector as it is frequently called, contains a cathode ray tube.

In the majority of UT sets, the information is presented on the screen in a display called the A Scan. The bottom of the CRT screen is a time base made to represent a distance - say 100mm. An echo from the backwall comes up on the screen as a signal, the amplitude of which represents the amount of sound returning to the probe. By seeing how far the signal comes along the screen we can measure the thickness of the material we are examining.

If that material contains a flaw, sound is reflected back from the flaw and appears on the screen as a signal in front of the backwall echo (BWE) as the sound reflected from the flaw has not had so far to travel as that from the backwall.



Ultrasonic signals

Anything that sends back sound energy to a probe to cause a signal on the screen is called a reflector. By measuring the distance from the edge of the CRT screen to the signal, we can calculate how far down in the material the reflector lies.

Radiographic testing (RT)

Radiography monitors the varying transmission of ionising radiation through a material with the aid of photographic film or fluorescent screens to detect changes in density and thickness. It will locate internal and surface-breaking defects.

Advantages	Disadvantages
Gives a permanent record, the radiograph	Radiation health hazard
Detects internal flaws	Can be sensitive to defect orientation and so can miss planar flaws
Detects volumetric flaws readily	Limited ability to detect fine cracks
Can be used on most materials	Access is required to both sides of the object
Can check for correct assembly	Skilled radiographic interpretation is required
Gives a direct image of flaws	Relatively slow method of inspection
Fluoroscopy can give real time imaging	High capital cost
	High running cost

History of radiographic testing

X-rays were discovered in 1895 by Wilhelm Conrad Roentgen (1845-1923) who was a Professor at Würzburg University in Germany. Whilst performing experiments in which he passed an electric current through a Crookes tube (an evacuated glass tube with an anode and a cathode), he found that when a high voltage was applied, the tube produced a fluorescent glow. Roentgen noticed that some nearby photographic plates became fogged. This caused Roentgen to conclude that a new type of ray was being emitted from the tube. He believed that unknown rays were passing from the tube and through the plates. He found that the new ray could pass through most substances. Roentgen also discovered that the ray could pass through the tissue of humans, but not bones and metal objects. One of Roentgen's first experiments late in 1895 was a film of the hand of his wife.

Shortly after the discovery of X-rays, another form of penetrating rays was discovered. In 1896 French scientist Henri Becquerel discovered natural radioactivity. Many scientists of the period were working with cathode rays, and other scientists were gathering evidence on the theory that the atom could be subdivided. Some of the new research showed that certain types of atoms disintegrate by themselves. It was Becquerel who discovered this phenomenon while investigating the properties of fluorescent minerals.

One of the minerals Becquerel worked with was a uranium compound. On a day when it was too cloudy to expose his samples to direct sunlight, Becquerel stored some of the compound in a drawer with photographic plates. Later when he developed these plates, he discovered that they were fogged (indicating exposure to light). Becquerel wondered what would have caused this fogging. He knew he had wrapped the plates tightly before using them, so the fogging was not due to stray light; in addition, he noticed that only the plates that were in the drawer with the uranium compound were fogged. Becquerel concluded that the uranium compound gave off a type of radiation that could penetrate heavy paper and expose photographic film. Becquerel continued to test samples of uranium compounds and determined that the source of radiation was the element uranium. Becquerel did not pursue his discovery of radioactivity, but others did.

While working in France at the time of Becquerel's discovery, Polish scientist Marie Curie became very interested in his work. She suspected that a uranium ore known as pitch-blende contained other radioactive elements. Marie and her husband, French scientist Pierre Curie, started looking for these other elements. In 1898, the Curies discovered another radio-active element in pitchblende, and named it polonium in honour of Marie’s native homeland. Later that year, the Curies discovered another radioactive element which they named ‘radium’, or shining element. Both polonium and radium were more radioactive than uranium. Due to her lifelong research in this field, Marie Curie is widely credited with the discovery of gamma radiation and the introduction of the new term: radio-active.

Since these discoveries, many other radioactive elements have been discovered or produced. Radiography in the form of NDT took shape in the early 1920s when H H Lester began testing on different materials. Radium became the initial industrial gamma ray source. The material allowed castings up to 10 to 12 inches thick to be radiographed. During the Second World War, industrial radiography grew tremendously as part of the Navy's shipbuilding programme. In 1946, man-made gamma ray sources from elements such as cobalt and iridium became available. These new sources were far stronger than radium and much less expensive. The man-made sources rapidly replaced radium, and the use of gamma rays increased quickly in industrial radiography.

William D Coolidge's name is inseparably linked with the X-ray tube popularly called the Coolidge tube. This invention completely revolutionised the generation of X-rays and remains the model upon which all X-ray tubes for medical applications are patterned. He invented ductile tungsten, the filament material still used in such lamps. He was awarded 83 patents.

Although the theories and practices have changed very little, radiographic equipment has developed. These developments include better images through higher quality films and also lighter, more portable equipment.

In addition to conventional film radiography, digital radiographic systems are now widespread within the NDT industry. The use of photostimulable phosphor (PSP) bearing imaging plates with photomultipliers to capture image signals and analogue-to-digital converters (ADC) are used extensively in computed radiography (CR).

Direct radiography (DR) systems are also used based upon complementary metal oxide sensor (CMOS) technology and TFT (thin film transistors). These systems have the ability to directly convert light into digital format; additionally, they may be coupled with a scintillator which coats CMOS and charged couple device (CCD) sensors. The scintillator converts photon energy to light before the sensor and ADC converts to digital format. Systems which use scintillators in this way are often referred to as indirect systems.

Quality issues of any digital system are based upon the effective pixel size and the signal-to-noise ratio (SNR). The benefits of using digital systems are the speed of inspection and the absence of chemical processing requirements and wet film; however, the initial equipment costs will be high.

NDT Certification Schemes

CSWIP – Certification Scheme for Personnel

Managed by TWI Certification Ltd (TWICL), a TWI Group company formed in 1993 to separate TWI's activities in the field of personnel and company certification thus ensuring continued compliance with international standards for certification bodies and is accredited by UKAS to BS EN ISO 17024.

TWICL establishes and implements certification schemes, approves training courses, and authorises examination bodies and assessors in a large variety of inspection fields, including; non-destructive testing (NDT), welding and plant inspectors, welding supervisors, welding coordination, plastic welders, underwater inspectors, integrity management, general inspection of offshore facilities, cathodic protection, heat treatment.

TWI Certification Ltd
Granta Park,
Great Abington,
Cambridge CB21 6AL,
United Kingdom
Tel: +44 (0) 1223 899000
Fax: +44 (0) 1223 894219
Email: twicertification@twi.co.uk
Website: www.cswip.com

PCN – Personal Certification in Non-destructive testing

Managed and marketed by the British Institute of Non-Destructive Testing (BINDT) which owns and operates the PCN Certification Scheme, it offeres a UKAS accreditied certification of competence for NDT and condition monitoring in a variety of product sectors.

The British Institute of Non-Destructive Testing
Certification Services Division,
Newton Building,
St. Georges Avenue,
Northampton,
NN2 6JB,
United Kingdom

Tel: +44 (0)1604 893811
Fax: +44 (0)1604 892868
Email: pcn@bindt.org
Website: http://www.bindt.org/Certification/General_Information

Both schemes offer NDT certification conforming to BS EN ISO 9712; Qualification and Certification of NDT personnel, this superseding EN473.

The PCN Scheme

What follows is a summary of the general requirements for qualification and PCN certification of NDT personnel as described in PCN/GEN Issue 5 Revision R.

PCN Certification is a scheme which covers the qualification of NDT inspection staff to meet the requirements of European and International Standards. Typically a standard or procedure will call for the Inspector to be certified in accordance with BS EN ISO 9712 and/or PCN requirements. The PCN Gen Document describes how the PCN system works.

The points below cover extracts from this document which are major items, the full document can be viewed on the BINDT website – www.bindt.org/certification/PCN.

References

PCN documents

PSL/4	Examination availability
PSL/8A	PCN documents – issue status
PSL/30	Log of pre-certification experience
PSL/31	Use of PCN & UKAS logo
PSL/42	Log of pre-certification on-the-job training
PSL/44	Vision requirements
PSL/49	Examination exemptions for holders of certification other than PCN
PSL/51	Acceptable certification for persons supervising PCN candidates gaining experience prior to certification
PSL/57C	Application for certification, experience gained post examination
PSL/67	Supplementary 56 day waiver
PSL/70	Request for L2 certificate issue to a L3 holder
CP9	Requirements for BINDT authorised qualifying bodies
CP16	Renewal and recertification of PCN Levels 1 & 2 certificates
CP17	Renewal and recertification of PCN Level 3 certificates
CP19	Informal access to authorised qualifying bodies by third parties
CP22	Marking and grading PCN examinations
CP25	Guidelines for the preparation of NDT procedures and instructions in PCN examinations
CP27	Code of ethics for PCN certificate holders

PCN/GEN Appendix Z1 – NDT Training Syllabi

Levels of PCN certification

Level 1 personnel are qualified to carry out NDT operations according to written instructions under the supervision of appropriately qualified Level 2 or 3 personnel. Within the scope of the competence defined on the certificate, Level 1 personnel may be authorised by the employer to perform the following in accordance with NDT instructions:

- Set up equipment.
- Carry out the test.
- Record and classify the results in terms of written criteria.
- Report the results.

Level 1 personnel have **not** demonstrated competence in the choice of test method or technique to be used, nor for the assessment, characterisation or interpretation of test results.

Level 2 personnel have demonstrated competence to perform and supervise non-destructive testing according to established or recognised procedures. Within the scope of the competence defined on the certificate, Level 2 personnel may be authorised by the employer to:

- Select the NDT technique for the test method to be used.
- Define the limitations of application of the testing method.
- Translate NDT standards and specifications into NDT instructions.
- Set up and verify equipment settings.
- Perform and supervise tests.
- Interpret and evaluate results according to applicable standards, codes or specifications.
- Prepare written NDT instructions.
- Carry out and supervise all Level 1 duties.
- Provide guidance for personnel at or below Level 2.
- Organise and report the results of non-destructive tests.

Level 3 personnel are qualified to direct any NDT operation for which they are certificated and may be authorised by the employer to:

- Assume full responsibility for a test facility or examination centre and staff.
- Establish, review for editorial and technical correctness and validate NDT instructions and procedures.
- Interpret codes, standards, specifications and procedures.
- Designate the particular test methods, techniques and procedures to be used.
- Within the scope and limitations of any certification held carry out all Level 1 and 2 duties and;
- Provide guidance and supervision at all levels.

Level 3 personnel have demonstrated:

- Competence to interpret and evaluate test results in terms of existing codes, standards and specifications.
- Possession of the required level of knowledge in applicable materials, fabrication and product technology sufficient to enable the selection of NDT methods and techniques and to assist in the establishment of test criteria where none are otherwise available.
- General familiarity with other NDT methods.

Level 3 certificated personnel may be authorised to carry out, manage and supervise PCN qualification examinations on behalf of the British Institute of NDT.

Where Level 3 duties require the individual to apply routine NDT by a method(s) within a particular product or industry sector, the British Institute of NDT strongly recommends that industry demand that this person should hold and maintain Level 2 certification in the applicable methods and sectors.

Training

Table 1 Minimum required duration of training.

NDT method	Level 1 hours	Level 2 hours[1]	Level 3 hours
ET	40	40	40
PT	16	24	24
MT	16	24	32
RT	40	80	72
RI	N/A	56	N/A
UT	40	80	72
VT	16	24	24
BRS	16	N/A	N/A
RPS	N/A	24	N\A
Basic knowledge	(Direct access to Level 3 examination parts A- C)	80	
Note 1. Direct access to Level 2 requires the total number of hours shown in Table 1 for Levels 1 and 2, and direct access to Level 3 requires the total number of hours shown in Table 1 for Levels 1-3. Up to one third of the total specified in this table may take the form of OTJ training documented using form PSL/42 provided it is verifiable and covered practical application of the syllabus detailed in CEN ISO/TR 25107:2006.			

Industrial NDT experience

- Industrial NDT experience in the appropriate sector may be acquired prior to or following success in the qualification examination.
- In the event that the experience is sought following successful examination, the results of the examination shall remain valid for up to two years.
- Documentary evidence (in a form acceptable to the British Institute of NDT, i.e. on PCN form PSL/30) of experience satisfying the following requirements shall be confirmed by the employer and submitted to BINDT AQB prior to examination, or directly to BINDT prior to the award of PCN certification in the event that experience is gained after examination.

Table 2 Minimum duration of experience for certification.

NDT method	Experience, months		
	Level 1	Level 2	Level 3
ET	3	9	18
MT	1	3	12
PT	1	3	12
RT	3	9	18
UT	3	9	18
RI	*N/A*	6	*N/A*
VT	1	3	12
Work experience in months is based on a nominal 40-hour week or the legal week of work. When an individual is working in excess of 40h/week, he may be credited with experience based on the total hours, but he shall be required to produce evidence of this experience. Direct access to Level 2 requires the total number of hours shown in Table 2 for Levels 1 and 2, and direct access to Level 3 requires the total number of hours shown in Table 2 for Levels 1-3			

Qualification examination

Table 3 Numbers of general questions.

NDT method	Level 1	Level 2
ET	40	40
PT	30	40
MT	30	40
RT	40	40
RI	N/A	40
UT	40	40
VT	30	40
BRS	30	N/A
RPS	N/A	20 plus 4 narrative
Note: All Level 1 specific theory papers have 30 questions. All Level 2 specific theory papers have 36 questions.		

Re-examination

a A candidate who fails to obtain the pass grade for any examination part (general, specific or practical) may be re-examined twice in the failed part(s), provided the re-examination takes place not sooner than one month, unless further training acceptable to BINDT is satisfactorily completed, nor later than twelve months after the original examination.

b A candidate who achieves a passing grade of 70% in each of the examination parts (general, specific or practical) but whose average score is less than the required 80% may be re-examined a maximum of two times in any or all of the examination parts in order to achieve an overall average score of 80%, provided the re-examination takes place not sooner than one month, unless further training acceptable to BINDT is satisfactorily completed, nor later than twelve months after the original examination.

c A candidate who fails all permitted re-examinations shall apply for and take the initial examination according to the procedure established for new candidates.

d A candidate whose examination results have not been accepted for reason of fraud or unethical behaviour shall wait at least twelve months before re-applying for examination.

Summary

The PCN scheme is managed and administered by the British Institute of NDT (BINDT) on behalf of its stakeholders. It meets or exceeds the criteria of BS EN ISO 9712.

There are 6 appendices covering various industry and product sectors,

1. Aerospace.
2. Castings.
3. Welds.
4. Wrought Products and Forgings.
5. Pre and in-service inspection (multi sector).
6. Railway.

There are many additional supporting documents varying from vision requirements PSL44 to renewal and recertification (Levels 1 and 2 – CP16; Level 3 – CP17) and so on.

The document defines many terms used in certification of NDT personnel (PCN Gen Section 3)

The certification body (BINDT) meets the requirements of BS EN ISO 17024 (PCN Gen section 5)

BINDT approves authorised qualifying bodies (AQBs) to carry out the examinations (PCN Gen Section 5)

a The document sets out the Levels of PCN certification and what each level of personnel is qualified to do (PCN Gen section 6). There are 3 Levels of PCN certification.
b Candidates for examination must have successfully completed a BINDT validated course of training at a BINDT authorised training organisation (PCN Gen Section 7).
c Table 1 shows the minimum required duration of training for all Levels and methods plus a section of notes.
d Table 2 gives the minimum duration of experience for each Level and method.
e A candidate is required to have a vision test of colour perception and a near vision test (Jaeger Number 1 or N4.5). PCN Gen Section a – the near vision test to be taken annually.
f Examination applications are made directly with the AQB.
g PCN Level 1s and 2 initial exams comprise general; specific and practical parts.
h Table 3 shows the number of general questions at Levels 1 and 2 examinations.
i There are 30 specific questions on the Level 1 papers.
j There are 36 questions on the Level 2 specific papers.
k A variety of practical samples are tested depending on the method and sector.
l A Level 3 examination comprises a basic and a method examination – however the basic examination needs to be passed only once. Table 4 shows the number of basic examination questions. Table 5 shows the number of Level 3 examination questions.

Table 4 Number of basic examination questions.

Part	Examination	Number of questions
A	Materials technology and science, including typical defects in a wide range of products including castings welds and wrought products.	30
B	Qualification and certification procedure in accordance with this document	10
C	15 general questions at Level 2 standard for each of four NDT methods chosen by the candidate, including at least one volumetric NDT method (UT or RT).	60

Table 5 Main method examination.

Part	Subject	Number of questions
D	Level 3 knowledge relating to the test method applied	30
E	Application of the NDT method in the sector concerned, including the applicable codes, standards, and specifications. This may be an open book examination in relation to codes, standards, and specifications.	20
F	Drafting of one or more NDT procedures in the relevant sector. The applicable codes, standards, and specifications shall be available to the candidate.	

m A pass is obtained where each part is 70% or over with an average grade of 80% or over.
n A PCN certificate is valid for 5 years.
o Renewal and recertification requirements are covered in CP16 for Level 1 and Level 2 and CP17 for Level 3.

Section 1
Physical Principles

1 Physical Principles

Sound is generated when something vibrates. You can twang a ruler on a table or flick a stretched elastic band to verify this. The stretched surface of the rubber band or the ruler vibrates and sets up a series of vibrations, sound waves, in the air. As the surface of the band or ruler pushes into the air, the air molecules are forced together and a region of high pressure forms; this process is called compression. As the surface moves back, the air molecules move apart, forming a low pressure area (rarefaction). As the surface vibrates, alternate compressions and rarefactions are set up in the air and travel out from the surface to form a sound wave. The air molecules don't move with the wave - they vibrate to and fro in time with the vibrating surface.

If we plot the displacement of the particle against time, it will produce a sine wave as shown below.

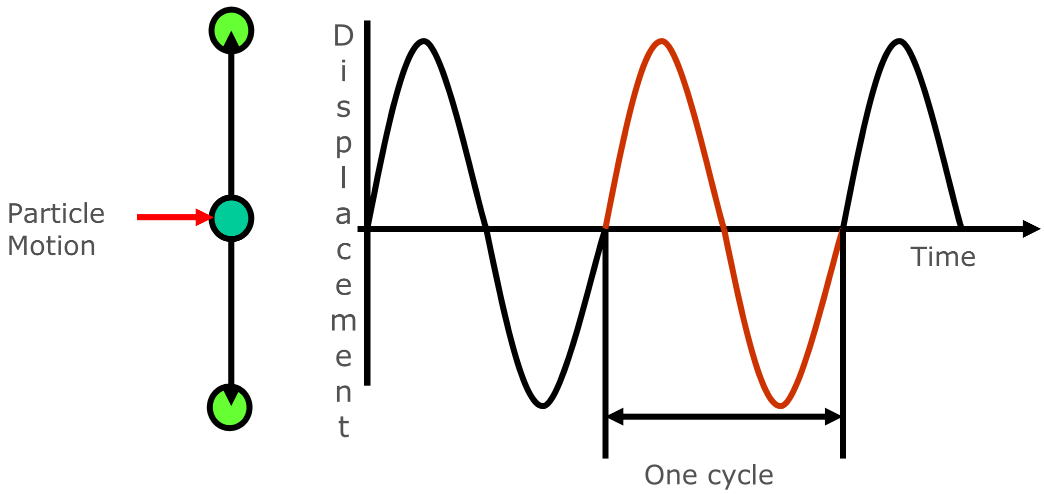


Figure 1.1 Ultrasonic vibration.

The sound wave thus produced travels through the air at a speed of about 332m/sec, at 0°C, at sea level. We hear the sound when it hits a membrane in our ear and causes it to vibrate.

Sound will travel through any medium that has molecules to move but it travels faster in more elastic materials because the vibrations are passed on more quickly. Sound travels faster in water or metal than it does in air because liquids and solids are more elastic than air. The speed of sound in a material increases with its stiffness (elasticity) and decreases with its density; more precisely, the square root of the stiffness divided by the density gives the speed of sound.

A sound wave is generally described in terms of its frequency, velocity and wavelength.

1.1 Frequency

As sound is a series of vibrations, one way of measuring it is to count the number of vibrations per second - the frequency. Frequency is measured in hertz (Hz). One vibration in one second is one hertz. Two vibrations in one second is two hertz. Ten vibrations in one second is 10 hertz and 1000 vibrations in one second is 1000 hertz or one kilohertz (kHz). One million vibrations in a second is one megahertz (MHz).

The higher the frequency - the higher the note sounds - the higher the pitch. If you twang the ruler or the rubber band hard, the noise is louder, it has greater amplitude but the note remains the same. If, however, you shorten the ruler or tighten the rubber band, they vibrate more quickly and the note given out is higher, the frequency is greater. To raise the pitch of their instrument, guitar players move their fingers down the frets, thus shortening the string and making it vibrate more quickly.

We can only hear sounds between certain frequencies - more than 20 and less than 20,000Hz. If you were able to move your arm up and down 20 times a second, it would sound like a very low hum. You cannot move your arm this fast, so you cannot hear the vibrations in the air caused by your moving arm. A dog whistle vibrating at 25,000Hz cannot be heard by humans but it can be heard by the sensitive ears of a dog.

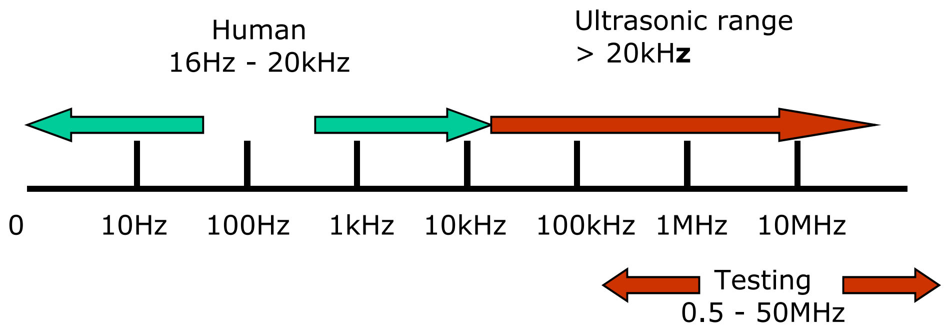


Figure 1.2 The sound spectrum.

It rarely occurs to us that there is a whole world of sound that we cannot hear. Some other animals can hear sounds at higher frequencies - bats can hear sound at 100,000Hz - and some animals, like snakes, have worse hearing than we have.

A sound with frequencies above the upper range of human hearing is called ultrasound. Sound below about 16Hz is called infrasound. Therefore the definition of ultrasound is sound with a frequency greater than 20kHz.

There is an advantage to using lower frequencies: The lower the frequency, the more penetrating a sound wave is - that is why foghorns give out very low notes and why the low throbbing notes from your neighbour's stereo set come through the wall rather than the high notes. Elephants and hippos can communicate over distances of up to 30 kilometres using ultrasound, while whales can communicate through water across an ocean!

1.2 Wavelength

A wave in the sea is a vibration of energy. As the wave passes a fixed point it produces a constant rise and fall of energy. A complete vibration is a change in energy from maximum to minimum and back to maximum. The distance over which one complete vibration of energy occurs is called a wavelength.

A wavelength is the distance between the highest points of energy. It varies with the speed of sound and with the frequency. Wavelength is represented by the Greek letter lambda (λ). We can work out the wavelength if we know the speed and frequency of a sound wave. Wavelength is the velocity in metres per second divided by the frequency.

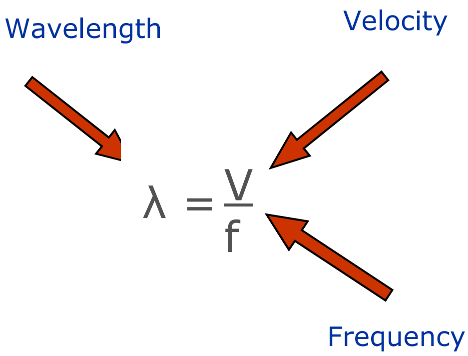


Figure 1.3 Wavelength, Velocity and Frequency relationships.

If we want to know the wavelength of a 200Hz frequency sound wave travelling through air, we can apply this formula, as we know that the speed of sound in air is 332m/sec.

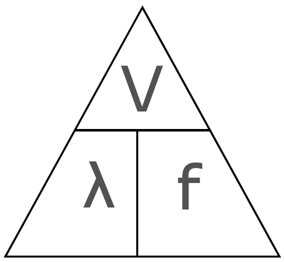
$$\lambda = \frac{332}{200} = 1.66\text{m}$$

If we want to know the wavelength of a 2MHz compression wave travelling through steel, we can again use the formula, as we know the compressional speed of sound in steel, 5,920m/s.

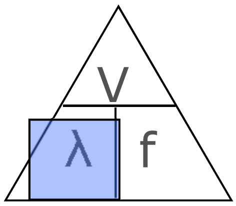
$$\lambda = \frac{5{,}920{,}000}{2{,}000{,}000} = 2.96\text{mm}$$

If we wanted to know the wavelength of a shear wave of 2MHz in steel, we could use the formula again but this time using the shear speed of sound in steel which is 3,250m/s.

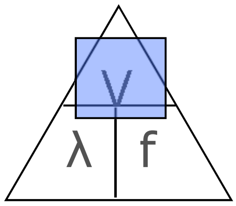
An easy way to remember how this formula works is to split it down within a triangle - with the velocity, wavelength and frequency at the corners. The velocity must be placed at the top (note how it forms a diamond shape) and the wavelength and frequency at either of the bottom two corners.



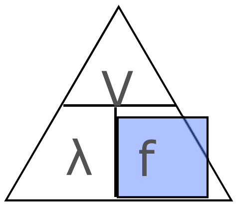
If we want to work out wavelength we cover the wavelength symbol - this leaves V over f. If we need to find the velocity, cover the V which gives us λ x f. Covering the frequency (f) will leave V over λ.



$$\lambda = \frac{V}{f}$$



$$V = \lambda f$$



$$f = \frac{V}{\lambda}$$

So the wavelength of ultrasonic waves is important because the shorter the wavelength, the smaller the flaws that can be detected. Defects of a diameter of less than half a wavelength may not show on the cathode ray tube (CRT). On the other hand, the shorter the wavelength the less the ultrasound will penetrate the test material. Beam shape is also affected by wavelength. These factors will be discussed later.

1.3 Resolution

Resolution is the ability of an equipment/probe combination to distinguish between two echoes from reflectors that are close together. To have good resolution, a probe must present two signals on a CRT screen from two separate reflectors: if it has poor resolution, the echoes from the two reflectors appear as one signal on the screen.

In the early days of ultrasonic testing, we used 100, 91 and 85mm steps at the radius end of the V1 block to test resolving power. However, today this is regarded as too crude a test and BS 4331 part 3 (now obsolete and superseded by BS EN 12668-3: Methods of assessing the performance characteristics of ultrasonic flaw detection equipment Part 1: Overall performance on-site methods) recommends that we should be able to recognise two discrete echoes less than two wavelengths apart. Discrete echoes means split by more than 6dB (see 1.4) or to more than half the total height of the signals.

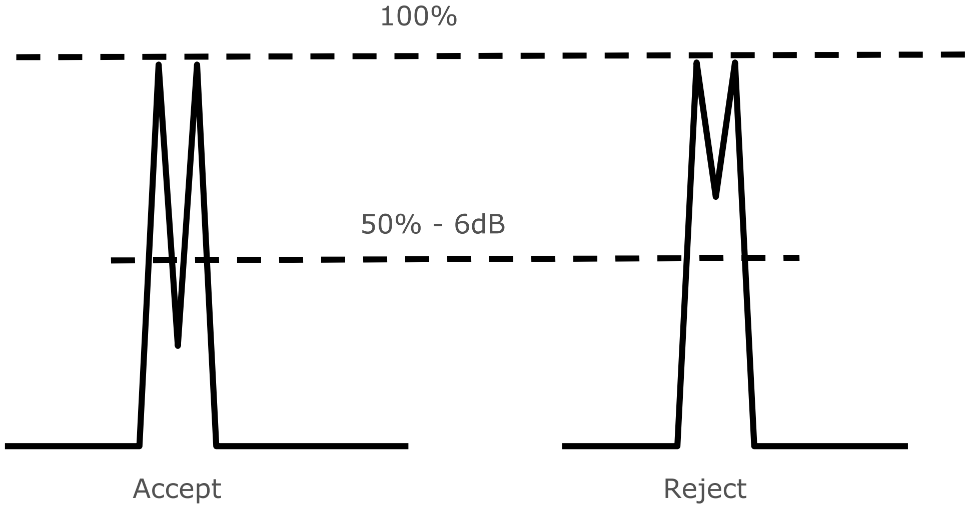


Figure 1.4 Echo resolution.

1.4 Signal amplitude

The amplitude of an ultrasonic signal is defined as the maximum displacement of the molecules from their equilibrium position. The energy of an ultrasonic wave is in turn expressed as the square of the amplitude.

The relative amplitude of ultrasonic signals is expressed using the decibel (dB), a logarithmic unit of comparison. When we compare the height of two signals on the CRT screen, we are in fact comparing the electric voltage that is being sent to the Y plates; electric voltage is proportional to the square of the current. To compare two signals we must use a formula that takes account of this fact:

$$Differencein\, dB = 20\, x \log_{10} \frac{H_1}{H_2}$$

For example, if we want to compare a signal of 40mm with one of 20mm on the CRT screen:

$$Difference\ in\ dB = 20 \log_{10} \frac{(40)}{(20)}$$
$$= 20 \log_{10} 2$$

Find the $\log_{10}$ of 2 in tables or a calculator.

20 x 0.301 = 6.02dB

So the answer is 6dB and this can be tested on a CRT screen by obtaining a signal from a backwall echo on a test block and increasing or decreasing the gain until the signal touches the top of the screen. Take out 6dB with the gain control and the signal should drop to 50% full screen height (FSH). If it does not, the vertical linearity of the UT set is out or inaccurate; the signal height is not changing in accordance with energy from the probe.

Using the formula, we discover that:

- 12dB difference means that one signal is 4 times bigger than another.
- 10dB difference means that one signal is 3 times bigger than another.
- 20dB difference means that one signal is 10 times bigger than another.

Remember that decibels are only a means of comparing signals. All UT sets are different, so a defect may be at FSH with a gain control reading of, say, 36dB on one set and be at FSH on another set with a gain control reading of only 28dB on another set. The gain control allows us to set sensitivities and forms the basis of ultrasonic sizing techniques.

Section 2
Modes of Sound Energy

2 Modes of Sound Energy

Sound waves propagate due to the vibrations or oscillatory motions of particles within a material. Within a freely vibrating medium each particle is subject to both inertial and elastic forces. These forces cause particles to exhibit oscillatory motions comparable to the free vibration of a system of masses and springs. The elastic restoring forces in a material can be described as microscopic spring forces as shown below.

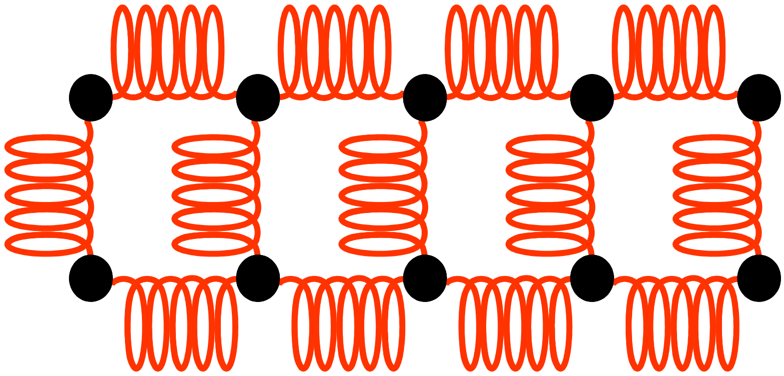


Figure 2.1 Representation of sound wave propagation using partial mass and microscopic restoring spring forces.

This theory agrees with both Hooke's Law and Newton's second law. Hooke's Law states that, within the elastic limit of any body, the ratio of the stress to the strain produced is constant; therefore, the more stress or force is placed on an object, the more it will strain or deform. Newton's second law of motion states that the force (F) equals the mass (m) times the acceleration (a).

$$F = ma$$

The spring theory makes accurate predictions for the propagation of sound. The propagation of a sound wave velocity is determined by the elastic properties and density of the material. The velocity of a longitudinal wave is described by the following equation:

$$V = f\lambda$$

2.1 Compressional waves

We cannot hear all sound; what we do hear is sound in a compressional mode, where molecules vibrate backwards and forwards in the same direction as the energy of propagation - rather like billiard balls in a line. A compressional wave of sound is also called a longitudinal wave: waves of this type consist of alternate compression and dilation in the direction of propagation. As each particle moves, it pushes or pulls the adjacent particle through elastic interconnection (see Figure 2.2). Gases, liquids and solids have elasticity, so compressional waves can travel in all of them.

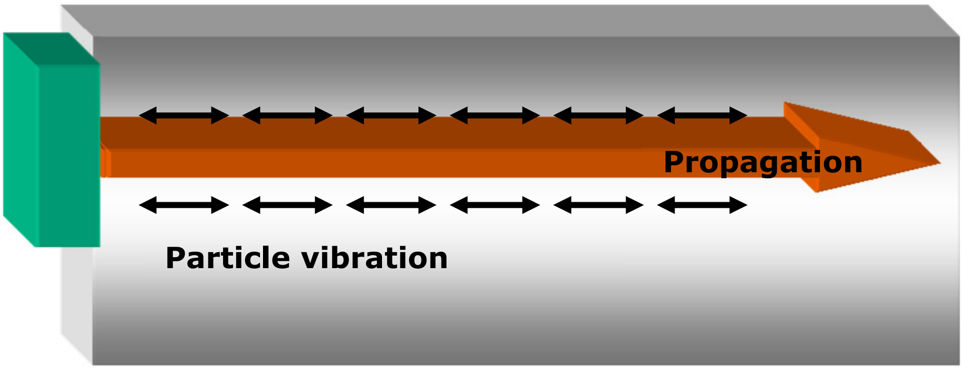


Figure 2.2 Compression wave propagation.

The velocity of a longitudinal wave is described by the following equation:

$$V_L = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}}$$

V_L = Longitudinal bulk wave velocity.
E = Young's modulus of elasticity.
μ = Poisson ratio.
ρ = Material density.

Sound travels through air in the compressional mode at 332m/sec, through water at 1480m/sec, Perspex at 2730m/sec, steel at 5920m/sec and aluminium at 6320m/sec.

Note: Sound can only travel through air and water in the compressional mode. Sound can travel through Perspex, steel and aluminium in modes other than the compressional mode.

2.2 Shear waves

Sound can travel in solids in a shear mode as well as a compressional mode. In the shear mode, molecules vibrate up and down, across the direction of propagation rather than to and fro; for this reason, the shear mode is also called the transverse mode, as particle vibration is transverse to the direction of sound energy (see Figure 2.3).

In the shear or transverse mode, molecules of a solid move rather like beach balls floating on the surface of the sea - they move up and down as a wave passes.

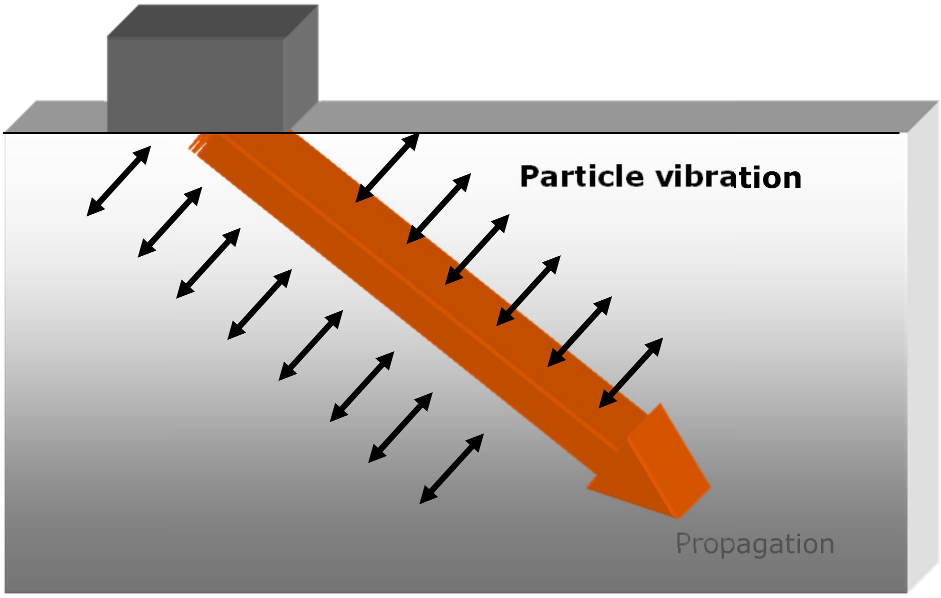


Figure 2.3 Shear wave propagation.

This type of sound travel can only happen when the molecules through which it propagates are joined together - as in a solid. A solid has rigidity as well as elasticity. Air and water, like other gases and liquids, do not have rigidity. Shear or transverse waves cannot travel in gases of liquids for this reason.

Shear (transverse) wave velocity can be written as:

$$V_s = \sqrt{\frac{E(1-\mu)}{2\rho(1+\mu)}} = \sqrt{\frac{G}{\rho}}$$

V_s = Shear wave velocity.
E = Young's modulus of elasticity.
μ = Poisson ratio.
ρ = Material density.
G = Shear modulus.

The speed of sound in the shear or transverse mode is less than it is in the compressional or longitudinal mode. The shear speed of sound in steel is 3250m/sec and in aluminium 3130m/sec. There is no shear or transverse speed for air or water, as shear waves cannot be supported in these media.

Table 2.1 Comparison of compression wave and shear wave velocities in different materials.

Material	Compression velocity, m/sec	Shear velocity, m/sec
Air	332	NA
Water	1480	NA
Steel	5920	3250
Aluminium	6320	3130
Perspex	2730	1430
Copper	4700	2260
Brass	4430	2120

Applying these values for one velocity of steel to the formula used previously for determining the wavelength, it can be seen that for a given frequency that the wavelength of the shear wave is less than that of the compression wave.

Table 2.2 Comparison of wavelength between compression and shear waves at different frequencies in steel.

Frequency, MHz	Compression wavelength, km	Shear wavelength, km
0.5	11.8	6.5
1	5.9	3.2
2	2.95	1.6
4	1.48	0.8
6	0.98	0.54

2.3 Rayleigh or surface waves

A third type of sound wave can travel along the surface of a solid: these are called Rayleigh or surface waves.

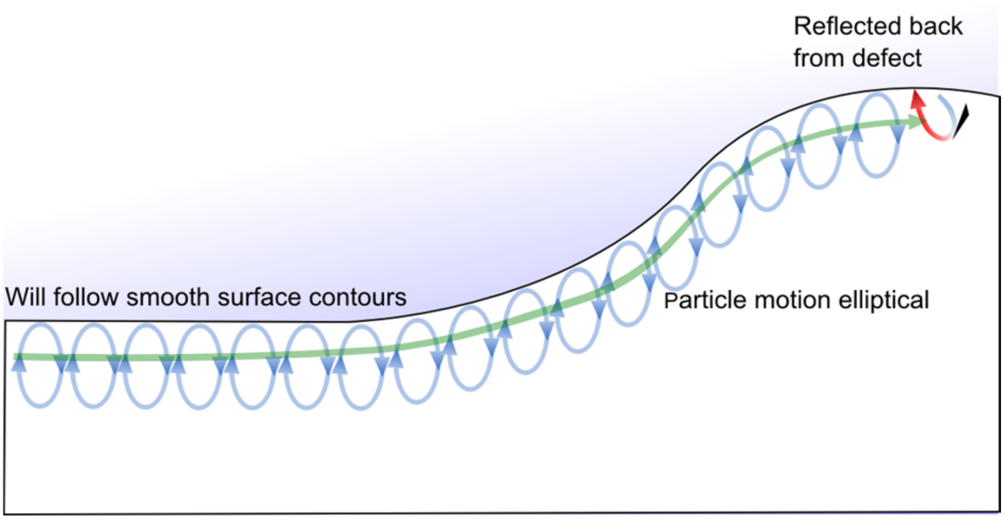


Figure 2.4 Surface wave propagation.

The surface molecules vibrate in an elliptical motion, though only to a depth of one wavelength in the carrier material. Surface waves are about 8% slower than shear waves and in steel they travel at about 3000m/sec.

2.4 Lamb waves

Another mode of sound travel is Lamb or plate waves which propagate in thin plate materials when the plate thickness is about the same as the wavelength. Lamb or plate waves travel at velocities which vary with the plate thickness and the wavelength. Particle motion is elliptical, as with surface waves.

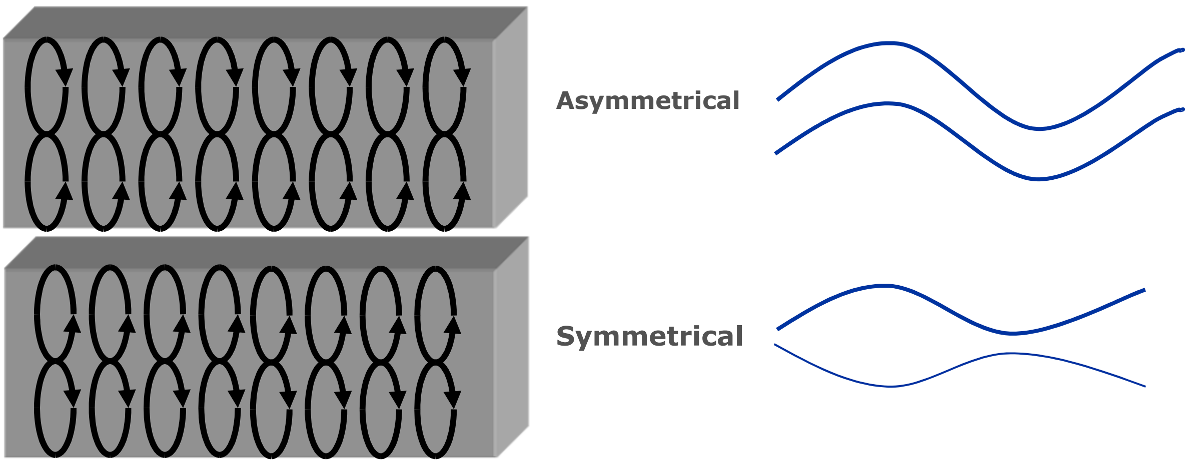


Figure 2.5 Lamb waves.

Section 3
Generating Ultrasound

3 Generating Ultrasound

Sound is created when something vibrates. It is a stress wave of mechanical energy. The piezo-electric effect changes mechanical energy into electrical energy. It is reversible, so electrical energy - a voltage - can be changed into mechanical energy or sound, which is the reverse piezo-electric effect. The first people to observe the piezo-electric effect were the Curie brothers who observed it in quartz crystals.

3.1 Piezo-electric crystals

Jacques and Pierre Curie used quartz for their first experiments. Nowadays polarised ceramics are used instead of quartz crystals.

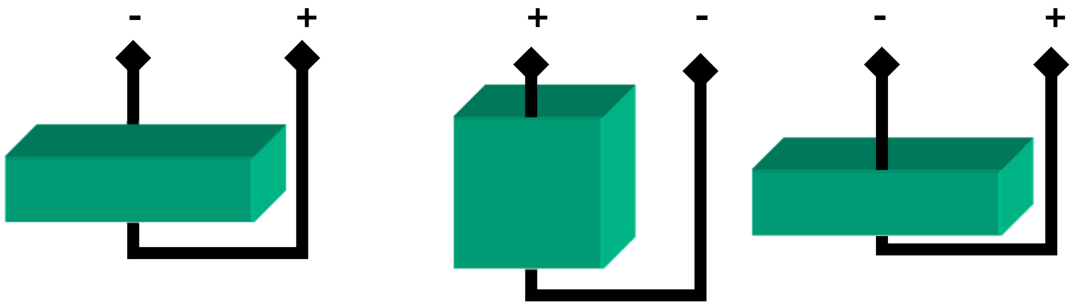


Figure 3.1 Illustration of the piezo-electric effect showing the effect of an applied voltage on a crystal.

It was later discovered that by varying the thickness of crystals and subjecting them to a voltage, they could be made to vibrate at different frequencies. The frequency depends on the thickness of the piezo-electric crystal, according to the following formula:

$$t = \frac{V}{2f}$$

Where:

t = Crystal thickness.
V = Velocity of sound in crystal.
f = Frequency.

3.2 Quartz or silicon oxide (SiO_2)

Found in granite as a natural crystal, quartz can produce compressional or shear waves according to the way the crystal is cut. An X-cut crystal is cut in a direction that directly crosses the axis joining two angles of the crystal. A Y-cut crystal is cut in a direction parallel to the axis joining two angles of the crystal (see Figure 3.2).

- X-cut crystals produce a compressional wave.
- Y-cut crystals produce a shear wave.

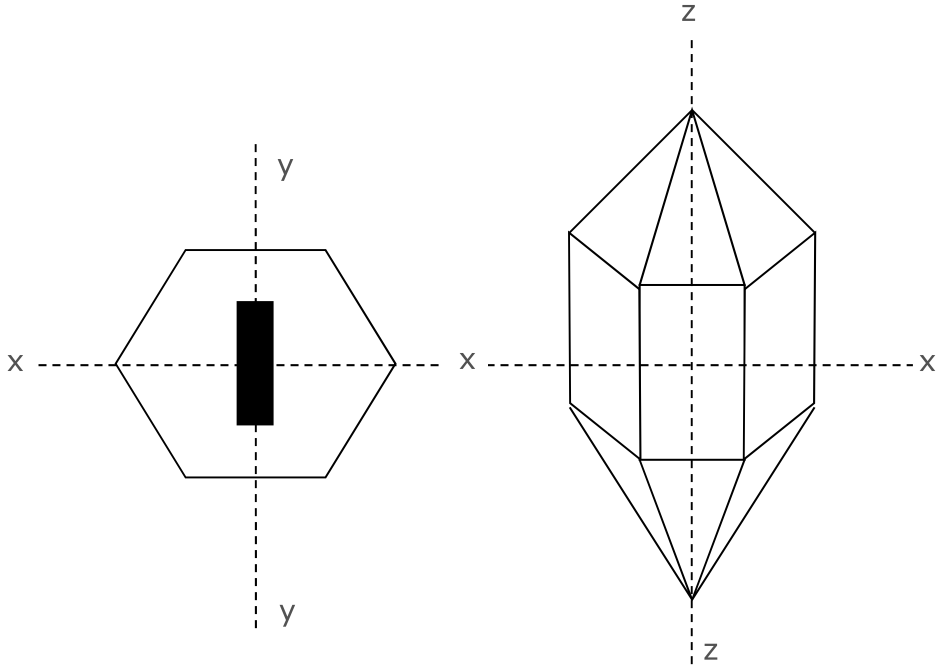


Figure 3.2 X-cut quartz crystal.

Quartz is not much used now. Several types of quartz crystal can be produced, each with its advantages and disadvantages, some of which are listed below.

Advantages

- Resistant to wear.
- Insoluble in water.
- Resistant to ageing.
- Easy to cut to give the required frequencies.

Disadvantages

- Needs a lot of electrical energy to produce a small amount of ultrasound, which means it is inefficient.
- Quartz crystals are susceptible to mode change.
- High voltage is needed to give low frequency sound.

For these reasons quartz has been largely superseded by other piezo-electric materials.

3.3 Lithium sulphate (Li_2SO_4)

Crystals grow as a solution of lithium sulphate is evaporated.

Advantages

- Most efficient receiver of ultrasound.
- Very low electrical impedance.
- Operate well at low voltages.
- Do not age.
- Very good resolution.
- Crystals are easily damped to give short pulse lengths (to give good resolution).

Disadvantages

- Soluble in water.
- Break easily.
- Decompose at temperatures above 130°C.

These disadvantages make lithium sulphate crystals unsuitable for industrial use, though they are used for medical ultrasonics in the examination of pregnant women and patients suffering from tumours. Polarised crystals were found to be most suitable for industrial use. Polarised crystals are made by heating powders to high temperatures, pressing them into shape and allowing them to cool in very strong electrical fields, which affect the atomic structure of the crystal lattice.

3.4 Barium titanate ($BaTiO_3$)

Crystals are made by baking barium titanate at 1,250°C and then cooling it in a 2kV/mm electrical field.

Advantages

- Efficient generator of sound.
- Only needs a low voltage.
- Good sensitivity.

Disadvantages

- Its Curie temperature, at which the crystal depolarises, is only about 120°C, which makes it susceptible to heating.
- Deteriorates over time.

3.5 Lead metaniobate ($PbNb_2O_6$)

Crystals are made in a similar way to barium titanate.

Advantages

- Heavy internal damping.
- Gives out very narrow pulses of ultrasound, which gives good resolution.

Disadvantages

- Much less sensitive than lead zirconate titanate (PZT).

3.6 Lead zirconate titanate ($PbZrO_3$, $PbTiO_3$)

Lead zirconate titanate (PZT) crystals have the best all-round performance for industrial testing.

Advantages

- A high Curie point, up to 350°C.
- Good resolution.
- Does not dissolve in water.
- Tough and resistant to ageing.
- Easily damped.

Because it has no major disadvantages, PZT is used in most probes.

3.7 Electromagnetic acoustic transducers

A feature of probes using piezo-electric crystals is that they require mechanical coupling to the solid under inspection. This is achieved either by immersing them in a tank filled with a fluid (usually water) or directly by the use of a thin (less than one quarter of the wavelength) fluid layer between the two. When shear waves are to be transmitted, the fluid is also generally selected to have a significant viscosity. The acoustic impedance of the couplant layer should also have a value somewhere between that of the probe and that of the material being tested.

Electromagnetic acoustic transducers (EMATs) rely upon a totally different physical principle. When a wire is placed near the surface of an electrically conducting object and a current of the required ultrasonic frequency is applied, eddy currents will be induced in a near-surface region of the object.

EMAT probes are used for the detection of flaws and the determination of material properties such as the precise velocity as well as attenuation measurements. They do not require the use of couplant and as such can operate without contact at elevated temperatures and in remote locations.

EMAT probes are, however, inefficient and require strong magnetic fields and large currents to produce ultrasound that is often weaker than that produced by piezo-electric transducers. Rare earth materials such as samarium-cobalt and neodymium-iron-boron are often used to produce sufficiently strong magnetic fields, which may also be generated by pulsed electromagnets.

EMAT probes generate ultrasonic waves due to the interaction between a static magnetic field of a magnet and the high frequency magnetic field generated by a coil. The eddy currents produced in the material due to the coil create a Lorentz force, causing the atomic lattice of the material to oscillate and produce an ultrasonic wave. A magnetic structure component is also generated by the EMAT and although not very efficient in terms of energy, the ultrasonic proportion can have useful in-service applications (see below).

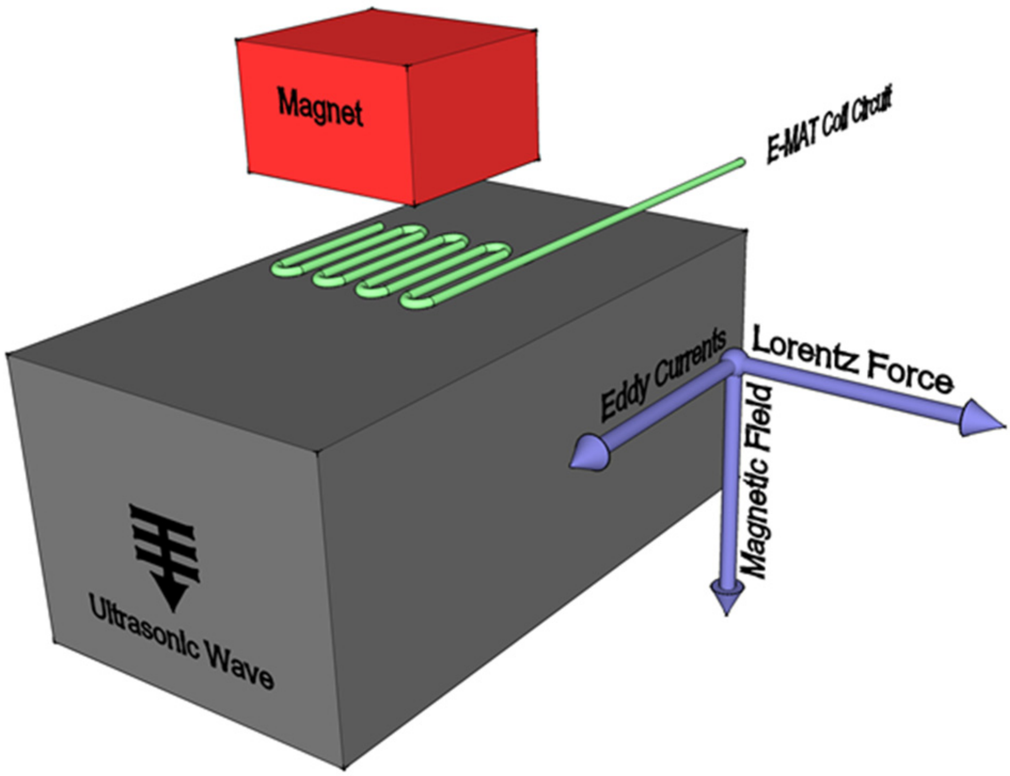


Figure 3.3 Method of ultrasonic wave generation from an EMAT probe.

Including a magnetic component in the structure of an EMAT probe can allow thickness measurement of sealed tubes (eg ferromagnetic boiler tubes) at elevated temperatures without the necessity to remove the oxide scale.

Section 4
Pulse Length and Damping

4 Pulse Length and Damping

A pulse of ultrasound from a piezo-electric crystal has a length or width of several vibrations or wavelengths. When you strike a bell it continues to ring for several seconds as the metal continues to vibrate. The vibrations get steadily weaker and the sound dies away. If you put your hand on the bell you stop the vibrations and the sound dies away more quickly - you dampen the sound.

A piezo-electric crystal continues to vibrate after it is hit by an electrical charge. This affects the sensitivity: the longer the pulse length, the worse the resolution. In most probes a slug of tungsten-loaded Araldite is placed behind the crystal to cut down the ringing time and to shorten the pulse length. Pulse length, duration and width are the same thing but we must not confuse them with wavelength.

Pulse length (or width) is also sometimes called wave train length. It is defined in a number of ways but not even the standards always agree. We choose the one in EN 1330 Part 4 NDT terminology – Part 4: Terms used in ultrasonic testing, which defines it as the leading and trailing edges of a pulse measured at a defined level below the peak amplitude.

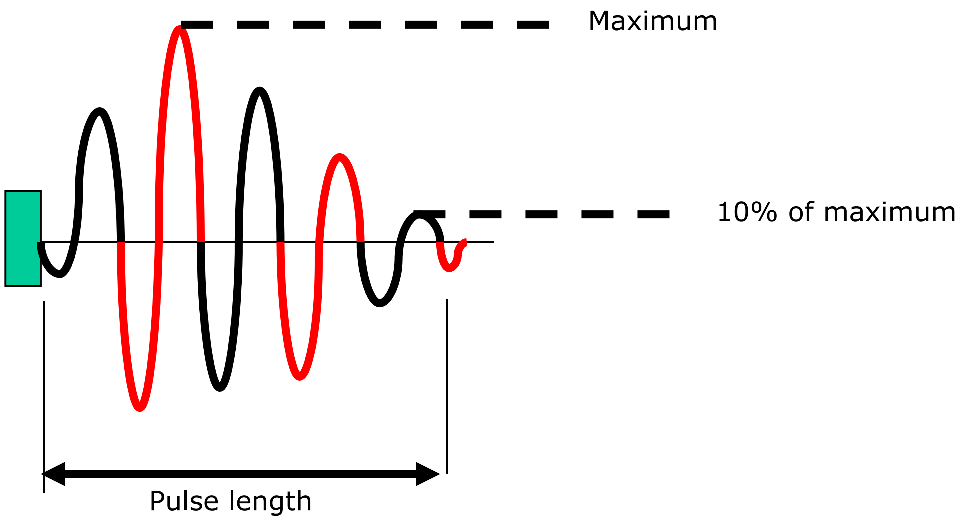


Figure 4.1 Ultrasonic pulse.

A long pulse may be 15 wavelengths (cycles, vibrations) while a short pulse may have as little as two cycles. The average pulse length is about five wavelengths. The longer the pulse length, the more penetrating the ultrasound, as it contains more energy but the worse the sensitivity and resolution; hence the need to compromise.

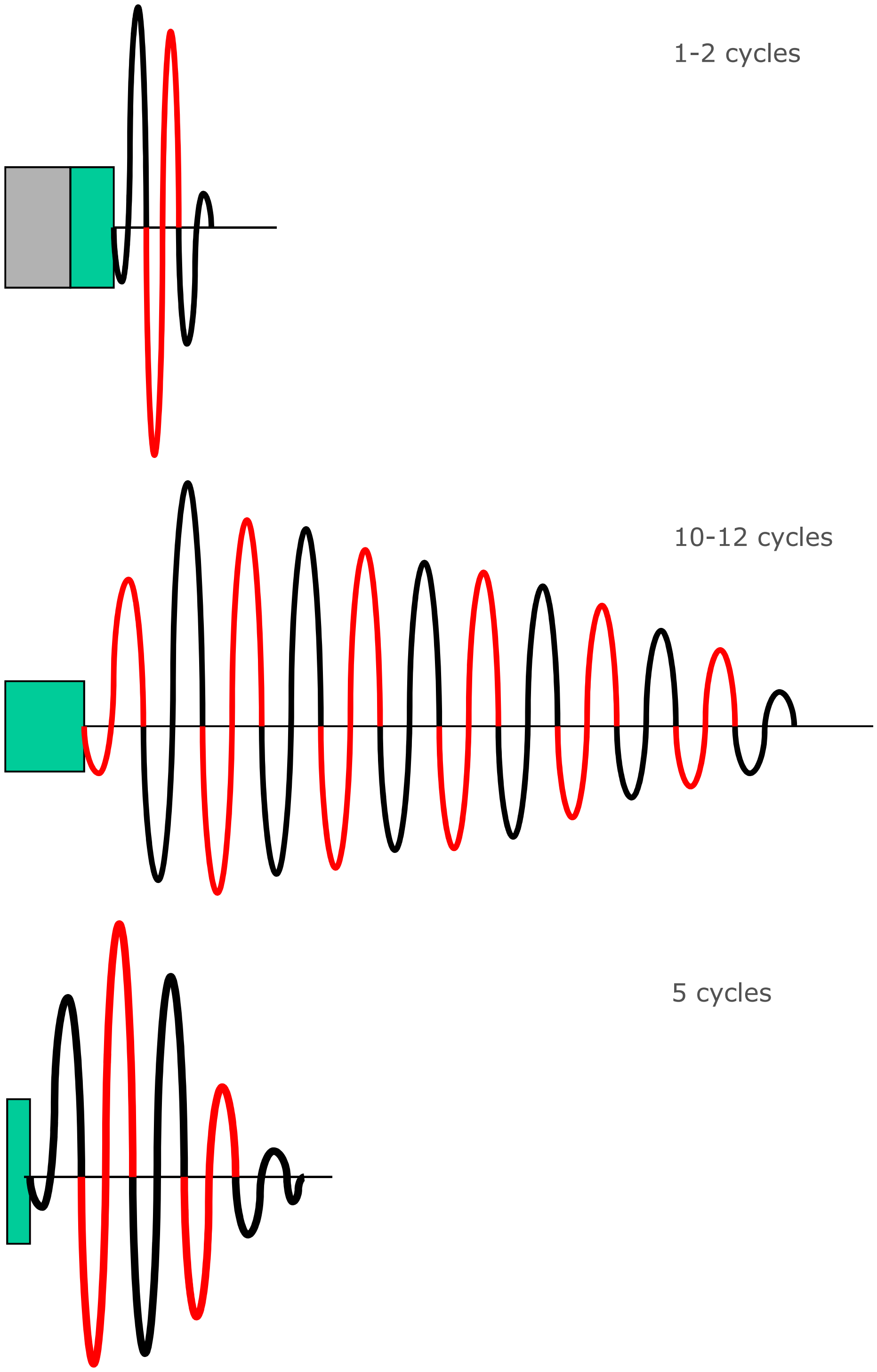
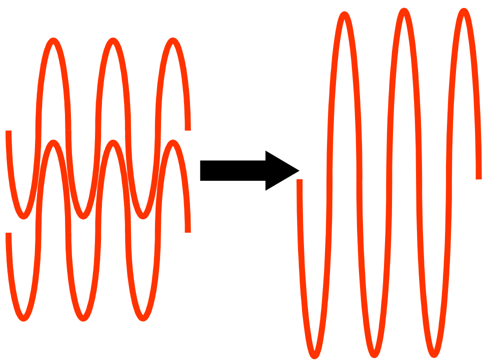


Figure 4.2 Pulse lengths.

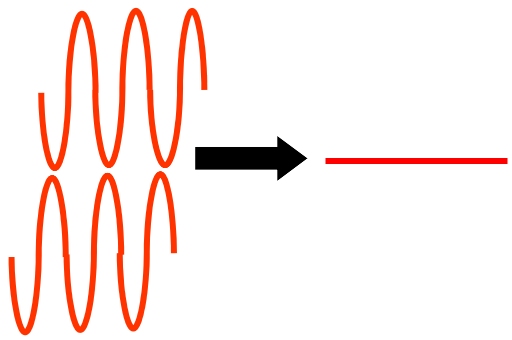
Section 5
The Sound Beam

5 The Sound Beam

The spread of sound waves from a piezo-electric crystal has been likened to the beam of a torch, ie an elongated cone. Just as the intensity of light from a torch diminishes with distance, so sound pulses get weaker the further they travel from the crystal. An acoustic sound wave has also previously been described as being a single sinusoidal wave propagating through a material. These analogies do not however present a totally true picture. The sound produced from an ultrasonic crystal does not originate from a single point but rather it is derived from many points along the surface of the piezo-electric crystal. This results in a sound field with many waves interacting or interfering with each other (see Figure 5.1).



Constructive interference



Destructive interference

Figure 5.1 Interaction of the ultrasonic beam.

When waves interact. they overlay each other and the amplitude of the sound pressure or particle displacement at any point of interaction is the sum of the amplitudes of the two individual waves. When the waves are fully in phase, the result is additive or constructive and the intensity is doubled. When completely out of phase, the result would be the amplitudes cancelling each other out. The interaction can vary between these two extremes and the wave produced will equal the sum of the amplitudes at all points with peaks of intensity referred to as nodes. In an ultrasonic probe the situation is further complicated as sound originates from not just two but many points on the crystal surface.

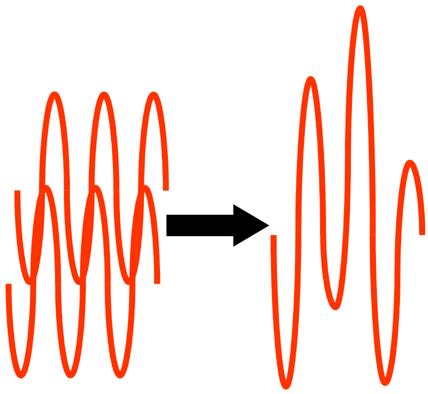


Figure 5.2 Additive nature of two sound waves interacting.

In an ultrasonic probe, one would expect the sound intensity to be highest at the probe face and to fall away gradually as the distance from the probe increases. Due to interactions near the face of the probe, however, the sound field is very uneven in this region with peaks and troughs in sound intensity. This area of intensity variation is known as the near field or Fresnel zone. As one moves farther away from the probe these variations are eliminated and the sound field behaviour becomes more uniform. This region of the sound beam is referred to as the far field, or Fraunhofer zone. In the far field, the intensity behaves as expected and is reduced exponentially with distance. The beam spreads out as a circular wave front.

5.1 Near zone (or near field)

A piezo-electric crystal is made up of millions of molecules. Each of these vibrates when the crystal is hit by an electric charge and they send out shock waves. The shock waves jostle each other.

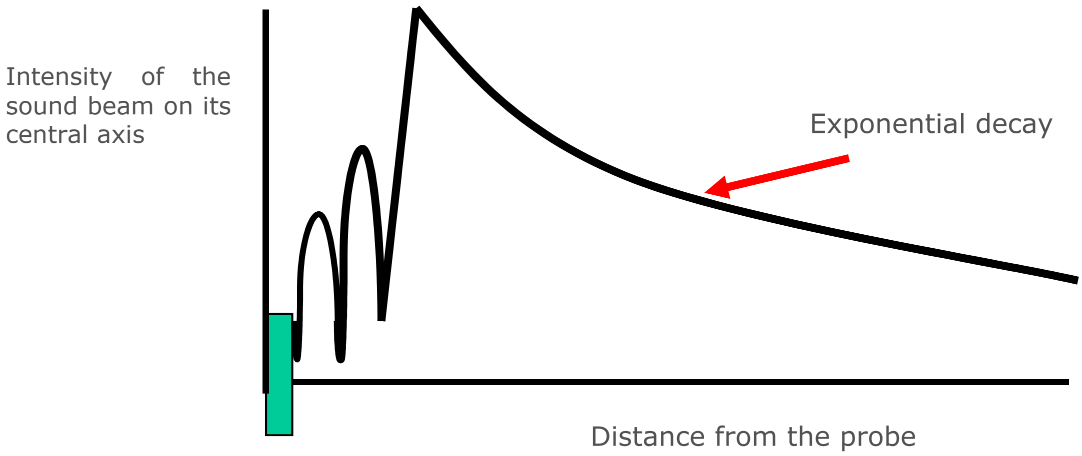


Figure 5.3 Variations in sound intensity.

After a time, the shock waves or pulses even out to form a continuous front. The area between the crystal and the point where the wave front evens out is what we call the near or Fresnel zone. Inside the near zone, signals from a reflector bear no accurate relation to the size of the reflector, as the sound vibrations are going in all directions. This affects the accuracy of flaw sizing of small reflectors inside the near zone.

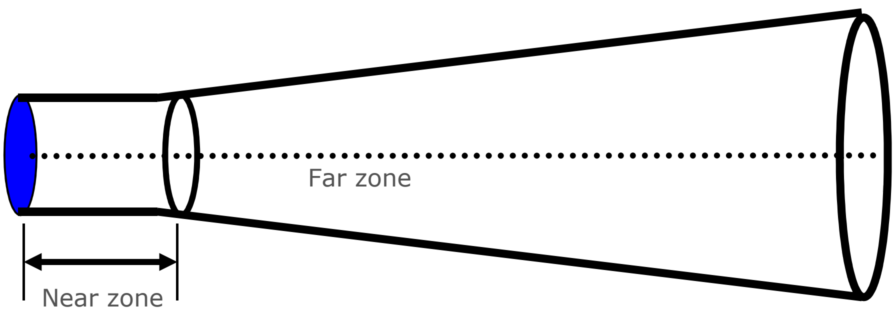


Figure 5.4 Regions of a sound beam.

The near zone of a crystal varies with the material being tested, but it can be worked out by a formula:

$$\text{Near zone} = \frac{D^2}{4\lambda}$$

$$\text{Or} \quad \frac{D^2 f}{4V}$$

D = Diameter
f = Frequency
λ = Wavelength
V = Velocity

For example, the near zone of a 5MHz compression probe with a 10mm diameter crystal will be, in steel:

$$\frac{10^2\,x\,5{,}000{,}000}{4\,x\,5{,}920{,}000} = 21.1mm$$

The near zone of a 2.5MHz probe with a 20mm diameter crystal will be:

$$\frac{20^2\,x\,2{,}500{,}000}{4\,x\,5{,}920{,}000} = 42.2mm$$

We can deduce from the formula that:

- The greater the diameter, the greater the near zone.
- The higher the frequency, the greater the near zone.

In twin crystal or angle beam probes with a Perspex stand-off component in the probe body, some or even all of the near zone is contained in the Perspex shoe. This must be taken into account when the calculation for near zone is applied.

We will need to know the length of the beam path within the Perspex, the velocity of the Perspex and the velocity of the test material, as well as the near zone within the test material.

The first step is to calculate the near zone in the test material; then the path length in the Perspex is multiplied by the velocity in the Perspex before dividing by the velocity in the test material; this is finally subtracted from the near zone length.

If a 2.5MHz, 20mm compression probe has a near zone of 42.2mm and a Perspex shoe of 15mm in front of the transducer, then the length of the near zone within the steel is:

15 x 2730 ÷ 5920 = 6.91mm

42.2 – 6.91 = 35.31mm of the near zone is in the test material.

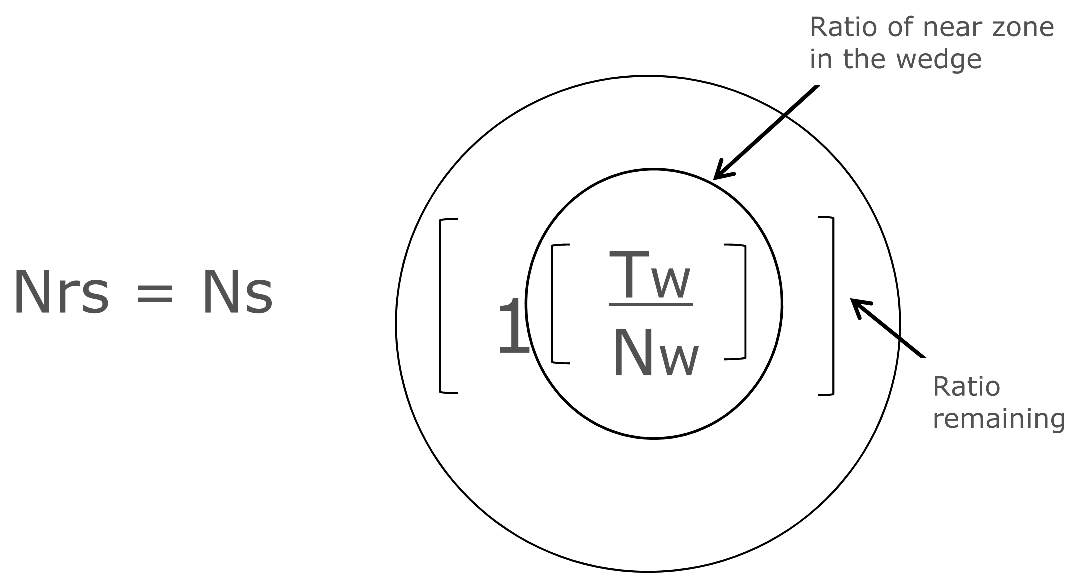


Figure 5.5 Near zone path distance in the steel test object and probe wedge.

Nrs = Near zone path length remaining in the steel (mm).
Ns = Near zone in steel (mm).
Tw = Thickness (mm) travelled through wedge.
Nw = Near zone in wedge (mm).

5.2 Far zone

In the far zone the sound pulses follow the inverse square law, spreading out as they move away from the crystal; the sound intensity decays exponentially.

$$I = \frac{1}{r^2}$$

If we double the distance, we quarter the intensity.
If we halve the distance, we increase the intensity fourfold.

I = Sound intensity.
r = Distance from the crystal.

The higher the frequency of the crystal, the less the beams spread out. The angle of beam spread can be found using the formula below:

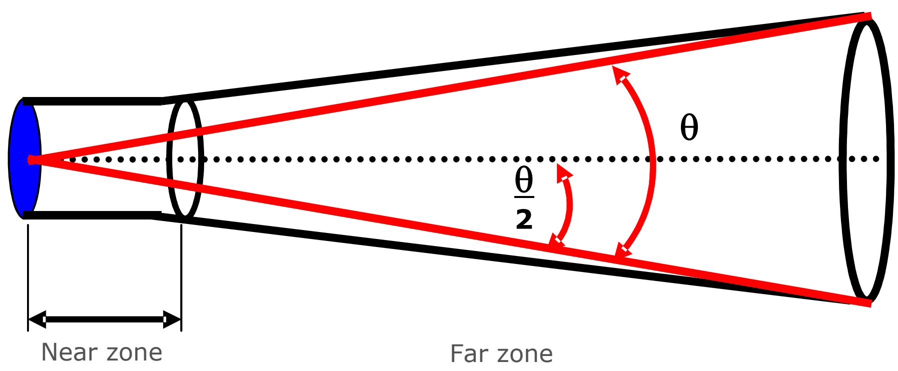


Figure 5.6 Beam spread.

$$\sin\ \theta/2 = \frac{K\lambda}{D} \text{ or } \frac{KV}{Df}$$

Where:

K = Constant for the edge of the beam spread.
D = Diameter of crystal.
V = Velocity of sound in material.
f = Crystal frequency.

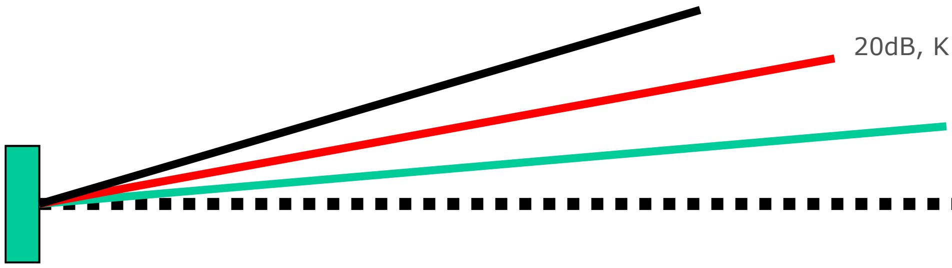


Figure 5.7 K values for the beam edge.

Where the sound intensity drops by 6dB (half the intensity), K is 0.56.

If we take the edge of the beam to be where the sound energy is 10% (20dB) of the energy at the beam centre, K is 1.08.

If we take the extreme edge of the sound beam to work out beam spread angles, then K is 1.22.

Example

The beam spread of a 10mm 5MHz probe in steel is calculated as follows:

$$\sin\ \theta/2 = 1.08 \text{ or } 1.22 \times \frac{5920}{5000x10}$$

$\sin\ \theta/2$ = 7.35° at the 20dB point or
8.3° at the edge

So the angle of beam spread is 14.7° if you take the edge of the beam to be where the energy is 10% of the main energy or 16.6° taking the extreme edge of the beam.

From the formula we can deduce that:

- The higher the frequency, the smaller the beam spread.
- The larger the crystal, the smaller the beam spread.

This is one of the reasons why low frequency probes have large diameter crystals.

Section 6
Total Attenuation Loss

6 Total Attenuation Loss

EN 1330 defines attenuation as the decrease in sound pressure that occurs when a wave travels through a material arising from absorption and scattering. The two components, absorption and scatter, are defined as:

Absorption

Component of the attenuation resulting from transformation of ultrasonic energy into other types of energy (eg thermal).

Absorption occurs as the sound pulse hits the molecules of the test material and makes them vibrate. The energy lost in vibrating the molecules turns to heat. The rate of absorption varies from one material to another and even from one type of steel to another. It is very high in Perspex, nylon and lead and is low in aluminium.

Scatter

Randomly reflected energy caused by grain structure and/or by small discontinuities in the beam path.

Scatter occurs as sound energy is reflected from grains in the test material. The larger the grains, the more scatter occurs. The grass at the bottom of the CRT screen is caused by reflections from grain boundaries in the test material. More grass arises from cast iron or brass than from small grained materials like refined steel or annealed aluminium.

The longer the wavelength of a sound pulse, the less energy is scattered. Where the wavelength is smaller than the grain size, a sound pulse is scattered very quickly. It is for this reason that a low frequency probe, with its longer wavelength, has greater penetration in a given material than a high frequency probe.

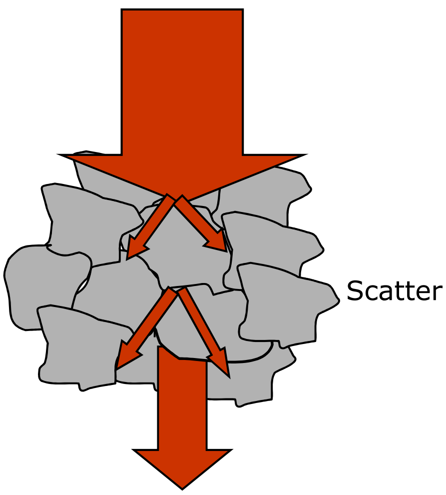


Figure 6.1 Scatter of the ultrasonic beam at grain boundaries.

6.1 Attenuation due to beam spread

The amount of energy reflected back depends on whether the reflector is bigger in area than the sound beam at that distance. If the reflector is bigger in area than the sound beam, the signal on the screen varies according to the law of large reflectors. If the reflector is smaller in area than the sound beam at that distance, it obeys the law of small reflectors.

Both of these laws only apply beyond a distance of three times the length of the near zone.

6.1.1 Law of the large reflector

Large reflectors outside three near zones obey the inverse law.

A large reflector at 20mm, if it is beyond three near zones, gives a signal at 80% FSH. If the dB setting is not altered, a large reflector in the same material at 40mm will give a signal at 40% FSH (inverse law).

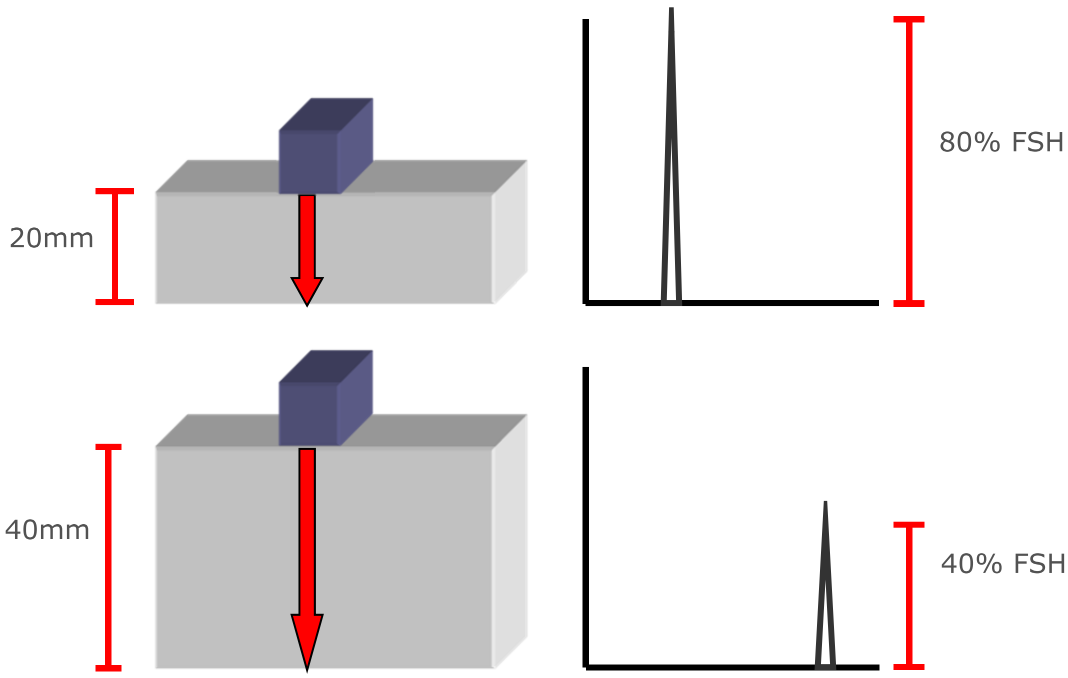


Figure 6.2 Law of the large reflector.

6.1.2 Law of the small reflector

Small reflectors outside three near zones obey the inverse square law.

A small reflector at 20mm, if it is beyond three near zones, gives a signal at 80% FSH. If the dB setting is not changed, a similar reflector in the same material at 40mm will give a signal at 20% FSH (inverse square law).

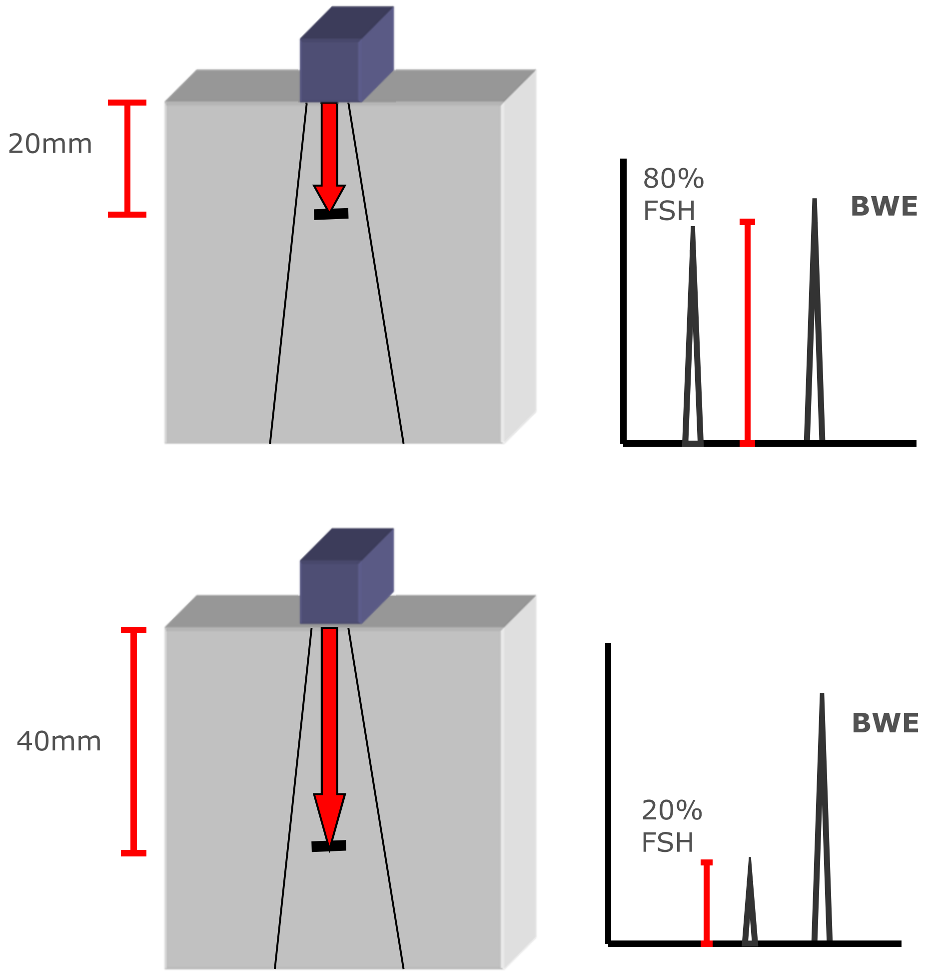


Figure 6.3 Law of the small reflector (ie smaller than the beam width).

Sound energy is lost in other ways:

- Reflection inside the probe.
- Scattering from a rough surface.
- Non-metallic inclusions or laminations in test material.
- Reflection from the surface of the test piece.
- Mode change.

Measurement of material attenuation

a Place a compression probe on a piece of the test material and turn the backwall echo to FSH. **Note:** If the back wall echo (BWE) is within three near zones of the probe, use the first BWE outside the distance of three near zones.

b Obtain an echo from twice the distance of the BWE used and increase the signal height until it is at FSH. **Note:** The dB difference.

c To remove the effects of beam spread we subtract 6dB (due to beam spread loss) from the dB difference and divide the remainder by the distance the sound has travelled between the two echoes. This is twice the distance shown on the CRT, as the sound has to travel to the backwall and back to trigger the probe.

d The answer will give the number of decibels lost per millimetre by attenuation. This can give an assessment of plate quality and heat treatment.

If the difference between the first and second backwall echoes from a 75mm thick block of steel was 9dB, what is the attenuation of the material?

9dB due to beam spread and attenuation combined.

9dB - 6dB = 3dB

This gives 3dB due to attenuation only as the sound travels through the block.

The 75mm block gives a sound path for the pulse echo of 150mm; the sound has to travel to the backwall, then back to the probe:

3/150 = 0.02

The attenuation within the block is 0.02dB/mm.

If we need the answer in dB/m, multiply by 1000 (1000mm in a metre):

Attenuation is 20dB/m.

Attenuation checks have to be made when dealing with distance amplitude correction (DAC) and distance gain size (DGS) systems; these will be discussed later.

Section 7
Acoustic Impedance

7 Acoustic Impedance

When a sound pulse arrives at an interface between different materials at right angles, some sound is reflected back into the material from whence it came. The rest of the sound, however, is transmitted into the second material. This is due to the difference in acoustic impedance of the two materials and is known as acoustic impedance mismatch or sometimes as interface behaviour.

We can calculate how much sound is transmitted and how much sound is reflected back if we know the acoustic impedance of both materials.

Acoustic impedance is represented by the letter Z and is the velocity of sound in the material multiplied by the material density:

$$Z = \rho V$$

Where ρ (the Greek letter rho) is the density and V is the sound velocity (compressional or shear, depending on the case).

Once we know the acoustic impedances of two materials, we can use a formula to work out how much sound will be reflected back. The formula is:

$$\left[\frac{Z_1 - Z_2}{Z_1 + Z_2}\right]^2 x100 = \% reflected$$

Where Z_1 is the acoustic impedance of the first material and Z_2 is the acoustic impedance of the second material.

Example

To calculate the amount of energy reflected back at a steel-water interface, we must find out the acoustic impedances of steel and water. They are:

Z_1 (steel) = 46.7 x 106 kg/m^{2}s

Z_2 (water) = 1.48 x 106 kg/m^{2}s

So, applying the formula:

$$\left(\frac{46.7 - 1.48}{46.7 + 1.48}\right)^2 x100$$

$$\left(\frac{45.22}{48.18}\right)^2 x100$$

0.93856^2 x 100

0.8809 x 100 = 88.09%

88% of the sound energy is reflected back at the interface. This means that 12% of the energy is transmitted at the interface. Using the same formula, the figures for other media can be worked out. At a steel/oil interface, 91% of sound energy is reflected back; at a glycerine/steel interface, 90% of energy is reflected back.

These substances, water, oil and glycerine, are used as couplants in ultrasonics to transmit sound energy from the probe into the test materials. So in fact, only about 10% of the energy generated by the probe crystal actually gets through the couplant into the test material.

When examining a piece of steel with a compression probe, we pass at most about 10% of sound energy from the crystal into the steel. Even if all that energy is reflected back from the backwall or a large flaw in the steel, only 10% of the returning energy will pass back through the interface into the probe. Consequently, at most 1% of energy generated by a probe crystal will come back into a probe, a very small amount indeed. A rule of thumb with UT is that whatever happens to sound going in one direction, happens also in the reverse direction.

Table 7.1 Characteristic acoustic impedance for different materials.

Material	Characteristic impedance ($10^6 kg/m^2s$)
Aluminium	17
Brass	36
Copper	41
Lead	27
Magnesium	93
Nickel	50
Steel	46.7
Glass	18
Polystyrene	29
Oil	1.3
Water	1.4
Air	0.0041

Section 8
Snell's Law

8 Snell's Law

When sound waves pass obliquely (not at 90°) between materials having different acoustic velocities, the direction of sound propagation is changed on passing through the interface and the sound wave is said to have been refracted.

Light is also refracted when passing from one medium to another with a different velocity; this means that objects seen across an interface appear to be shifted relative to where they really are.

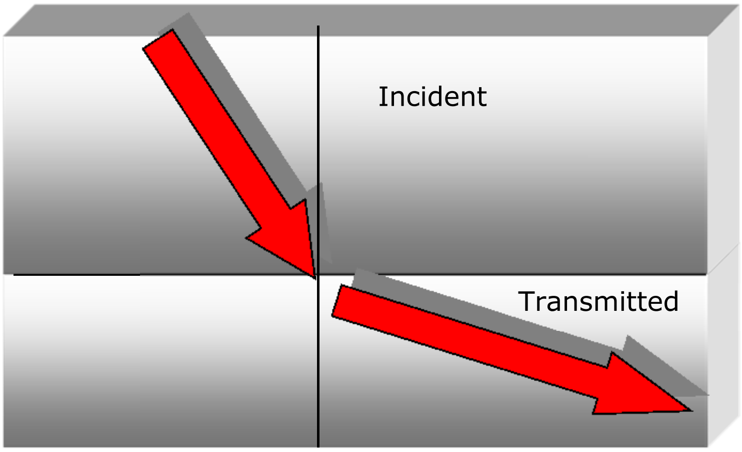
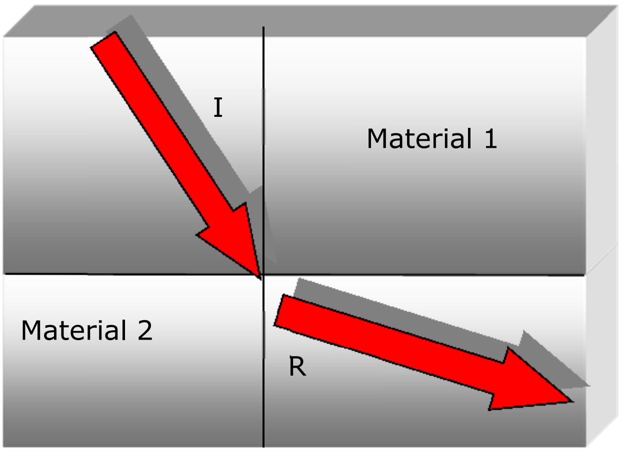


Figure 8.1 Refraction.

Snell's law states that the ratio between sound speeds in two materials is the same as the ratio between the sine of the incident and refracted angles (to the vertical).



$$\frac{\sin I}{\sin R} = \frac{V_1}{V_2}$$

Where:

I = Incident angle
R = Refracted angle
V_1 = Velocity in material 1
V_2 = Velocity in material 2

Figure 8.2 Snell's law.

If we want to make a probe transmitting a shear wave at a certain angle, we have to transpose the formula:

$$\sin \mathrm{I} = \frac{\sin \mathrm{R}\ \mathrm{V}_1}{\mathrm{V}_2}$$

For example, if we want a probe giving a 45° shear wave in steel, we must calculate the angle at which to cut the Perspex wedge - the incident angle. The compression speed of sound in Perspex is 2730m/s, the shear speed of sound in steel is 3250m/s and the refracted angle we need is 45°.

$$\sin \mathrm{I} = \frac{\sin 45^\circ \mathrm{x} 2730}{3250}$$

$$\sin \mathrm{I} = \frac{0.7071 \mathrm{x} 2730}{3250}$$

$$\sin \mathrm{I} = 0.594$$

$$\mathrm{I} = 36.44^\circ$$

However, when the incident angle in the Perspex shoe is less than 27°, both compression and shear waves are generated in the steel. This makes interpretation very confusing. To get a shear wave on its own, the angle of incidence must be more than 27.4°, called the first critical angle. This gives a shear wave of 33° (the lowest standard angle probe manufactured is 35°).

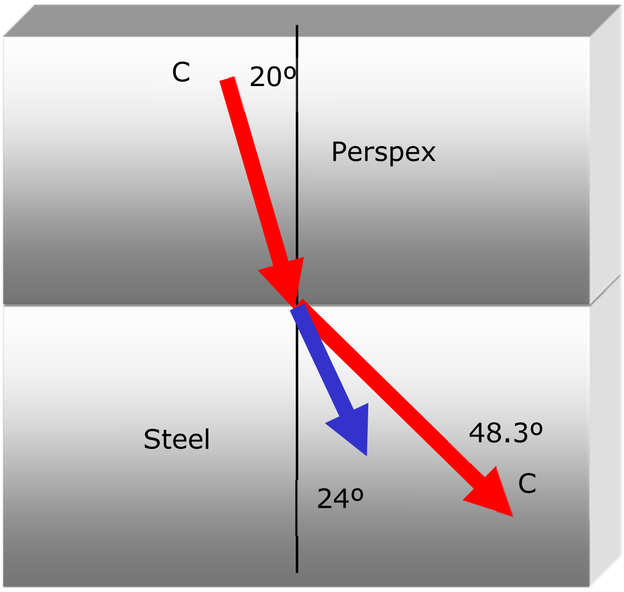
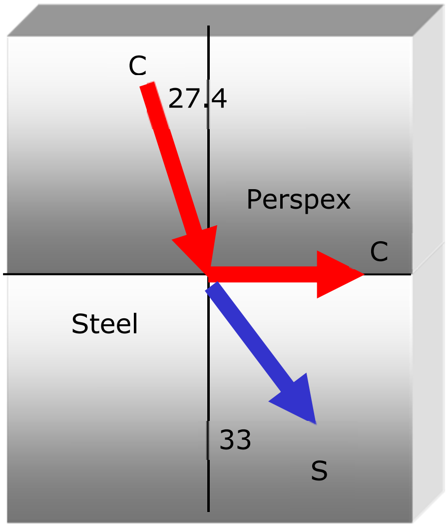


Figure 8.3 Two sound modes.

If the incident angle is above 57.14°, the shear wave is replaced by a surface wave. This angle is called the second critical angle.



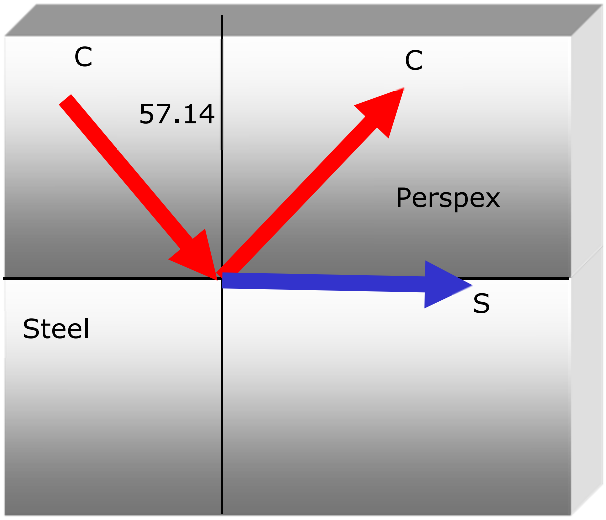


Figure 8.4(a) First critical angle. (b) Second critical angle.

The largest probe angle below a surface (90°) wave probe available from manufacturers without a special order is 80°.

Shear waves on their own in steel are only possible when the incident angles are between 27.4 and 57.14°. This is worked out by the probe manufacturers and it must be borne in mind that a probe which gives a refracted angle of 45° in steel will give a different refracted angle in other materials.

8.1 Critical angle calculation

Snell's law can be used for working out critical angles in non-ferrous metals. For example, during immersion scanning the incident material is water, so a whole new set of angles need to be worked out.

The first critical angle is the incident angle at which the compression wave in the test material is generated at 90°. So using Snell's law:

$$\frac{\sin \mathrm{I}}{\sin 90^\circ} = \frac{2730}{5960}$$

$$\sin 90^\circ = 1$$

$$\sin \mathrm{I} = \frac{2730}{5960}$$

The second critical angle is the incident angle at which a shear wave is generated in the material at 90°. Use Snell's law again:

$$\frac{\sin I}{\sin 90^{\circ}} = \frac{2730}{3240}\frac{\text{m/s}}{\text{m/s}}$$

$$\sin I = \frac{2730}{3240}$$

$$\sin I = 0.8245$$

$$I = 57.4^{\circ}$$

8.2 Mode conversion

When sound travels in a solid material, one form of wave energy can be transformed into another. When a longitudinal wave strikes an interface at an angle, some of the energy can cause particle movement in the transverse direction to start a shear (transverse) wave. This phenomenon is referred to as mode conversion and will occur every time a wave encounters an interface between materials of different acoustic impedance and the incident angle is not at 90° to the interface. Mode conversion can, therefore, cause numerous spurious indications to arise during an inspection which the inspector must eliminate.

Section 9
Probe Design

9 Probe Design

In the US, a probe is usually called a search unit or formerly a transducer. However, we generally now understand the transducer to be the crystal. There are a number of probe designs and configurations. We shall deal with those most commonly used in weld, aerospace and general ultrasonic testing.

9.1 Compression wave probes

Compression probes (see Figures 9.1 and 9.2) generate compressional or longitudinal waves in test materials and are sometimes called normal degree probes. A typical compression probe is composed of a crystal in a metal or plastic housing, with wires connected to it which carry the electrical pulse from the flaw detector and cause the crystal to vibrate. The crystal is surrounded by a damping material at the back to restrict vibration and a plastic disc in front to prevent crystal wear.

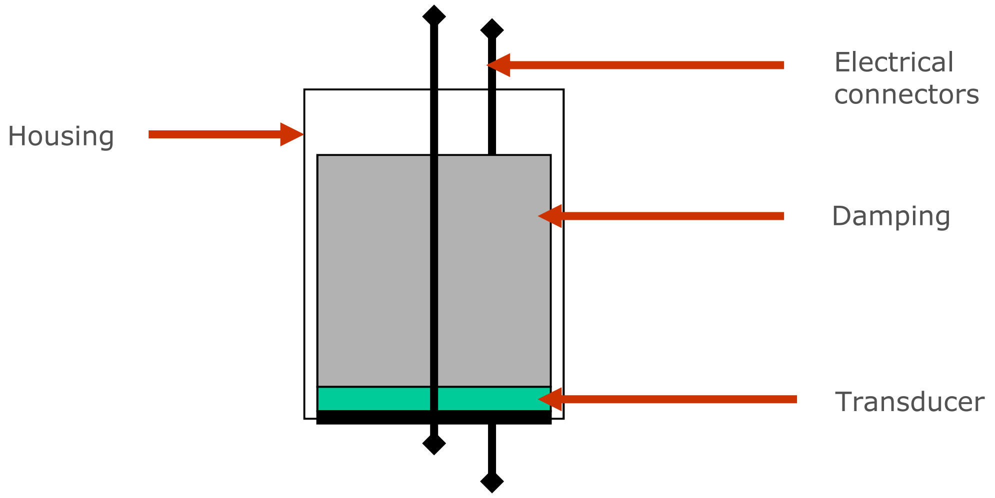


Figure 9.1 Compression wave probe: Schematic drawing.

Figure 9.2 Compression wave probe: Cross section.

9.2 Angle probes

An angle probe is a piezo-electric crystal mounted on a Perspex wedge at an angle calculated to generate a shear (transverse) wave in the test material.

The wedge is made of Perspex because:

a The compressional speed of sound in Perspex (2730m/s) is lower than the shear velocity of sound in steel (3250m/s) so refracted angles are greater than incident angles.

b Perspex is very absorptive and attenuates unwanted echoes from the compressional wave as it hits the Perspex test material interface.

The piezo-electric crystal generates a compressional wave which it transmits into the Perspex wedge. When the compressional wave hits the bottom surface of the wedge, most of the energy is reflected away from the interface and back into the Perspex. It is damped by tungsten powder in epoxy resin on the Perspex wedge.

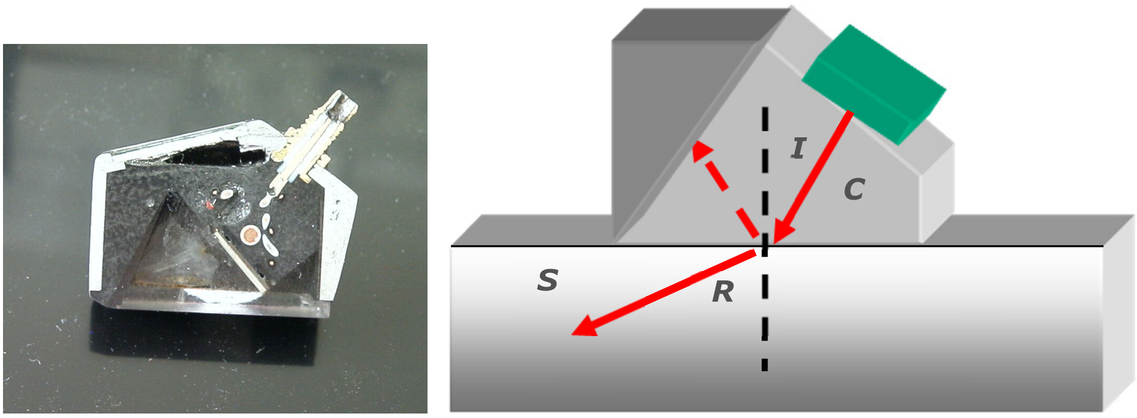


Figure 9.3 Angle probe: Photograph and schematic drawing.

If there is no couplant on the bottom surface of the Perspex wedge, all the energy is reflected back into the probe. If there is couplant and if the probe is placed on a test material, sound energy passes into the test material and generates a shear wave. Angle probes use compression probes mounted on a wedge of Perspex. The wedge of such a probe is cut to a particular angle to enable the beam to refract into the test material at a chosen angle.

Angle probes usually transmit a shear or sometimes a surface wave into test materials and are used largely in weld testing, casting and forging inspection and in aerospace applications.

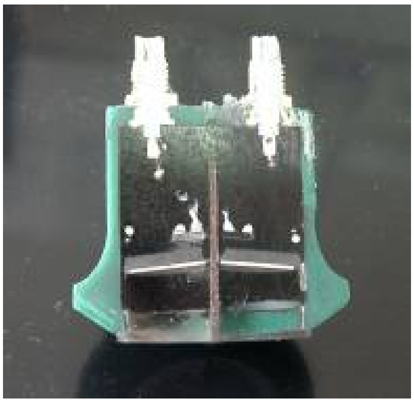
9.3 Twin crystal probes

A single crystal probe transmits and receives ultrasound with one crystal: the crystal transmits the pulse and vibrates when the pulse returns from a backwall echo or a flow. However, when a single crystal probe is used, a signal appears on the screen at the beginning of the time base. It is caused by vibrations immediately adjacent to the crystal and is known by several names: initial pulse, transmission signal, crystal strike or main bang.

For a single crystal probe, the length of the initial pulse is the dead zone and any signal from a reflector at a shorter distance than this will be concealed in the initial pulse.

In twin crystal probes, the initial pulse is deliberately delayed beyond the left of the time base by mounting the transducers of a twin (or double) crystal probe onto plastic wedges. This, in addition to the focusing of the crystals, reduces the dead zone considerably and flaws can be assessed anywhere except where the transmission and receptive beams do not overlap.

A twin or double crystal probe is designed to minimise the problem of the dead zone. A twin crystal probe has two crystals mounted on Perspex shoes, angled slightly inward to focus at a set distance in the test material. If the crystals were not angled, the pulse would be reflected straight back into the transmitting crystal.



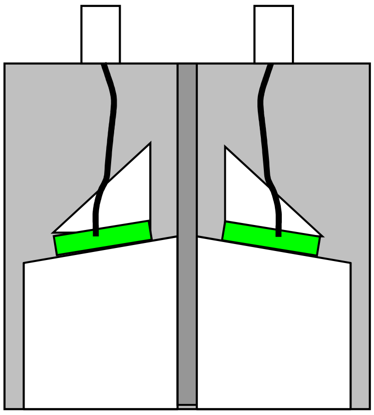


Figure 9.4 Twin crystal probe: Photograph and schematic drawing.

The Perspex shoes hold the crystals away from the test surface so that the initial pulse does not appear on the CRT screen. The dead zone is greatly reduced to the region adjoining the test surface, where the transmission and reception beams do not overlap.

Additional advantages of double crystal probes:

- Can be focused.
- Can measure thin plates.
- Can detect near-surface flaws.
- Good near-surface resolution.

Disadvantages:

- Good contact is difficult with curved surfaces.
- Difficult to size small defects accurately as the width of a double crystal probe is usually greater than that of a single crystal probe.
- The amplitude of a signal decreases the further a reflector is situated from the focal distance - a response curve can be made out.

Therefore single and twin crystal probes are complementary.

9.4 Other probe types

Immersion probes are designed for use where the test part is immersed in water. They are typically used inside a water tank or as part of a squirter or bubbler system in scanning applications. Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and thus into the component being inspected. Immersion transducers can be purchased in a flat, cylindrically or spherically focused lens. A focused transducer can improve sensitivity and axial resolution by concentrating the sound energy to a smaller area.

Delay line probes, as the name implies, introduce a time delay between the generation of the sound wave and the arrival of any reflected waves. This allows the crystal to complete its transmission function before it begins to receive returning signals. Delay line transducers are recommended for applications that require a contact transducer with good near-surface resolution and are designed for use in applications such as high-precision thickness gauging of thin materials and delamination checks in composite materials. They are also useful in high temperature measurement applications since the delay line provides some heat insulation to the piezo-electric element.

High frequency broadband probes with frequencies between 20 and 150MHz are commercially available and can dramatically improve flaw resolution and thickness measurement capabilities.

Section 10
Test Techniques

10 Test Techniques

10.1 Pulse echo

Ultrasonic inspections are largely performed by the pulse echo technique, in which a single probe is used to both transmit and receive ultrasound. In addition to the fact that access is required from one surface only, a further advantage of this technique is that it gives an indication of not only the type of defect but also its size and exact location within the item being tested.

The major disadvantage is that pulse echo inspection is reliant upon the defects having the correct orientation relative to the beam in order to generate a returning signal to the probe and is therefore not considered fail safe (see Figures 10.1 and 10.2). If the sound pulse hits the flaw at an angle other than 90°, much of the energy will be reflected away and not return to the probe with the result that the flaw will not show up on the screen.

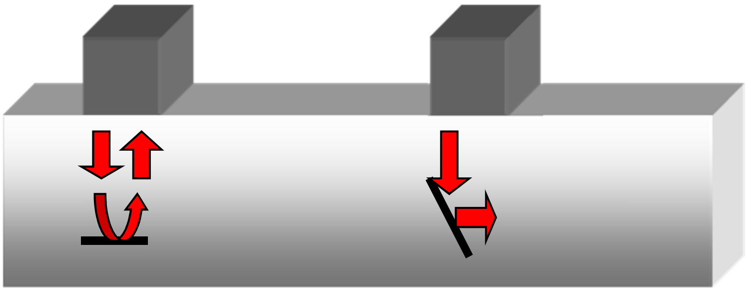


Figure 10.1 Schematic drawing of the pulse echo technique showing specular reflection from a discontinuity: Normal compression probe.

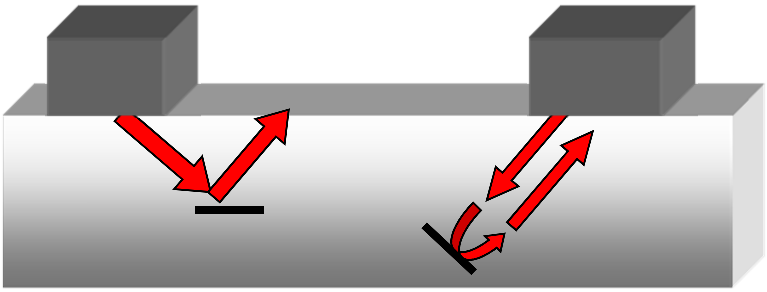


Figure 10.2 Schematic drawing of the pulse echo technique showing specular reflection from a discontinuity: Shear wave angle probe.

10.2 Through-transmission

Through-transmission was used in the early days of UT and is still used in plate and bar production. A probe on one side of a component transmits an ultrasonic pulse to a receptor/receiver probe on the other side. The absence of a pulse arriving at the receiver indicates a defect.

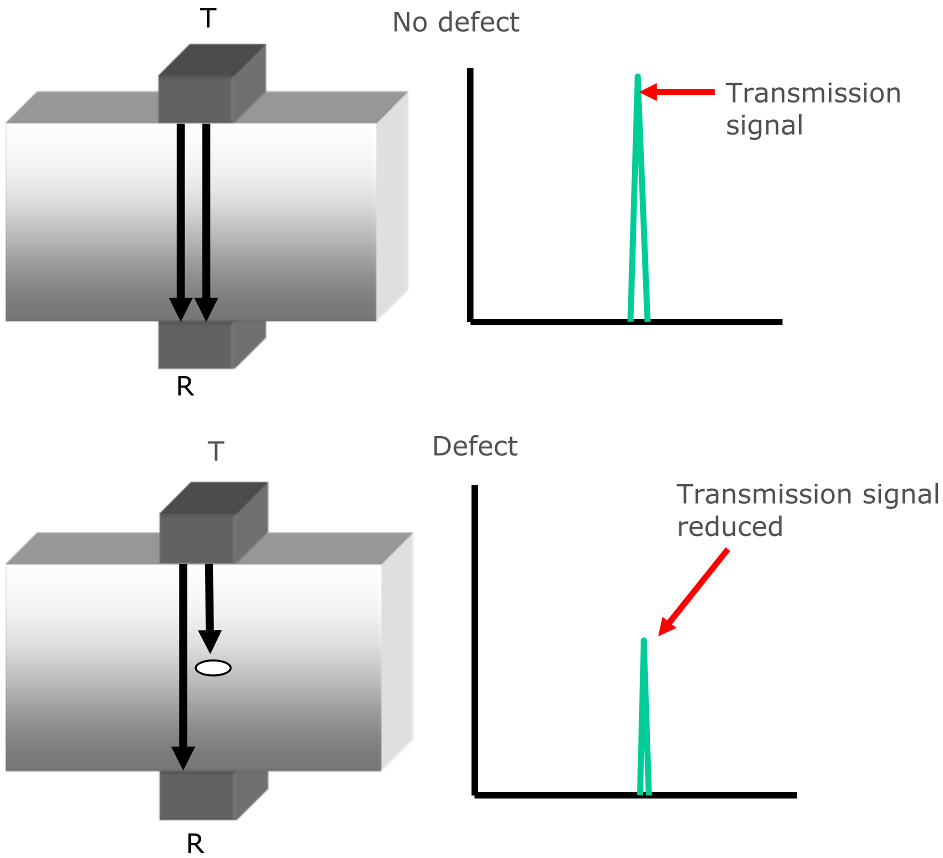


Figure 10.3 Through-transmission.

Advantages

- Less attenuation of sound energy.
- No probe ringing.
- No dead zone on the screen.
- Orientation of a defect does not matter as much as on the pulse echo display.

Disadvantages

- Defect cannot be located.
- Defect cannot be identified.
- Component surfaces must be parallel.
- Vertical defects do not show.
- Process must be automated.
- Requires access to both sides of the component.

10.3 Tandem scanning

Tandem scanning is used mainly to locate defects lying perpendicular to the surface. It involves the use of two or more angle probes of the same angle of incidence and facing the same direction with one probe acting as the transmitter and the others as receivers.

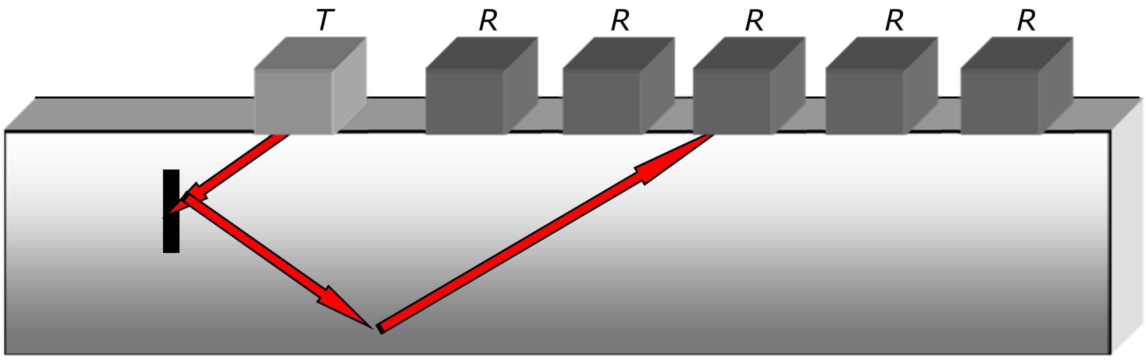


Figure 10.4 Tandem scanning (T=Transmitter, R=Receiver).

10.4 Contact scanning

Contact scanning is defined by BS EN 1330 as scanning by means of (an) ultrasonic probe(s) in direct contact with the object under examination (with or without couplant). A thin film of couplant between the probe and the test surface usually serves to transmit ultrasound, to lubricate the surface and to reduce wear on the probe face. Ideally the acoustic impedance of the couplant should be between that of the probe (Perspex) and that of the material under test.

10.5 Gap scanning

Gap scanning is a technique in which the probe is not in direct contact with the surface of the specimen but rather coupled to it through a column of liquid no more than a few wavelengths thick.

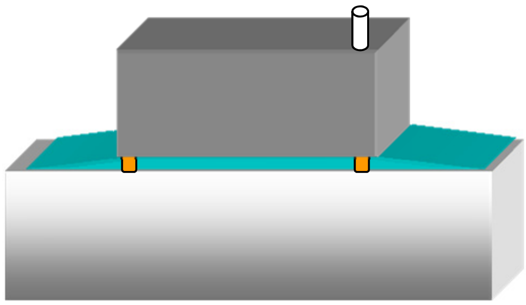


Figure 10.5 Gap scanning.

10.6 Immersion testing

Immersion testing involves the test object being submerged in a liquid, usually water and the probe being scanned at a fixed distance above the component. The water serves to provide constant coupling conditions and amounts to a long fluid delay line. Although the probe itself requires a compression wave, shear waves can be produced within the sample by angulation of the probe. This technique frequently uses high frequency probes (25-50MHz) and focused probes for automated inspections and is suited to the inspection of complex components, see eg BS M36: Ultrasonic Testing of Special Forgings By an Immersion Technique.

Wheel probes, squirters and bubblers are also considered to be immersion systems.

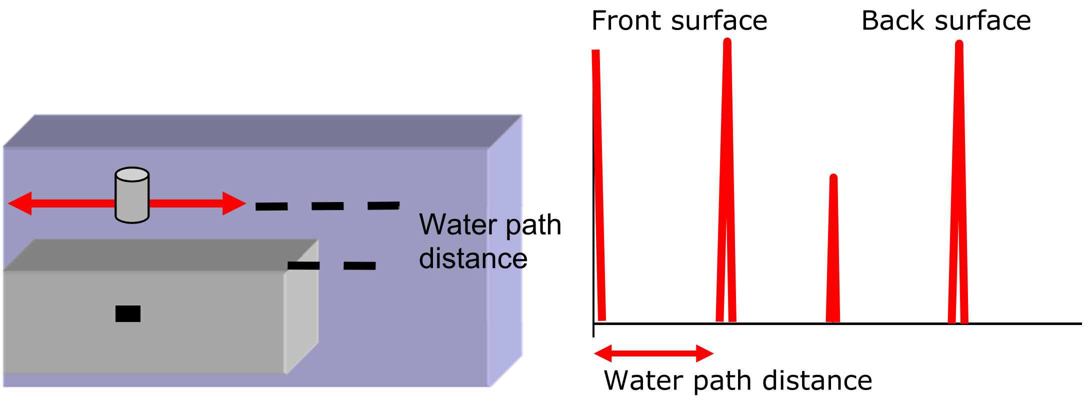


Figure 10.6 Immersion scanning.

10.7 Presentation

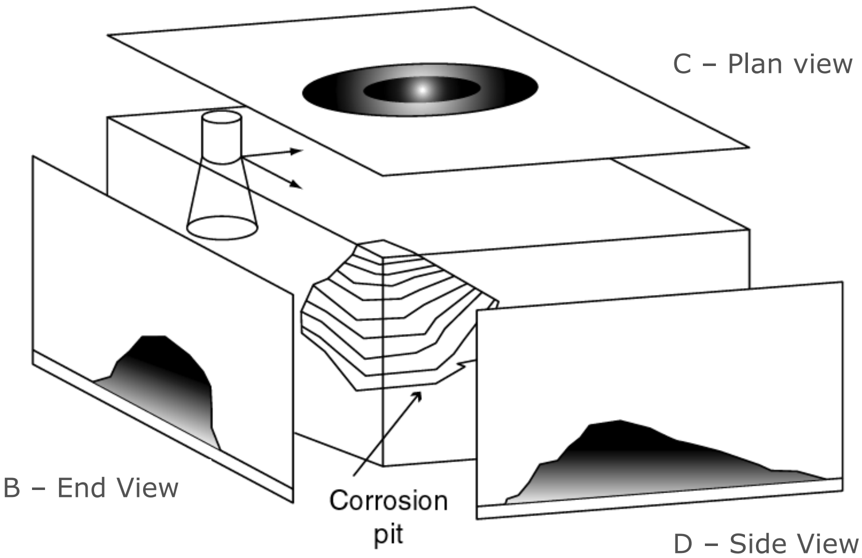


Figure 10.7 B, C and D scans.

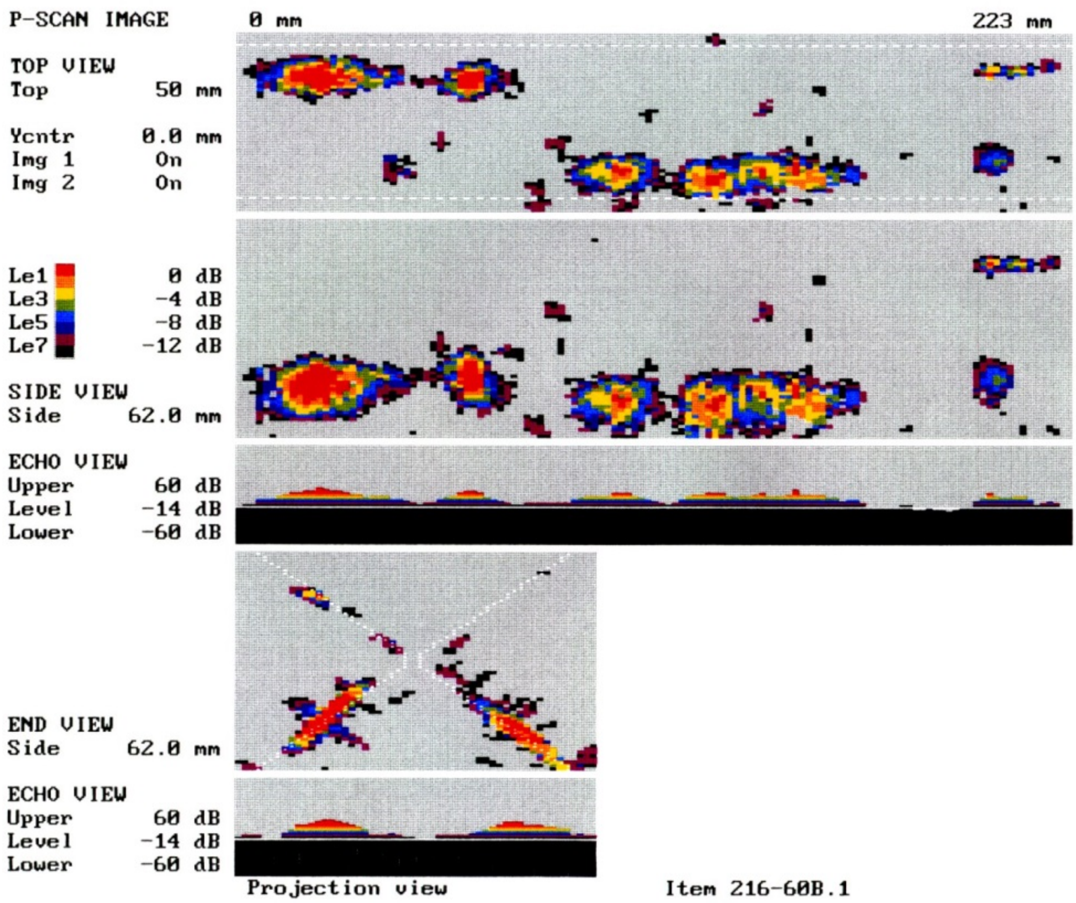


Figure 10.8 P scan image.

Scan image consisting of (from top to bottom):

- Top view – C scan.
- Side view - D scan.
- Echo view - A scan (cumulative).
- End view - B scan.
- Projection view – P scan.

10.7.1 A scan

The flaw detector or UT set sends ultrasound energy into test materials. Some of this energy returns to the set to be presented as information on a cathode ray tube (CRT) screen. This is an A scan display with the amplitude of signals displayed as a function of time or distance.

10.7.2 B scan

This gives an end or cross-sectional view of the component being examined, with the position of the probe displayed on one axis and the distance from the surface to the signal on the other (see Figure 10.7). The B scan is used in hospitals and on aircraft components. It is often used with specimens immersed in water and with an automated scanning device.

10.7.3 C scan

The C scan gives a plan view of a defect (see Figure 10.7). It is often used as an automated process to map out laminations in plate. It gives the area of a defect, so it is good for plotting the extent of laminations in metal sheets.

10.7.4 D scan

The D scan gives a side view of the defect seen from a viewpoint normal to the B scan (see Figure 10.7). It is usually automated and shows the length, depth and through thickness of a defect. The D scan should not be confused with the delta technique.

Section 11
Ultrasonic Flaw Detector

11 Ultrasonic Flaw Detector

11.1 Principles

The ultrasonic flaw detector, which is part of the UT set, sends a voltage down a coaxial cable (sometimes called the lead) to a probe. The piezo-electric crystal in the probe is hit by the voltage and vibrates. The vibration creates an ultrasonic pulse which enters the test material. The pulse travels through the material until it strikes a reflector and is reflected back to the probe.

It re-enters the probe, hits the crystal and vibrates it, causing it to generate a voltage. The voltage causes a current which travels back to the flaw detector along the cable. The set displays the time the pulse has taken through the test material and therefore the distance travelled back and the strength amplitude of the pulse as a signal on the CRT screen.

In essence, a UT set transmits energy into a material via a probe and measures the time in microseconds that the sound pulse takes to return to the probe. The controls on the UT set are almost entirely concerned with presenting a display on the CRT screen for the operator to interpret.

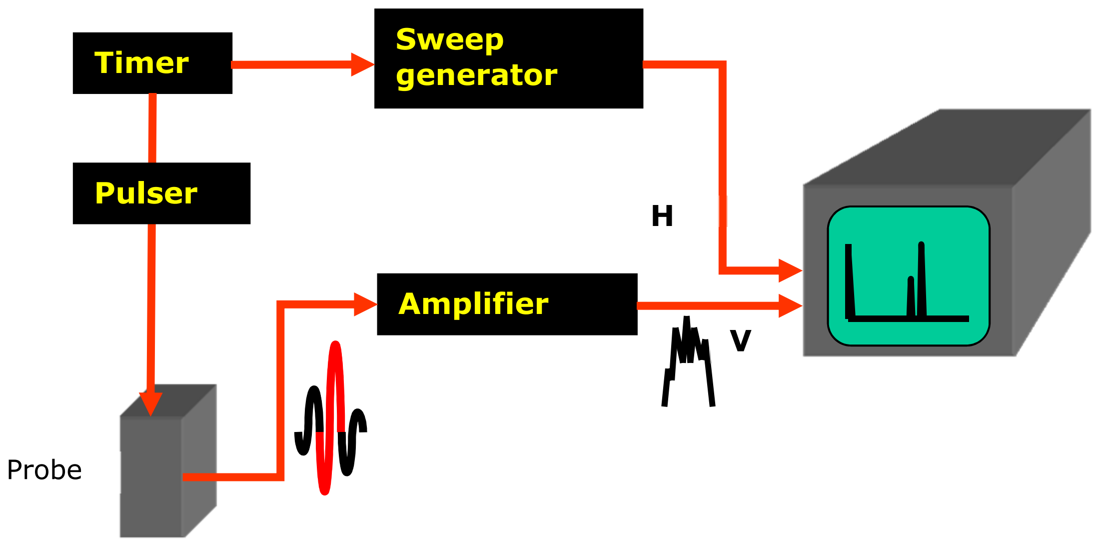


Figure 11.1 Block diagram of an ultrasonic flaw detector instrument.

11.2 Cathode ray tube

The cathode ray tube (CRT) is a device for measuring very small periods of time. The CRT displays electrical pulses on a screen in a linear time/distance relationship. This means that the longer the distance on the on-screen time base, the longer the time that has been measured.

How the CRT works

A filament is heated in a vacuum tube. The heat causes the particles of the filament to vibrate and electrons start 'boiling' out of the surface, a process known as thermionic emission.

A positive potential electric charge is positioned further down the vacuum tube and the negatively charged electrons from the filament are attracted towards it.

The electrons pass through a negatively charged focusing ring which pushes them towards the centre of the tube, forcing them into a fine stream. This stream of electrons hits a phosphor-covered screen at the end of the tube. The electron bombardment forces the phosphor to give out light and a green dot appears on the screen.

The X and Y plates above, below and beside the electron stream carry potentials that move the electron stream from side to side and up and down, moving the green dot on the screen.

The X plates control horizontal movement and the Y plates control vertical movement. By altering the potential of the X and Y plates, the dot can be moved on the screen.

11.3 Pulse generation

The pulse generator in a UT set is a timer which gives out a number of electrical pulses every second. This is called the pulse repetition rate or pulse repetition frequency (PRF) and must not be confused with probe frequency.

The PRF on most sets is about 1000 pulses/s, though this can be varied on most sets from 50 for thick specimens to 1250 pulses/s for thinner specimens.

The pulse generator sends the pulse to the time base generator on the CRT and to the pulse transmitter.

The time base generator sends the green dot moving across the CRT screen by generating a charge in the X plates in the tube.

Simultaneously the pulse transmitter sends an electric voltage down the coaxial cable to the piezo-electric crystal in the probe. The crystal vibrates, transmitting the pulse of sound into the test material.

At the end of each pulse, the green dot on the CRT screen flies back to the left-hand side of the screen to await the next pulse.

If the test material is thick, the dot must travel across the screen fairly slowly, as the pulse repetition rate is lowered. Only one pulse may be in the test material at any one time or confusing echoes will result. For this reason the PRF is lowered when thicker specimens are examined.

11.4 Range control

The range control varies the speed of the green dot across the screen. It is divided into the coarse range, which allows large changes in range (eg 10 to 100 to 500mm), and the fine range which allows small adjustments in distance between these. As mentioned above, the dot travels slowly for thick specimens, while for thin specimens its speed is increased. Adjusting the speed of the dot in relation to the time taken for the sound pulse to enter the test specimen and to be reflected back to the probe is called setting a time base.

If the speed of the dot across the screen is not even, as a result of equipment failure, we say the time base is not linear. Flaw detectors should be checked frequently to assess time base linearity.

11.5 Delay

The delay control makes the time base generator wait before sending the green dot moving across the screen.

Twin crystal and angle probes have Perspex blocks or wedges between the crystal and the test material. This need not be shown on the CRT screen, so we adjust the delay to move it sideways off the display, so the passage of the ultrasound through the Perspex in the probe does not appear on the screen.

You can also use the delay control to wait until the sound has travelled part of the way through the test piece itself before representation on the screen. For example, if you only want to look at the bottom 25mm of a 200mm specimen, you can adjust the delay so that the green dot begins to travel across the screen at 175mm. During thickness checks, this can make for more accurate readings for thicker specimens.

11.6 Calibrated gain/attenuator control

If the sound pulse sent into the test material is reflected back at the proper angle, it returns to the probe and hits the receiver crystal. The crystal sends a current back to the UT set. For technical reasons this current must be very small.

The current returning to the set goes to an amplifier which increases it and filters out irrelevant signals. The returning current is alternating (AC) and must therefore pass through the rectifier before going to the CRT.

The rectified current now goes to the attenuator, which uses a variable resistance to control the current passed on to the CRT. The greater the resistance, the smaller the current. This attenuator is controlled by the calibrated gain/attenuator control on the set.

From the attenuator, the current goes to the Y plates in the CRT. When the current hits the Y plates, they pull the electron stream upwards and the green dot jumps from the bottom of the screen to make a signal. The height of the signal is increased or decreased by turning the gain up or down.

This control is a method of controlling the amplitude of a signal. It is also a means of comparing the height of one signal with the height of another. So the UT set can tell us two things:

a The position of a reflector below the probe.
b The comparative amount of energy reflected from that reflector.

We can find the latter by comparing a signal from the reflector in the test piece with a signal from an artificial reflector in a reference block.

11.7 Reject/suppression control

When measuring high attenuating material, there is often a corresponding high level of grass (US: hash) on the time base. It is possible to reduce this to an acceptable level by means of the reject/suppression control and, providing the calibration is verified, accurate thickness measurements are possible. However, reject often makes the vertical axis non-linear so must NOT be used if readings related to the decibel are made.

11.8 The decibel

Gain is measured in decibel (dB) - tenths of a unit called a bel. When we compare the height of two signals on the CRT screen, we are in fact comparing the electric voltage that is being sent to the Y plates; electric voltage is proportional to the square of the current. To compare two signals, we must use a formula that takes account of this fact (see Section 1.4).

Section 12
Calibration and Sensitivity

12 Calibration and Sensitivity

Angle probes, initial checks and calibration

Before we can start to use an angle probe, we need to find out more about it. For instance:

a Where is the sound coming out of the Perspex shoe?
b Is it the angle that it is supposed to be?
c Has the angle changed since it was last used?

So we must check the probe before we can calibrate the time base for use. The following paragraphs also describe a number of other performance checks which should be carried out at specified intervals.

12.1 Finding the probe index

The point at which the centre of the beam leaves the probe and enters the test material is called the probe index or emission point. It should be marked on each side of the probe and checked regularly. As the probe surface wears down, the probe index can change. Stand-off measurements are taken from the probe index and used to check the probe angle (another check that the UT technician must perform regularly), so this is the master reference point or datum.

To find the probe index, place the probe on a Calibration Block No 1 (see BS EN ISO 2400 Ultrasonic Testing Specification for Calibration Block No 1), also referred to as a V1 Block, and obtain an echo from the 100mm radius and establish it at more than 50% FSH using the gain control. Maximise the echo by moving the probe backwards and forwards. Mark a line on each side of the probe directly above the slots which indicate the centre of the 100mm radius. This is the probe index, where the axis of the beam leaves the Perspex shoe.

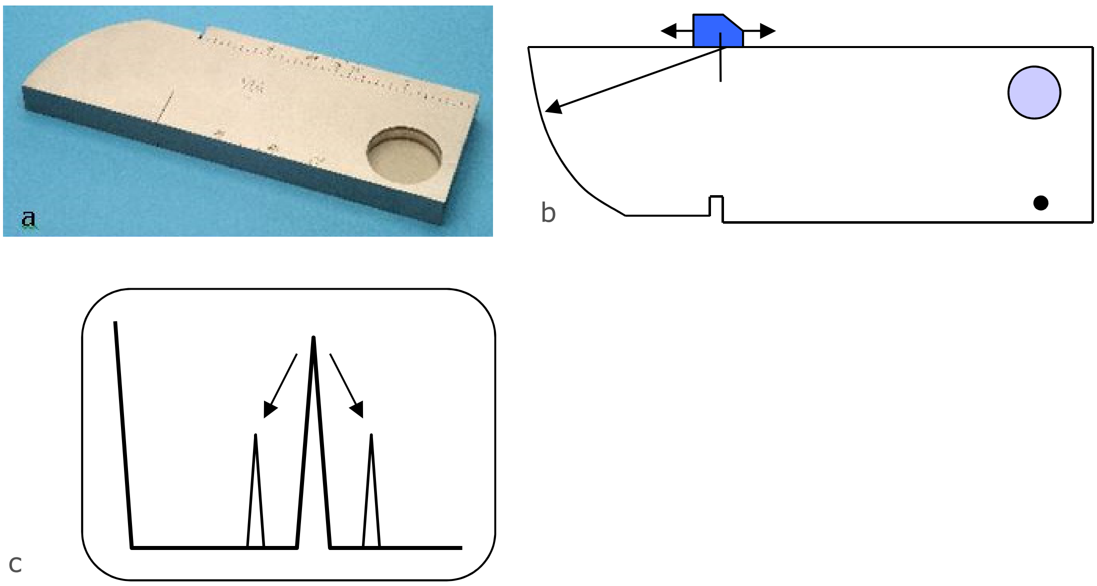


Figure 12.1 Determination of probe index:

a Calibration Block No 1;

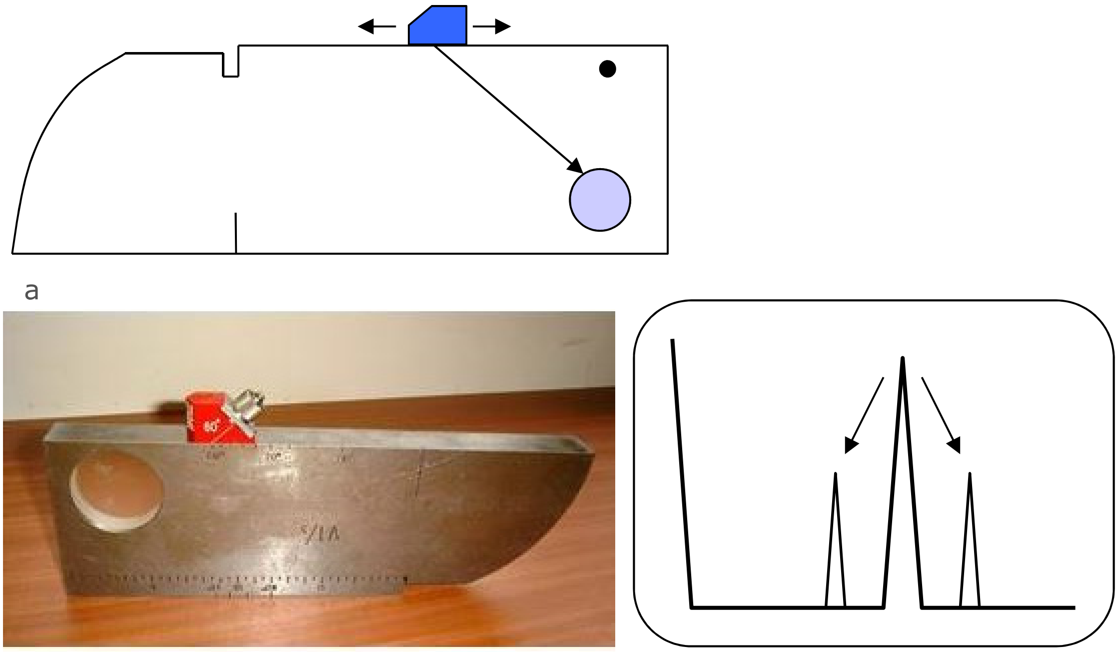
b Schematic drawing of Calibration Block No 1 with angle probe at 100mm radius;

c 'A' scan display.

12.2 Checking the probe angle

For a 45° or 60° probe, place it on the Calibration Block No 1, approximately adjacent to where the appropriate angle is inscribed, directed towards the plastic insert. Obtain a signal on the screen from the plastic insert and maximise it. Find the position where the probe index coincides with the angle indicated on the side of the No 1 Block and this will tell you the probe angle.

This procedure can be repeated for a 70° probe, but reflecting the energy from the plastic insert radius is unreliable. Therefore we suggest you use the 1.5mm hole as a target.



a

b

c

Figure 12.2 Determination of probe angle:
a and b Angle probe in position;
c 'A' scan display.

12.3 Calibration of shear waves for range

12.3.1 Calibration with the Calibration Block No 1 (V1 block)

By range in angle probe testing we mean the distance a reflector is from the probe index.

It is possible on some flaw detectors to calibrate the time base to 100mm range from the Calibration Block No 1. However, this involves delaying the signal by 100mm and not all equipment can do this on the appropriate scale expansion setting, so we will confine ourselves to calibrating for 200mm full screen width.

Place the probe on the Calibration Block No 1 and obtain a boundary echo from the 100mm radius. Establish this signal to more than 50%FSH using the gain control. Further maximise the echo by moving the probe backwards and forwards, then keep the probe stationary.

Wind in or out on the scale expansion/range control to establish a second boundary echo at 200mm range.

Place the signal from 100mm at 5 (half scale) on the time base and the one from 200mm at 10 (full scale), using the delay and range controls. The time base is calibrated for 200mm; longer ranges can be catered for in multiples of 100mm.

However, the Calibration Block No 1 is bulky and inconvenient for site work, so it is not always possible to calibrate for 100mm and we tend to use the Calibration Block No 2 (also referred to as the V2 Block).

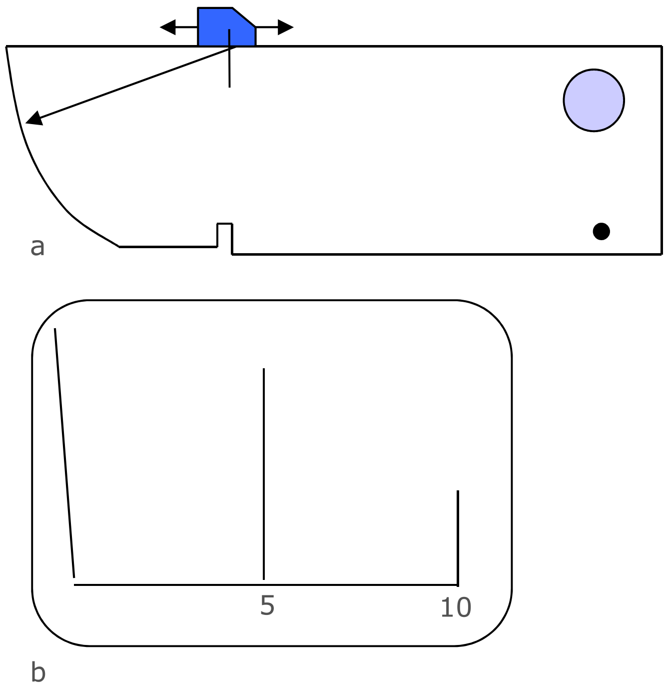


Figure 12.3: Calibration of the time base (range) of the flaw detector:
a Schematic drawing of shear wave probe positioned on Block No 2;
b 'A' scan display.

12.3.2 Calibration with the Calibration Block No 2 (V2 block)

The V2 Block (see BS EN ISO 7963 Non Destructive Testing: Ultrasonic Testing; Specification for Calibration Block No 2) is the most convenient calibration block to use with angle probes. It has two arcs, at 25 and at 50mm (see Figure 12.4).

12.3.3 Calibration for 100mm

Place the probe on the block and point it at the 25mm arc. Adjust the delay and range controls until you have two signals on the screen; the first will represent 25mm and the second will represent 100mm. Maximise the signals by sliding the probe forward and backward. Adjust range and delay until the first echo comes a quarter of the way across the screen at 2.5 and the second echo comes at the extreme edge of the screen on the right-hand side at 10.

The time base now represents 100mm. Check this by turning the probe around and pointing it at the 50mm arc. If you have calibrated correctly, the signal when maximised will come up exactly in the middle of the screen at 5.

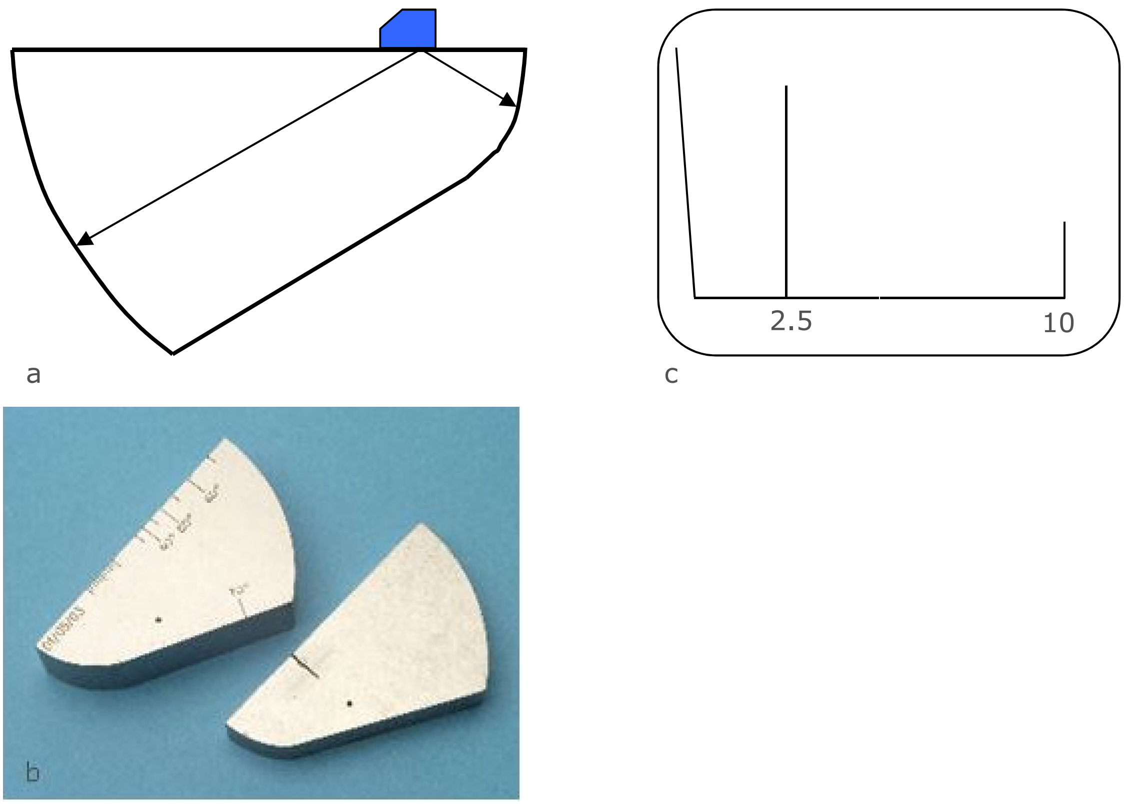


Figure 12.4 Calibrations using Block No 2:

a Schematic drawing of Block No 2 with angle probe, first reflection at 25mm and second at 100mm;

b Block No 2 with 25mm and 75mm arc (radius);

c 'A' scan display for probe in position as pictured in a.

12.3.4 Calibration for 200mm

Point the probe at the 50mm arc on the Block No 2 and obtain three echoes on the screen. These represent 50, 125 and 200mm. Maximise these signals by sliding the probe forward and backward. Adjust the range and delay until the first signal comes a quarter of the way across the screen at 2.5 and the third echo comes at the extreme edge of the screen at 10.

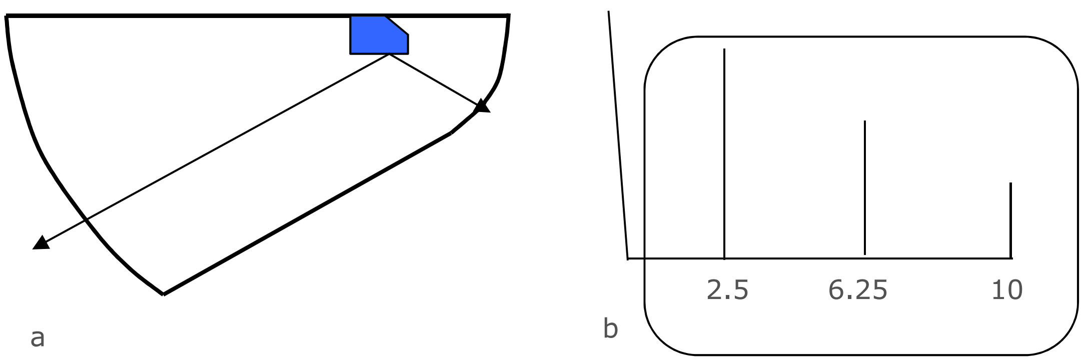


Figure 12.5 Block No 2 Calibration for 200mm range:

a Schematic drawing of Calibration Block No 2 with probe partitioned for the 50mm arc (radius);

b 'A' scan display with echoes at 2.5 (50mm), 6.25 (125mm) and 10 (200mm).

Calibration for 250mm

Point the probe at the 25mm radius arc on a Calibration Block No 2 (V2 Block) and adjust the set until you get four echoes. These represent 25, 100, 175 and 250mm. Maximise these signals by sliding the probe forward and backward. Adjust range and delay until the first echo comes one tenth of the way across the screen at 1 and the fourth echo comes at the extreme edge of screen at 10. Check on a Calibration Block No 1. On the 100mm arc you should get one echo 4/10 across the screen and the other 7/10 across the screen.

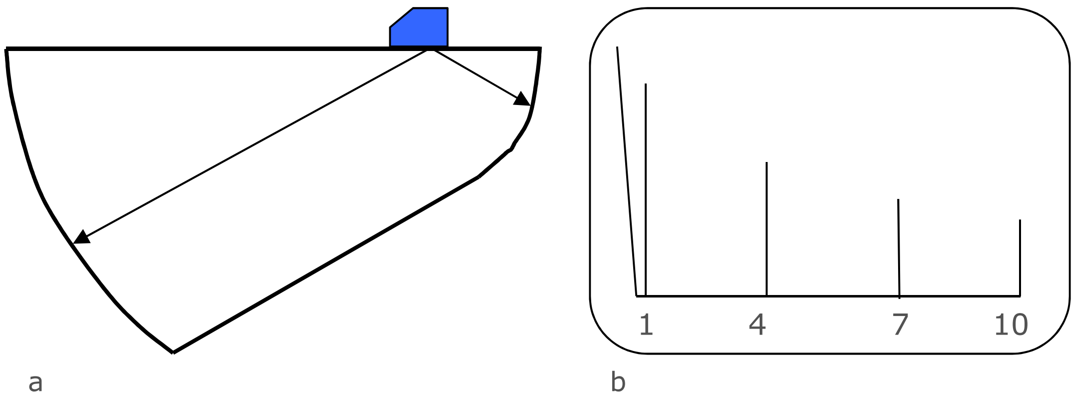


Figure 12.6 Block No 2 Calibration for 250mm range:

a Schematic drawing of Calibration Block No 2 with probe positioned for the 25mm arc (radius);

b 'A' scan display with echoes at 1 (25mm), 4 (100mm), 7 (175mm) and 10 (250mm).

Section 13
Flaw Location

13 Flaw Location

You can calculate the location of a flaw by using trigonometric formulas as shown below. You need to know the angle of the probe and the stand-off measured from the centre of a weld.

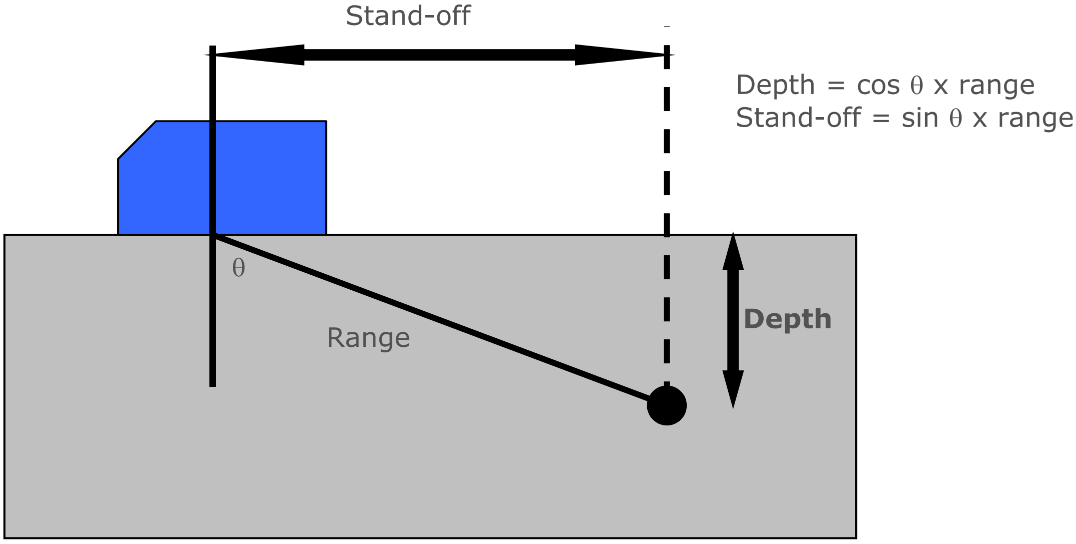


Figure 13.1 Reflector depth and probe stand-off as a function of probe angle.

A general rule of thumb used to calculate the depth of an indication from the range on the screen is:

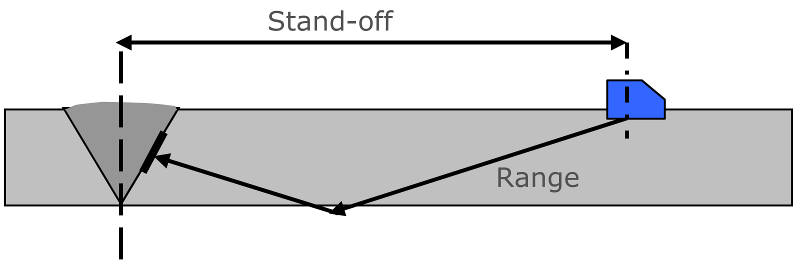
- 45° probe - range is approximately 1.5 x depth.
- 60° probe - range is exactly 2 x depth.
- 70° probe - range is approximately 3 x depth.

It is quicker and easier, however, to use a flaw location slide and a beam plot or even a piece of clear plastic film with the probe angle drawn on it (see Figure 13.2). Use the slide as follows:

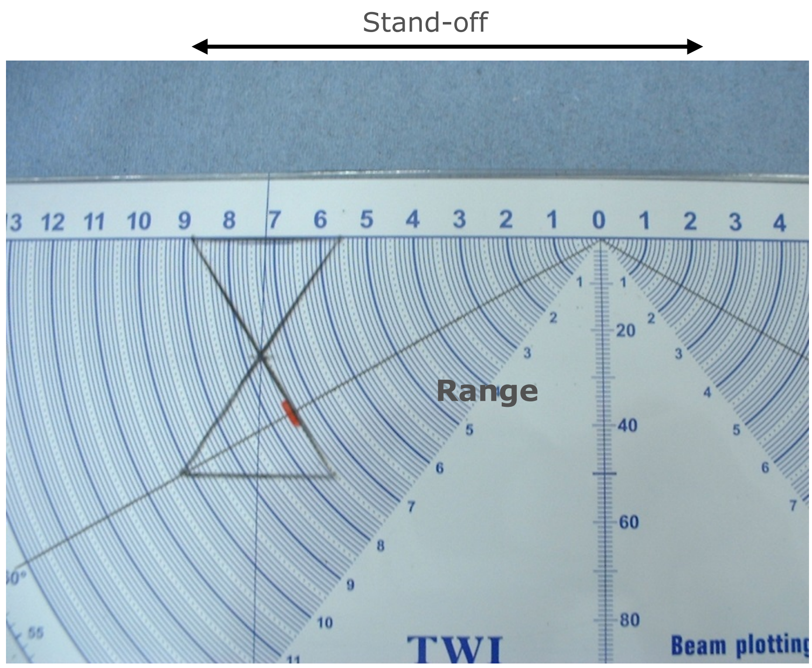
a Draw a cross section of the weld on the transparent outer envelope of the slide.
b Draw a mirror image of the weld cross section immediately under it if the sound energy is going to bounce off the backwall, ie using full skip.
c Use the printed datum line on the plastic envelope as the centre of the weld and measure all stand-offs from it.
d Maximise the echo from a defect and mark where the index point falls on the parent metal. Measure its distance from the centre of the weld.

Note: The defect on a sketch as well as the stand-off and range of the centre of the defect.

e Move the weld datum line on the plastic envelope to the stand-off distance.
f Look along the centre of the beam plot until you come to the range shown on the screen.
g Make a mark on the envelope; this represents the centre of the defect. It shows the position of the defect in the weld body.



a



b

Figure 13.2 Determination of flaw location using the flaw location slide:
a Probe position for 'full skip' into the weld for detection of side wall defect;
b Flaw location slide showing graduated range, stand-off and defect depth.

Section 14
Flaw Sizing

14 Flaw Sizing

14.1 The 6dB drop sizing method

This method is used for sizing large reflectors. If the probe is moved until the signal amplitude from a reflector drops to half its original screen height, then it can be said that the sound beam is half on and half off the reflector. So by moving the probe until the signal from the end of a large reflector halves in height, we can estimate that the edge of the reflector is immediately below the centre of the probe.

This method is called the 6dB drop sizing method because the amplitude of the signal drops by half, which corresponds to 6dB, when the probe is moved to the edge of a large reflector.

Note: The last peak on the screen before the probe goes off the end of the reflector is usually considered as the peak of the reflector, rather than the maximum signal from the reflector.

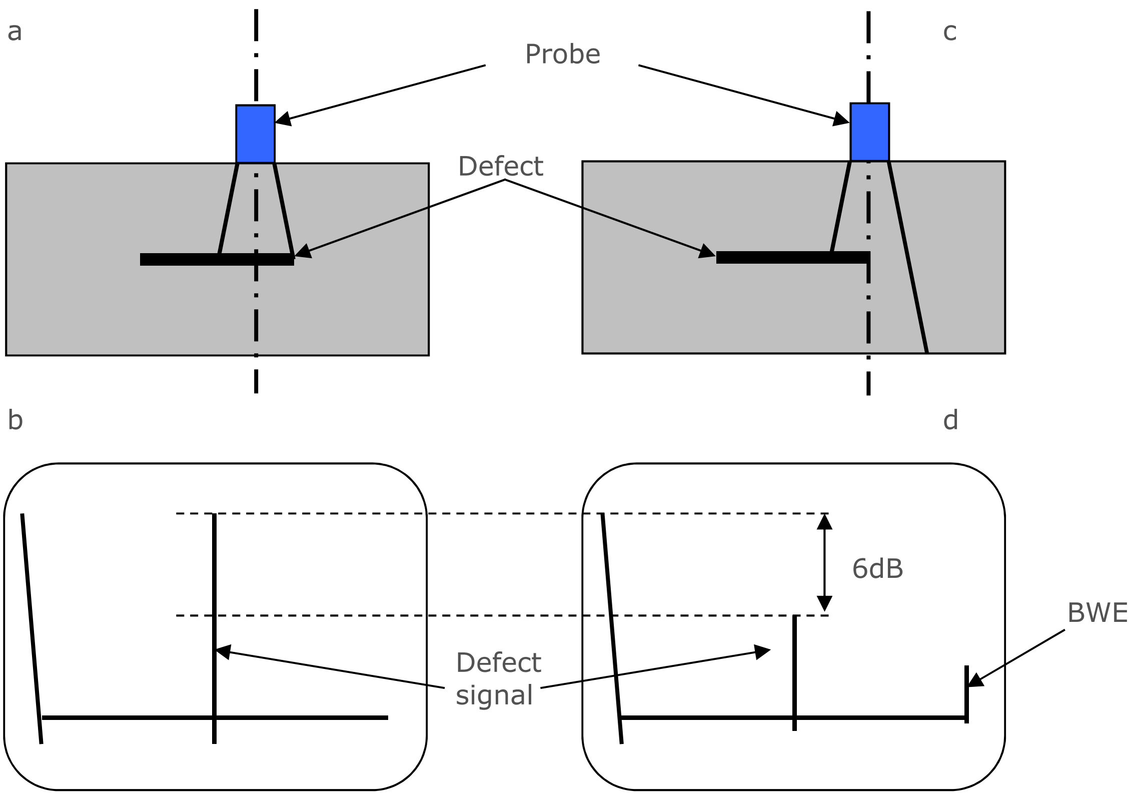


Figure 14.1: 6dB drop sizing:

a Maximum signal position of probe;

b 'A' scan response at maximum signed height;

c Probe position for signal at 50% of maximum response;

d 'A' scan response at 50% of maximum response, ie 6dB drop from maximum echo height.

14.2 The 20dB drop sizing method

We can use a beam plot to find the edge of a defect by using the edge of the sound beam.

If we know the width of a beam at a certain distance from the crystal, we can mark the distance across a defect from where the extreme edges of the beam touch each end of the defect and then subtract the beam width to get the defect size.

When the signal from the defect drops by 20dB from its peak, we judge that the edge of the beam is just touching the end through-thickness extremity of the defect. We can find the width of the sound beam at that range by consulting the beam plot we have made.

Note: The last peak on the screen before the probe goes off the end of the defect is usually considered as the peak of the defect, rather than the maximum signal from the defect.

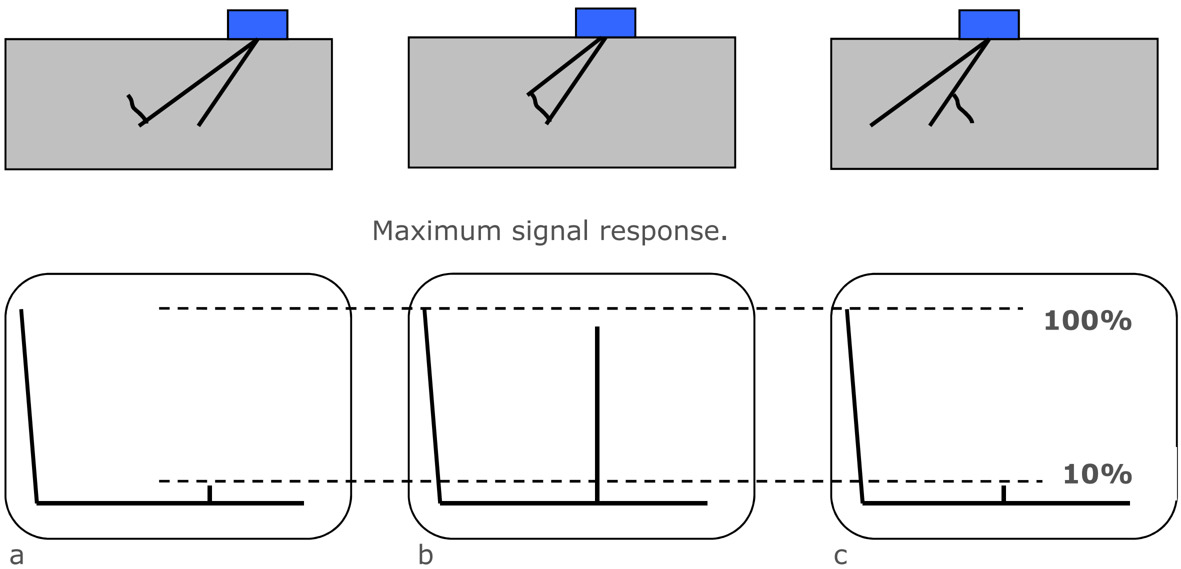
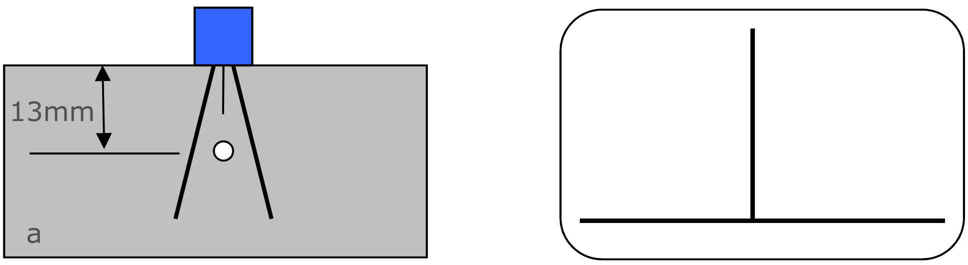


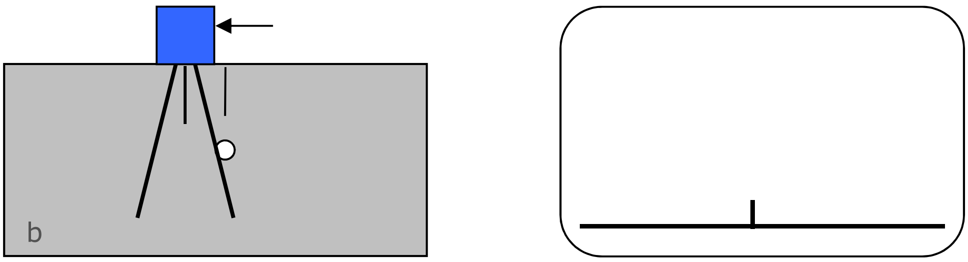
Figure 14.2 Probe and 'A' scan displays:
a Top edge of the ultrasonic beam detecting the bottom edge of the defect;
b Maximum signal response from the defect;
c Bottom edge of the ultrasonic beam detecting the top edge of the defect.

14.3 Construction of a beam edge plot - 20dB

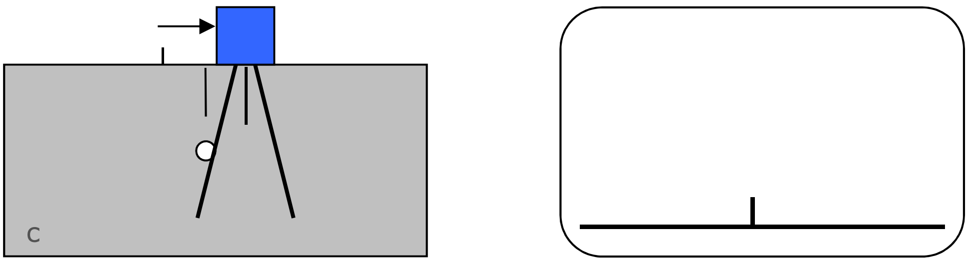
Find the hole at a depth of 13mm on an IOW block with a 0° probe and maximise the signal. Move the probe until you get the highest signal you can from the hole, then turn the signal to FSH using gain. Mark the position of the middle of the probe on the side of the block.



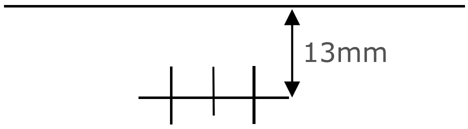
Move the probe to one side until the signal drops to 10% FSH (-20dB) and mark the centre of the probe on the side of the block.



Move the probe to the other side of the hole until the signal drops to 10% FSH (-20dB) and mark the centre of the probe on the block.

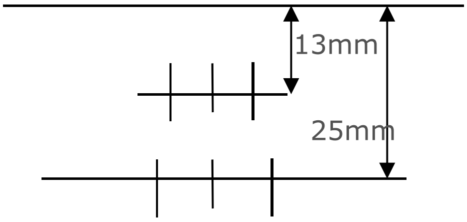


Use the distances between the marks on the block to plot the beam on a piece of graph paper. Measure 13mm depth on the paper then mark the distances of the probe centre at -20dB from the beam centre at 100% FSH on either side.



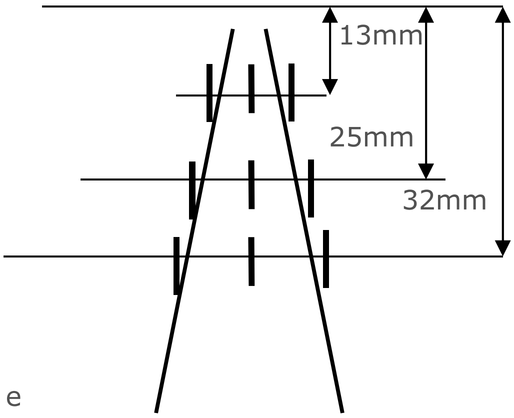
Now find the 25mm hole and maximise the signal, turning it to 100% FSH. Move the probe to either side of the hole, marking the centre of the probe on the side of the block where the signal drops by 20dB.

Measure 25mm on the paper and use the distances on the block to plot the beam dimensions at 25mm.



d

Repeat using the 32mm hole. Join up the points marking the probe centre at 20dB to obtain a beam plot.



e

Figure 14.3 Construction of the 20db beam plot:
a Maximum signal – centre beam;
b-e Determination of the 20dB ultrasonic beam edge.

Note: We have only drawn the beam width in one plane, so the probe must be marked accordingly and used to measure defects in this plane. We use knowledge of the beam spread to size defects, find their edges and hence their width, length and sometimes orientation.

14.4 Constructing an angle beam plot

An IOW reference block is convenient for constructing a beam plot. It has a number of 1.5mm side-drilled holes at different depths and is used mainly for setting sensitivity. Use a 20dB beam edge for 45° and 60° probes, but use a 10dB beam edge for 70° probes. With the 70° probe, a 20dB beam spread is so wide and difficult to construct that it is effectively useless.

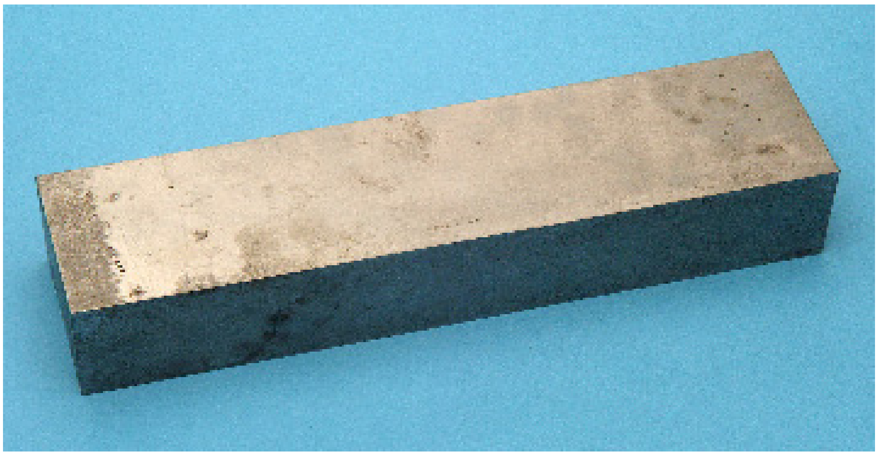


Figure 14.4 IOW reference block with 1.5mm side-drilled holes at different depths.

We will start with a 60° probe. Using the probe, find the hole which is 13mm below the top surface and maximise the signal to 100% FSH. Mark where the index point comes on the block with a pencil or crayon. Move the probe forward until the signal drops to one tenth screen height (20dB drop). Make a second mark on the block where the index point on the probe stands on the block.

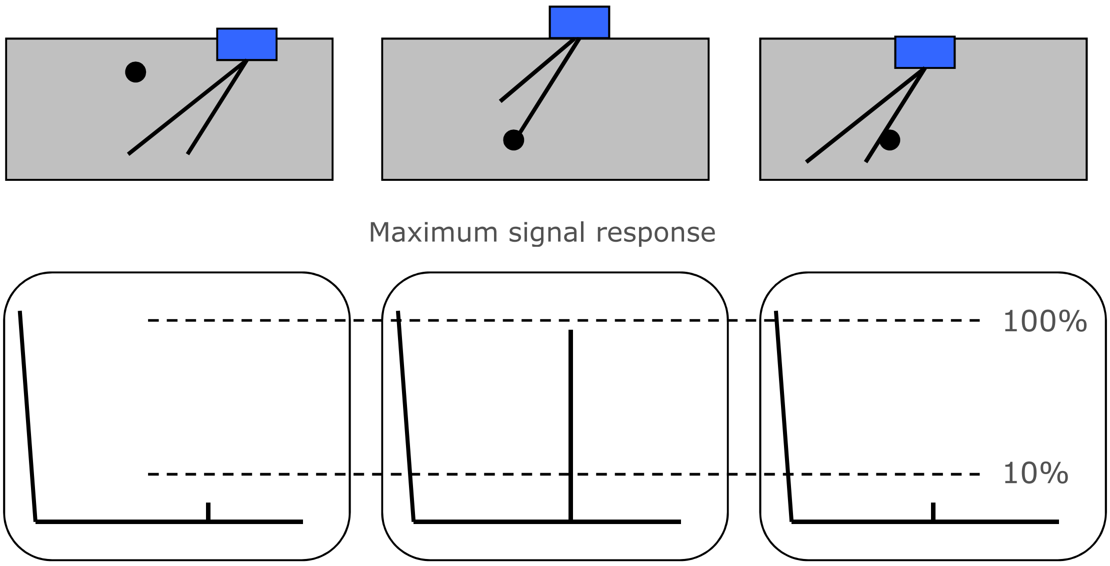


Figure 14.5 Angle beam plot construction.

Move the probe backwards until the signal maximises and then drops down to 1/10 screen height. Mark where the index point now stands and draw a vertical line on the block from the hole to the upper edge. Measure the distances of the three index point marks from the top of the line and note them down.

Now find an echo from the 19mm deep hole and repeat the process, noting the distances and repeat the process a third time using the 25mm hole.

Take the slide out of a beam plotting chart and draw three faint lines across it at depths of 13, 19 and 25mm.

Transfer the distances of the index points from the vertical lines to the relevant pencil lines on the chart. Join the marks up. The centre line represents the main energy of the beam and the other two marks represent the leading and trailing edges of the beam.

With a 45° probe, use the 19, 25 and 32mm depth holes as the 13mm hole may be in the probes near zone.

Use a 10dB drop with a 70° probe and instead of dropping the signal to 1/10 FSH for the leading and trailing edges, use the 3/10 line on the screen.

14.5 Proving the beam plot

Use the six side-drilled holes in the IOW block:

Use the corner of the block as a reference point from which to measure stand-offs.

On the cover of the beam plotting chart, use the corner of the block to represent the centre line.

Calibrate the probe to 100mm (200mm for a 70° probe).

Obtain a signal from the top hole of the six, maximise it, then push the probe towards the block corner until the signal drops to 1/10 FSH (3/10 for a 70° probe). Mark where the index point occurs on the block and measure the stand-off. Note the range of the reflector on the screen.

Use the stand-off and the range to plot the defect along the trailing edge of your beam spread. Mark it on the slide cover.

Now obtain a signal from the bottom hole of the six, maximise it and turn it up to FSH on your screen. Pull the probe back until the signal drops to 1/10 FSH (3/10 for a 70° probe). Plot the bottom of the defect on your slide cover using the leading edge of your beam plot.

Lay the transparent slide over the IOW block; the top and bottom of the drilled holes should coincide with the marks on the slide. If they do not, your beam plot is off or you are going wrong somewhere. If they do, you have just sized a defect by the 20dB drop method (10dB drop for the 70° probe).

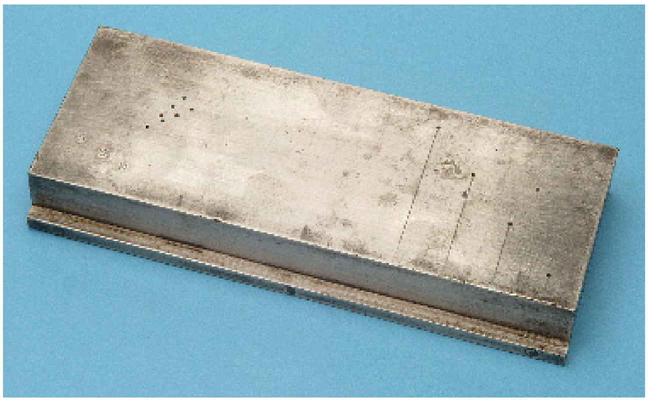


Figure 14.6 Example of bespoke reference block to check beam characteristics including beam edge resolution and near-zone approximation.

14.6 Modified near zone angle probes

We must now consider the part of the beam which is in the near zone on an angle shear wave probe because with a beam edge method of flaw sizing, we cannot assess small defects in the near zone.

However, the beam starts to travel in the plastic wedge and is then refracted and carries on in the material being tested. We are only concerned with the part of the beam near zone registering later than zero on the time base, ie in the test material. This is called the modified near zone.

Here is an example:

A 5MHz shear probe has a 10mm diameter crystal. The beam travels in Perspex for 10mm. What is the modified near zone?

NZ, if totally developed in steel $= \dfrac{D^2 f}{4V}$

$$= \frac{10^2 \text{ x } 5 \text{ x } 1{,}000{,}000}{4 \text{ x } 3250 \text{ x } 1000} \text{ mm} = 38.46\text{mm}$$

We must now subtract the Perspex wedge part of the beam which is 10mm, multiplied by the ratio of the Perspex and steel velocities which is
10 x 2730/3250 = 8.4mm

Therefore: modified near zone = 38.46 - 8.4 = 30mm.

14.7 Horizontal beam plot

A number of methods can be used to find the -20dB edge of a beam in the horizontal plane. Some use the ends of the side-drilled holes in the IOW block to determine the edge. However, we prefer to use the 1.5mm through-drilled hole in the IOW calibration block.

Method:

a Place the probe to pick up the 1.5mm hole at ½ skip and maximise the signal from the intersection of the hole and the opposite face. Mark the straight edge adjacent to the near centre of the probe to indicate the beam centre.

b Position a straight edge either in front of or behind the probe to hold the probe in the fixed transverse position. Scan the probe laterally (sideways) until the hole signal drops by 20dB. Mark on the straight edge adjacent to the rear centre position of the probe. This registers half a beam at the ½ skip range.

c Scan the probe laterally the other way, through the maximum signal position, until the hole signal again drops by 20dB. Mark the straight edge as before.

d You now have three marks on the straight edge to indicate the beam width at that range. Transfer these to the beam plotting chart as appropriate.

e Repeat steps a-d, but at full skip and 1½ skip for a 45° probe (only at full skip for a 60° probe). Note that mode conversion reduces the 1½ skip signal on a 60° probe to too low a level to be reliable.

f Join up the three points on either side of the centre line to complete the beam. Only take the lines back to the near zone because the edge is not reliable beyond that.

Section 15
Sensitivity Setting

15 Sensitivity Setting

Setting a sensitivity level is essential to providing reproducible results when the same inspection is carried out by different operators, using different probe set combinations and maybe working in different locations. They must all see the same flaw giving the same signal height and therefore have the same data on which to base their accept/reject decisions.

There are several systems for setting sensitivity. We have already encountered the method of setting the first backwall echo (BWE) to FSH for lamination checks. However, when checking plates adjacent to a weld, the second BWE should be set to FSH.

When setting the sensitivity, we must be sure that a signal from a defect will be visible on the CRT screen and that we will be able to distinguish the defect signal from background noise or grass. All UT sets differ slightly, so we cannot say, 'Set the sensitivity to xdB', as different probes and equipment will give entirely different signals from the same reflector. The methods of setting sensitivity have evolved to attain some uniformity.

Different methods are used in different places. At TWI, the IOW block is used as the recommended method for PCN examinations. On North Sea contracts, either the distance amplitude correction (DAC) curve or the American Society of Mechanical Engineering (ASME) curve is used. The DAC method is recommended in BS EN ISO 17640 (Non-destructive testing of welds – ultrasonic testing techniques, testing levels and assessment), while in Germany the distance gain size (DGS) system is usually applied, especially when evaluating small reflectors.

The purpose of sensitivity setting is to find a gain level sufficient to find a flaw and depends on the:

a Probe used, in particular its frequency.
b Flaw detector.
c Properties of the test material.
d Ratio of noise to BWE or flaw echo.

15.1 The Institute of Welding (IOW) block

We met the Institute of Welding block when studying beam profiles. The block contains 1.5mm side-drilled holes at different depths and allows the holes to be detected from different angles with angle probes. To use it is simple and straightforward.

Find a hole on the block that approximately coincides with the thickness of the material you are testing. Double the thickness if you are examining at full skip, ie bouncing your sound beam off the backwall.

Obtain a signal from the hole and turn the gain control until the signal is at FSH.

Work out the transfer correction.

You have now set the sensitivity and can be assured that flaws having the equivalent reflectivity of 1.5mm side-drilled holes will appear on the screen.

This method has several advantages:

- Simple to use.
- Provides a uniform system of reference.
- A fairly large and visible echo is assured from small flaws.
- Side-drilled hole reflectors are independent of angle.

But also some disadvantages:

- Block is heavy and expensive.
- Only applies to 1.5mm side-drilled holes.
- Not a reliable method for sizing defects.
- Sensitivity will be higher for ranges shorter than the SDH used.

Figure 15.1 The IOW reference block containing a series of 1.5mm SDH at different depths. A 60° angle probe is shown in position on the block.

15.2 Distance amplitude correction (DAC) curves

BS EN ISO 17640 and all US specifications recommend this method. A special reference block of the same material as the test object is usually necessary, though the curves can be constructed from an IOW block.

The type of block recommended by BS EN ISO 17640, which is an ASME block, is shown below.

Figure 15.2 Distance amplitude correction (DAC) reference block.

The procedure described in BS EN ISO 17640 for constructing a DAC curve is:

- Calibrate the time base for the maximum sound path length to be used.
- Adjust the gain so that the amplitude from the series of reflectors falls between 20 and 80% FSH.
- Without altering the gain setting, maximise the amplitude of each reflector in turn and mark the tip of the signal, either on the screen or on a transparent overlay.
- Record the gain setting used for plotting the DAC curve and reference this to some other reflector, such as the radius in a V calibration block. This action enables the gain to be reset without the reference block.

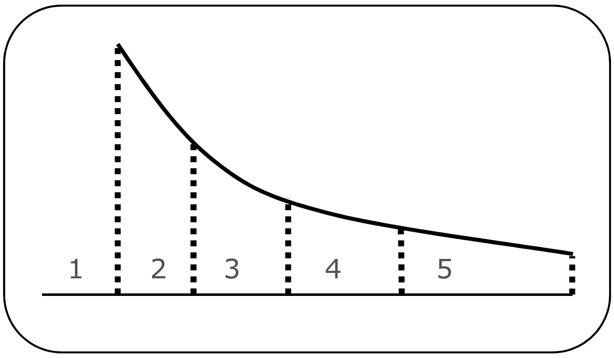


Figure 15.3 DAC construction from a series of reflector SDHs to cover the thickness range of the test component.

Note: Should the difference in height between the largest and the smallest echoes exceed the range of 20-80%FSH, the line shall be split and separate curves plotted at different gain settings. The difference in gain between the two curves shall be noted.

Examine the test material as instructed in the specifications, comparing the signals from discontinuities to the curves on your screen. Any signal above the curve shows a reflector larger than the reference hole. Accept or reject discontinuities as instructed in the specification you are working to.

Advantages

- A quick way of accepting or rejecting discontinuities without too much time consumed in sizing reflectors.
- Some idea can be gained of the size of the discontinuities in relation to the reference holes.
- Uniformity provided by all technicians constructing their curves from the same test block.

Disadvantages

- Curves must be constructed for each probe in conjunction with each UT set.
- Transfer correction must be worked out.

15.3 Flat-bottomed holes (FBH)

Blocks are drilled with flat-bottomed holes to precise diameters at set distances from the top of the block. These diameters and distances are stamped on the side of the block.

When setting sensitivities, the specification or technique will specify the block to be used and the amplitude of the signal to be obtained from the FBH.

Blocks are cut for use with 0° probes or angle probes in different materials. This method is mostly used in aerospace applications.

Advantages

- Easy to use.
- Uniformity assured when different technicians use the same blocks.
- Blocks can be made from different materials.

Disadvantages

- Fairly rigid system for specific applications.
- Large number of blocks needed for different settings.
- Transfer correction usually needed.
- Blocks for angle probes are rarely cut exactly normal to the beam.

You may hear these blocks called HITT or ALCOA blocks, after the originators.

15.4 Using noise

Work out the maximum range at which you will be examining the test material. Place the probe on the material with couplant applied. Turn up the gain until you have 2mm grass on the screen at the maximum range. You will now have the assurance of knowing that any discontinuity larger than the grain size will show up on the screen.

Advantages

- Quick and easy.
- No reference block is needed.
- Any defect larger than the material grains will show up.
- No transfer correction needed.

Disadvantages

- No accurate sizing of the defect.
- Discontinuities near the surface of the test material may be hidden in the grass.

15.5 Transfer correction

Reference blocks usually have smooth machined surfaces, while test objects frequently have rougher, more uneven surfaces. Also the attenuation of sound in the reference block might be different to that in the test material. Usually, the attenuation in the reference block is smaller than that of test material, but not always. This means that allowances must be made for the differences in sound energy transfer between probe and test material and probe and reference block. More energy can be passed into a reference block than into a rougher surfaced component.

Therefore, the artificial defects in a reference block may give higher amplitude signals (anything up to 6dB or even more) than signals from similarly sized discontinuities in the test materials.

Allowances have to be made for this and corrections made for different surfaces. This allowance is named transfer correction or transfer loss.

There are several methods of determining the transfer correction, some requiring the construction of separate DAC curves and some requiring calculation according to formulae. Two simple methods are explained below.

15.5.1 Compression probe method

Place the probe on the reference block and turn the BWE up to FSH. Note the gain settings. Now place the probe on the test material and at a similar range bring the BWE to FSH. Again note the gain setting. The difference between them is the transfer correction.

15.5.2 Angle probe method

As you cannot get a BWE with angle probes from a plate or pipe wall, you have to use two probes with the same angle.

Place the two probes opposite each other on the reference block with one probe transmitting and the other receiving, so that the sound energy is bounced off the backwall and caught by the receiving probe (pitch and catch).

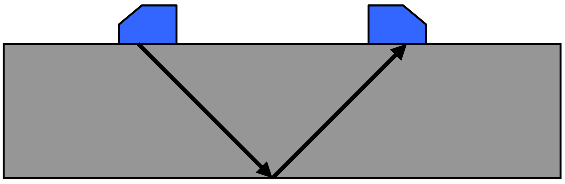


Figure 15.4 Schematic drawing of the transfer correction method for angle probes.

Maximise the signal and adjust the gain until it is at FSH.

Place the two probes on a piece of test material of the same thickness as the reference block and repeat the process.

Note the difference between the two gain settings. This is the transfer correction needed.

Other methods of transfer correction are described in EN 17640 and in literature concerning the distance gain size (DGS) system.

15.6 The distance gain size (DGS) method

The DGS system relies on the laws of large and small reflectors in the far zone and was developed to relate the amplitude of a signal to various sizes of perfect disc reflectors (flat-bottomed holes), so it does not actually size flaws but relates them to an equivalent reflector. The relative heights of signals from different sizes of flat-bottomed holes at different distances were plotted as curves.

Reflector sizes are expressed in terms of the probe diameter and distances from the probe are expressed as multiples of the near zone.

If you have a signal from a flaw at a certain depth, you can compare the signal size to what the signal of a BWE should be at that depth and estimate the size of a flat-bottomed hole that would give such a signal at that depth. The defect can then be sized according to its flat-bottomed hole equivalent.

The attenuation factor for the test material must be taken into consideration when using the DGS system.

Example

You are using a 5MHz 10mm diameter compression probe on a 100mm steel plate and you find a defect at 60mm depth which gives a signal at FSH with a 30dB gain setting. What is its flat-bottomed hole equivalent?

First, work out the probe near zone. It is 21mm, so the defect is at a distance of three near zones.

Now get a BWE and find what the dB reading is. Say it is 20dB when the BWE is at FSH. 100mm is five near zones. What will it be at 60mm – three near zones? Refer to the DGS curves. If the BWE is at FSH with 20dB at 100mm, by the law of large reflectors and according to the BWE line on the DGS curves, a BWE at 60mm should reach FSH at 16dB - 4dB less than at 100mm.

The signal height from the flaw is 30dB, which is 14dB more than the BWE. Look down the scale 14dB at three near zones from the BWE and you find that the nearest line is at 0.5 of the probe diameter. The probe diameter is 10mm so the nearest equivalent flat bottomed hole to the flaw had a diameter of 5mm.

By a similar process, a sensitivity setting can be worked out for a flat-bottomed hole of a certain diameter at a given range to a given screen height and the flaw detector gain set accordingly.

Advantages

- Can choose a gain level for sizing.
- Tells you the smallest defect you can find at a given range.
- Provides the basis for an accept/reject system.
- Gives a rough equivalent to the size of a flaw.
- Uniformity between results from different technicians.

Disadvantages

- Operators must keep referring to a chart and making calculations.
- Attenuation must be taken into account.
- No account is taken of the flaw orientation.
- Most effective on small defects.
- An equivalence system, not a sizing system.
- Flaw surfaces and shapes are not ideal reflectors; therefore, the signal amplitudes are not the same as those of a comparable flat-bottomed hole.

For angle probes, plastic slides have been manufactured by Krautkramer to fit over the CRT screen. The set is calibrated and gain setting is performed by bringing the BWE or the echo from the 1.5mm hole on the V2 block up to marks on the slide. Flat-bottomed hole equivalents for flaws can then be read straight off the slide. The DGS system is widely used in Germany.

15.7 Signal-to-noise ratio (SNR)

It has been mentioned elsewhere that frequency and wavelength have a major influence on flaw detection. However, the detection of a defect is also influenced by many other factors. The amount of sound that reflects from a defect is, for example, dependent on the acoustic impedance mismatch between the flaw and the surrounding material. A gas-filled defect such as a lack of fusion is generally a better reflector than a metallic inclusion because the difference in acoustic impedance is greater between air and metal than between a metal and another metal.

The nature of the surrounding material also greatly affects the detection of defects with coarse-grain structures, reducing defect detectability. A measure of detectability of a flaw and the effect of the many factors involved is its signal-to-noise ratio (SNR). The SNR is a measure of how the signal from the defect compares to other background reflections (categorised as noise). An SNR of 3-1 is often required as a minimum.

The absolute noise level and the absolute strength of an echo from a small defect depend on a number of factors:

- Probe size and focal properties.
- Probe frequency, bandwidth and efficiency.
- Inspection path and distance (water and/or solid).
- Interface (surface curvature and roughness).
- Flaw location with respect to the incident beam.
- Inherent noisiness of the metal microstructure.
- Inherent reflectivity of the flaw, which is dependent on its acoustic impedance, size, shape and orientation.
- Cracks and volumetric defects can reflect ultrasonic waves quite differently. Many cracks are invisible from one direction and strong reflectors from another.
- Multi-faceted flaws will tend to scatter sound away from the transducer.

General factors to consider with respect to SNR and therefore defect detection:

- Increases with increasing flaw size (scattering amplitude). The detectability of a defect is directly proportional to its size.
- Increases with a more focused beam. In other words, flaw detectability is inversely proportional to the transducer beam width.
- Increases with decreasing pulse width. In other words, flaw detectability is inversely proportional to the duration of the pulse produced by an ultrasonic transducer. The shorter the pulse (often higher frequency), the better the detection of the defect. Shorter pulses correspond to broader bandwidth frequency response.
- Decreases in materials with high density and/or a high ultrasonic velocity. The SNR is inversely proportional to material density and acoustic velocity.
- Generally increases with frequency.

Section 16
Ultrasonic Equipment Checks

16 Ultrasonic Equipment Checks

16.1 Linearity of time base

General

This check may be carried out using a standard calibration block, eg Block 1 (see BS EN ISO 2400), and a compression wave probe. The linearity should be checked over a range at least equal to that which is to be used in subsequent testing.

Method

a Place the probe on the 25mm thickness of Calibration Block 1 and adjust the controls to display ten BWEs.
b Adjust the controls so that the first and last BWEs coincide with the scale marks at 1 and 10.
c Increase the gain to bring successive backwall echoes to 80% FSH. The leading edge of each echo should line up with the appropriate graticule line.
d Record any deviations at approximately half screen height. Deviations should be expressed as a percentage of the range between the first and last echoes displayed (ie 225mm).

Tolerance

Unless otherwise specified by the testing standard, a tolerance of ±2% is considered acceptable.

Frequency of checking

This check shall be carried out at least once per week.

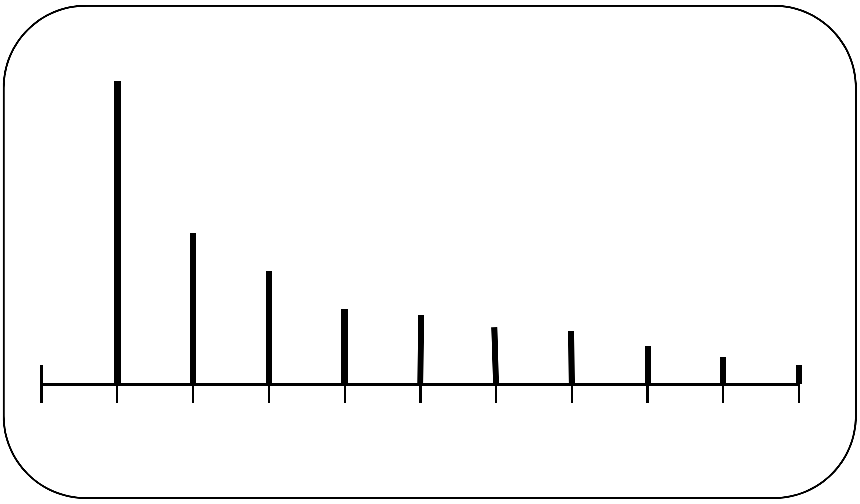


Figure 16.1 'A' scan flaw detector showing signal amplitude vs distance (transit time) for linearity of time base checks.

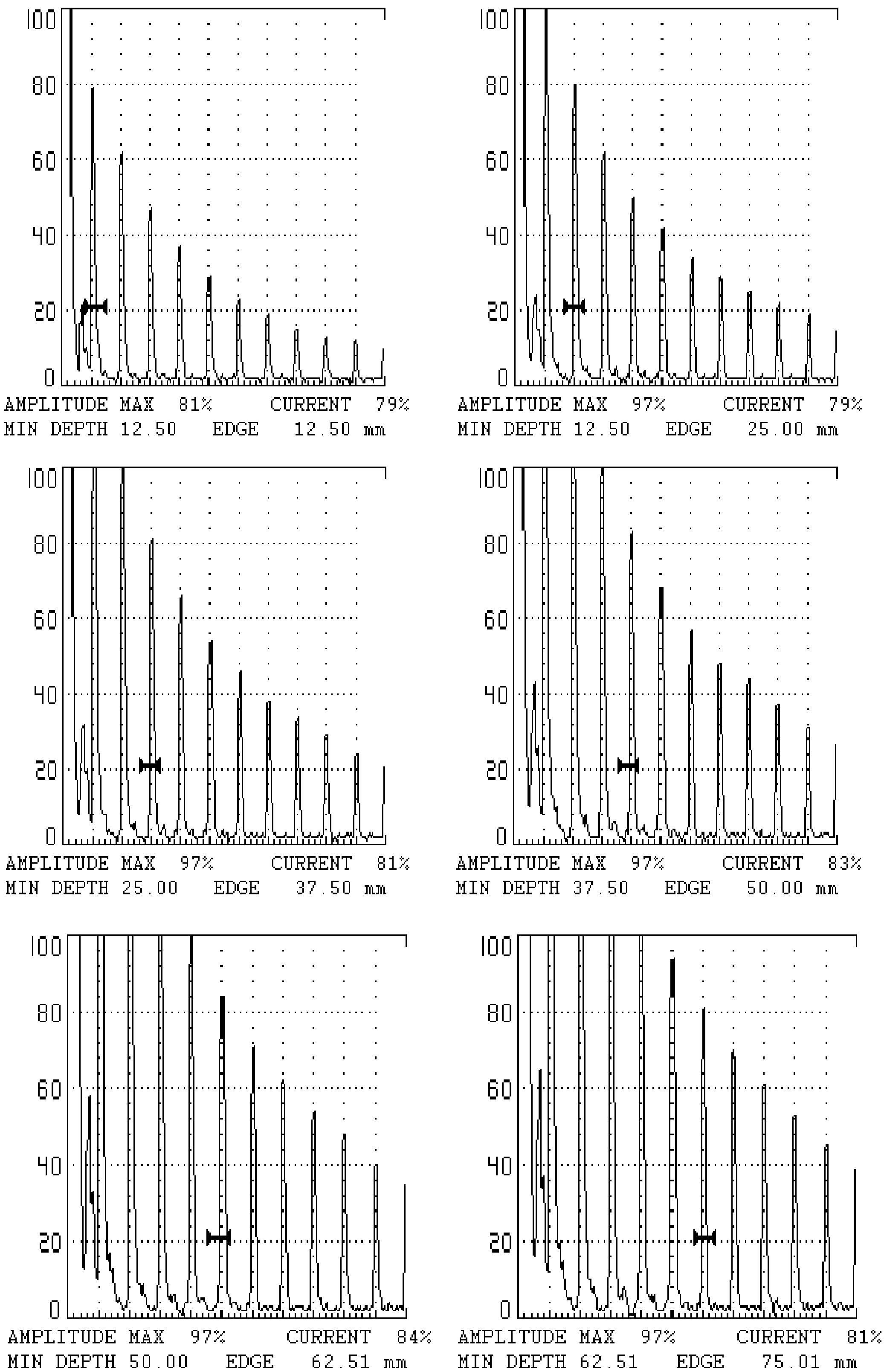


Figure 16.2 'A' scan (echo amplitude at approximately 80% vs depth distance) presentations.

16.2 Linearity of equipment gain

General

This is a check on both the linearity of the amplifier within the set and the calibrated gain control. It can be carried out on any calibration block containing a side-drilled hole; the probe should be the same that is used in subsequent testing. Reject/suppression controls shall be switched off.

Method

- Position the probe on a calibration block to obtain a reflected signal from a small reflector, eg the 1.5mm hole in Calibration Block No 1.
- Adjust the gain to set this signal to 80% FSH and note the gain setting (dB).
  - Increase the gain by 2dB and record the amplitude of the signal.
  - Remove the 2dB again and return the signal to 80% FSH.
  - Reduce the gain by 6dB and record the signal amplitude.
  - Reduce the gain by a further 12dB (18 in total) and record the signal amplitude.
  - Reduce the gain by a further 6dB (24 in total) and record the signal amplitude.

Tolerance

Table 16.1 Expected screen height results and limits for equipment gain check.

Gain, dB	Expected screen height (%)	Recorded amplitude	Limits
+2	101		No less than 95%
0	80		(Reference line)
-6	40		37-43%
-12	20		17-23%
-18	10		8-12%
-24	5		Visible, below 8%

Frequency of checking

The check shall be carried out at least once per week.

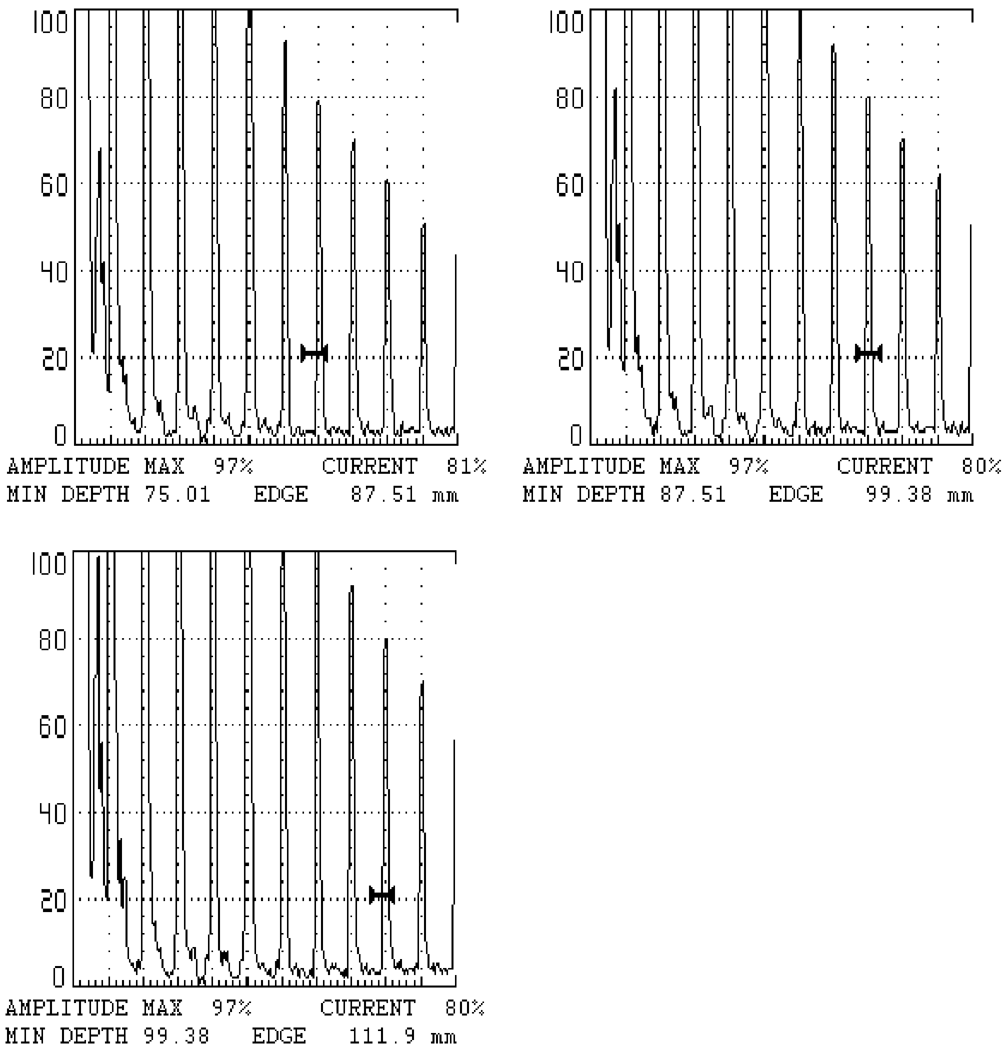


Figure 16.3 'A' scan presentations showing respective echoes set at 80% FSH.

16.3 Probe index and beam alignment

16.3.1 Index point

General

The probe index only needs to be checked in shear wave angle probes, but for them it should be the first probe characteristic to be checked. The standard Calibration Block No 1 may be used for this purpose.

Method

a Position the probe on the appropriate side of the block to obtain a reflection from the quadrant.

b Move the probe backwards and forwards to maximise the amplitude of the reflected signal.

c When the signal is at maximum, the probe index will correspond to the engraved line on the block. Mark this position on the side of the probe.

Tolerance

The tolerance depends on the application, but for plotting of defects it is recommended that the probe index be accurate to within ±1mm.

Frequency of checking

When a probe is in continuous use, it is recommended that the check be carried out every few hours; otherwise, a daily check is recommended.

16.3.2 Beam alignment (squint)

With the probe still in position, a check of the beam alignment can be performed. If the probe beam is correctly aligned, the edge of the probe will be parallel to the edge of the block. If this is not the case, measure the squint angle between the two edges.

The tolerance depends upon the accuracy of defect plotting required.

This check should be carried out once per week.

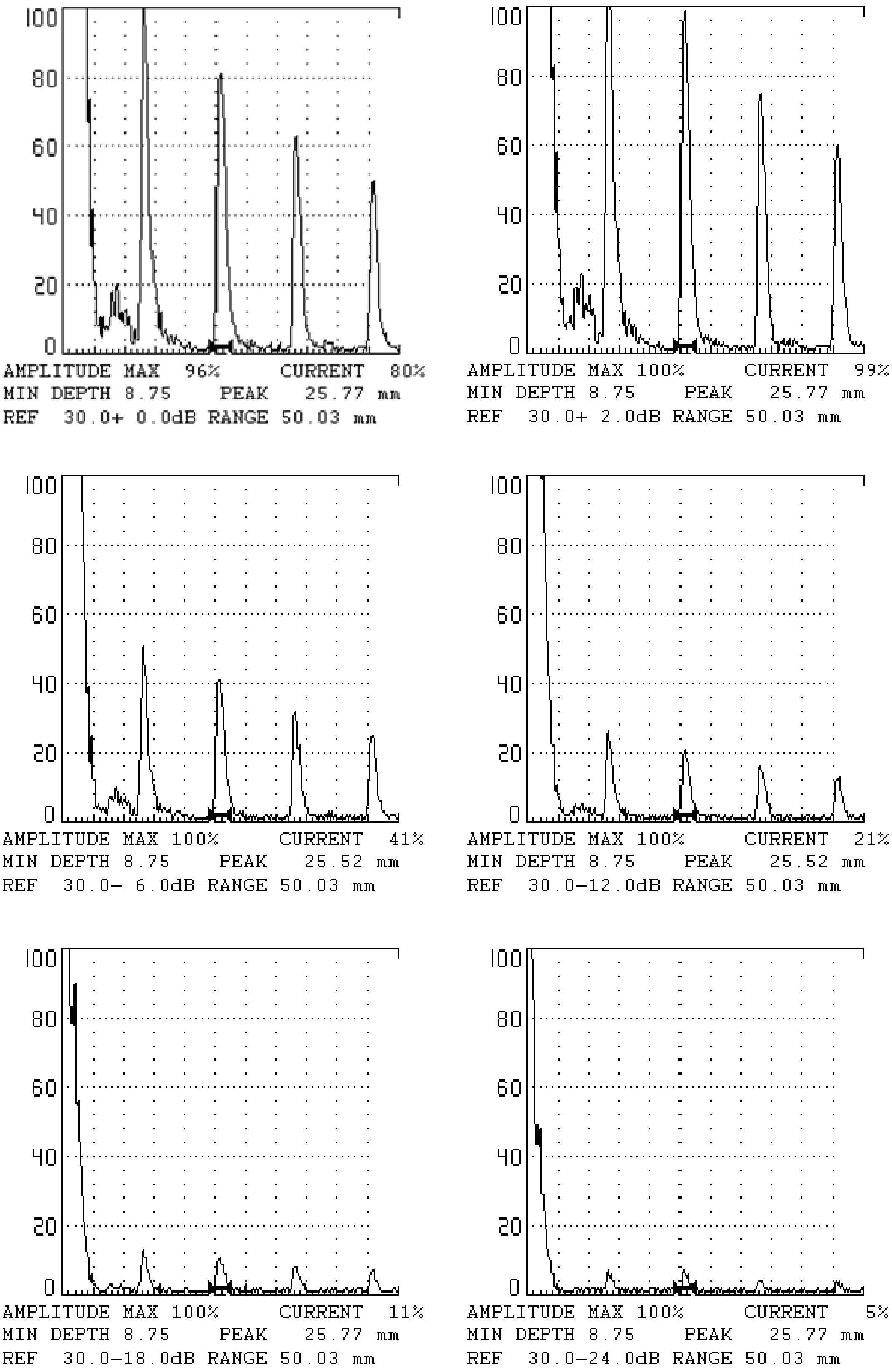


Figure 16.4 Amplifier and gain control checks at 0db to 24db.

16.4 Beam angle

General

The beam angle can be checked on several calibration blocks, eg Calibration Block No 1 (BS EN ISO 2400) or Beam Calibration Block (BCB, A5 Block). The beam angle check shall preferably be made on a probe in conjunction with the flaw detector to be used in subsequent testing.

Method

a Place the probe in such a position as to receive a reflected signal from the selected transverse hole in the calibration block (eg the 19mm deep hole in the BCB).
b Maximise the signal from the hole and mark the index point of the probe on the block.
c Measure the distance from the marked point on the block to the edge of the block. Knowing the position of the drilled hole will allow the beam angle to be calculated (see below).

Note If only a rapid check is required, maximise the signal from the 50mm hole in Calibration Block No 1. The angle can then be assessed by visual interpolation between the reference markings on the block.

Tolerance

The accuracy achieved by the described method is ±1.5°.
The accuracy in this case can only be assumed to be ±3°.

Frequency of checking

When a probe is in continuous use, it is recommended that the check be carried out at least every few hours; otherwise, a daily check is recommended.

16.5 Sensitivity and signal-to-noise ratio

General

The main objective of this check is to provide the operator with a simple method which will identify the deterioration in sensitivity of the combination of probe and flaw detector.

Method (see Figure 16.5)

a Place the probe on Calibration Block No 1 (also referred to as the V1 Block) and adjust its position to maximise the signal from the 1.5mm diameter hole.
b Adjust the gain control to set this signal to 20%FSH and note the dB setting.
c Increase the gain until the overall system noise (electronic noise and grain structure grass) at the same range as the target hole reaches 20%FSH and note the new dB setting.
d The first gain measurement noted provides a check on the sensitivity of the probe and flaw detector and the difference between the first and second measurements (dB) gives the SNR.

Note 1: A demonstration of the sensitivity of the probe and the flaw detector on a calibration block does not guarantee that the same size of reflector could be detected in the workpiece.

Note 2: If it is desired to check the sensitivity as a function of range, the use of the standard Beam Calibration Block (also referred to as the A5 Block) is recommended for longer ranges.

Tolerance

The tolerance depends on the application. Any deterioration in the sensitivity value indicates a problem with the probe or flaw detector. A low SNR would be typical of a coarse-grained material.

Frequency of checking

Unless otherwise agreed, the check shall be carried out once per probe per day.

16.6 Pulse duration

General

This check on the combination of probe and flaw detector measures the effect on the displayed signal of probe damping, amplifier bandwidth, built-in suppression and smoothing circuits. The standard No 1 Calibration Block may be used for this check.

Method

a Calibrate the time base in millimetres to a range that is to be used in subsequent testing.
b Maximise the signal from the 1.5mm side-drilled hole for shear wave probes or a BWE for compression wave probes and set its peak to 100% screen height.
c Measure the width of the signal in millimetres at the 10% screen height position.
d If desired, the measurement in millimetres can be converted into microseconds by dividing it by the relevant sound velocity.

Tolerance

The tolerance depends upon the application. A long pulse duration will limit range resolution and indicate the need for a resolution check*, while a short pulse duration may indicate that the flaw detector has built-in suppression that could prevent the observation of small signals.

*A resolution check is described in Section 16.7.

Frequency of checking

Unless otherwise agreed, the check should be carried out daily.

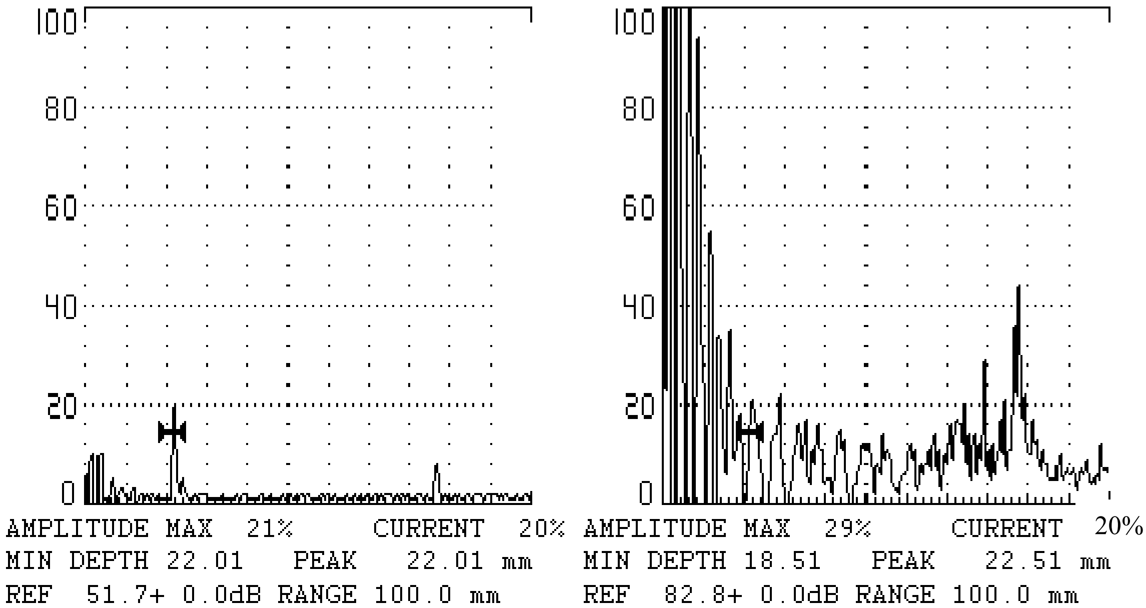


Figure 16.5 Sensitivity and signal-to-noise ratio (SNR) check.

16.7 Resolving power (resolution)

General

This check determines the ability of an ultrasonic flaw detection system to give separate indications of discontinuities which are situated close together and simultaneously hit by the sound beam.

Method

a Calibrate the time base to a range of 0-100mm for either the compression or the shear wave probe.

b Place the probe so that the axis of the beam impinges upon the 2mm step in the A7 'resolution' calibration block for shear wave probes, or the 3mm step for compression wave probes.

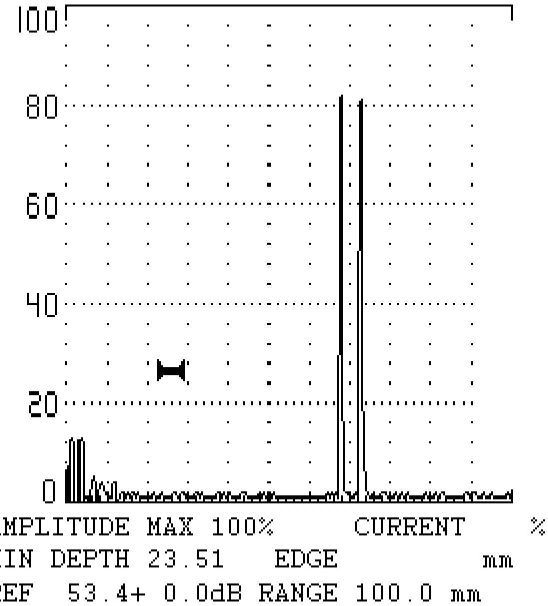
c Adjust the position of the probe so that the echoes from the two targets are of the same height (approximately half the full graticule height).

d The steps are said to be resolved when their echoes are clearly separated at half maximum echo height or lower.

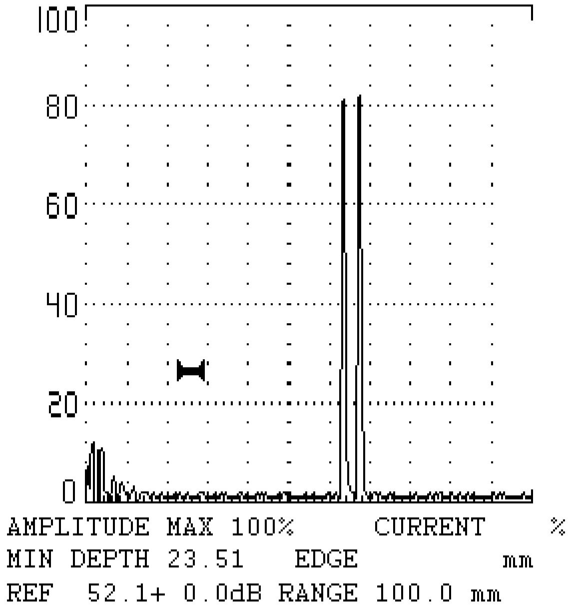
Note: The 3mm steps between the 9mm and 3mm drilled holes in the A6 calibration block may also be used when checking compression probes.

Frequency of checking

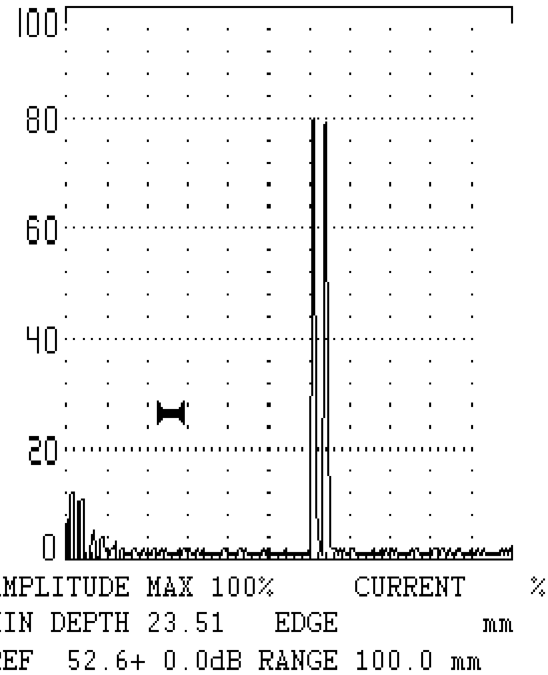
This check shall be carried out monthly, or when too long a pulse duration is suspected.



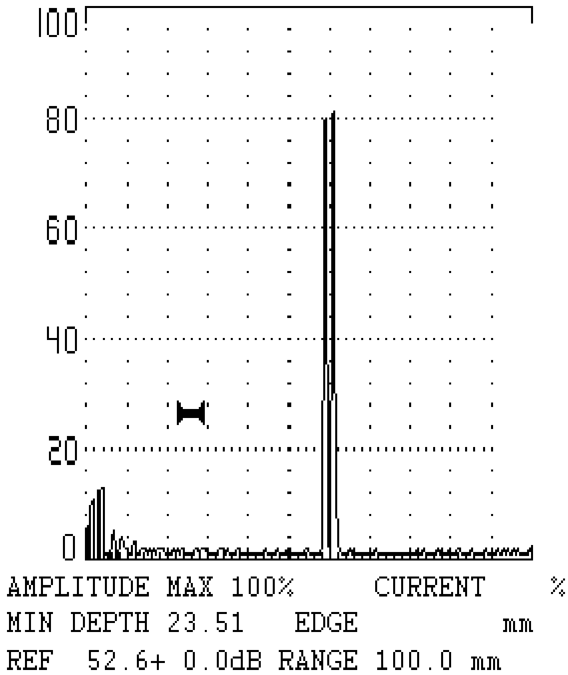
a



b



c



d

Figure 16.6 Flaw detector and probe system resolving power (resolution) check to give separate indications of closely situated reflections (note how discontinuities a and b above give clear echo resolution).

Section 17
Practical Weld Inspection

17 Practical Welding Inspection

Equipment (instrumental and probe) sensitivity is set in accordance with one of the methods described in Section 15, with calibration covered in Section 12 and flaw location and sizing covered in Sections 13 and 14, respectively.

17.1 Identifying flaws in butt welds

It is not always easy to identify a defect, but by noting its position in the weld and moving the probe around the defect and watching the changing signal on the screen you can come to a reasonably accurate conclusion. Knowledge of the welding process is essential, as is knowledge of the weld preparation, weld dimensions, size of the gap and other factors. Slag is unlikely in a TIG weld and lack of sidewall fusion is not likely in the middle of the weld metal. Cracks are more likely in thicker welds than in thinner welds and fusion defects are more likely to result from automatic than manual welding processes.

The shape, amplitude and time spread of a reflector, as represented on the screen, can also give clues as to the identity of a flaw. Specular reflectors are those with a mirror-like face, where all the sound is reflected back to the source of energy, providing that the probe and flaw are correctly orientated. A sidewall fusion flaw is nearest to this ideal.

However, at the other extreme, porosity can be considered as a large number of small spherical reflectors which cause the energy to reflect everywhere, rather like the light reflecting from a disco ball hanging from the ceiling. Porosity is a diffuse reflector.

By combining these movements and watching the movement of the signal on the screen, conclusions can be drawn. The characteristics of different defects are shown in the accompanying diagrams, with explanations adjacent.

Guidance in the classification of ultrasonic indications can be found in:

BS EN ISO 23279	Ultrasonic testing	Characterisation of indications in welds
BS EN ISO 16827	Ultrasonic testing	Characterisation and sizing of discontinuities

BS EN ISO 23279 contains a flowchart to be followed in order to determine the exact nature of any indications. The stages involved are:

- Echo amplitude.
- Directional reflectivity.
- Echostatic pattern (A scan).
- Echodynamic pattern.

The first stage of assessing the echo amplitude involves comparing the amplitude of an indication to DAC level and classifying it into one of the four categories shown in the table below.

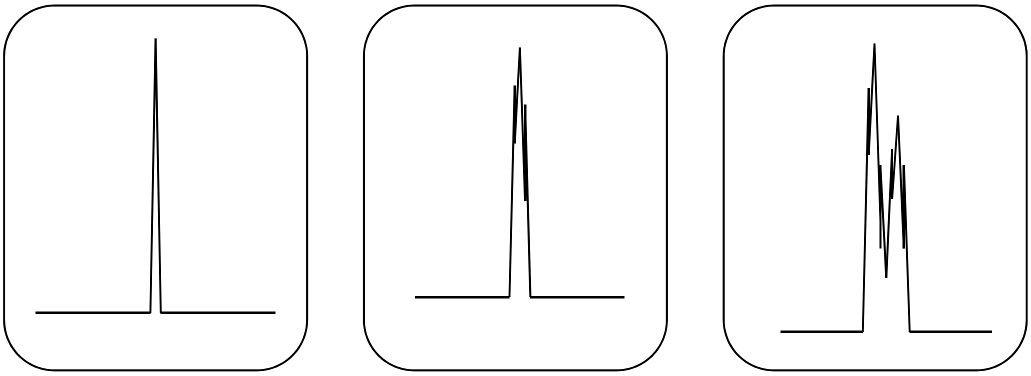
Table 17.1 Echo amplitude vs DAC level.

S1	S2	S3	S4
DAC −10dB	DAC +6dB	DAC −6dB	9/15dB

Indications falling into the S1 category would be immediately discounted. All other indications would then proceed to be assessed for directional reflectivity, which is defined as the variation in echo amplitude from a discontinuity in relation to the angle at which the ultrasonic beam is incident upon it. A spherical indication would show the same echo amplitude over a wide range of incident angles, eg 45°, 60° and 70°, and is said to have low directional reflectivity. A large smooth planar reflector would show a great variation in echo amplitude and would therefore be said to have high directional reflectivity.

The next two stages of the process analyse firstly the shape of the signal as displayed on the A scan equipment and finally the behaviour of the signal when the probe is scanned at 90° to the discontinuity (traversing). Echostatic patterns are categorised as:

- Single and smooth.
- Single and jagged.
- Multiple.



a b c

Figure 17.1 Echostatic patterns:
a Single and smooth reflector;
b Single and jagged reflector;
c Multiple facet reflector.

With respect to echodynamic patterns, indications fall into one of five categories dependent upon the changes observed in the signal on the A scan in response to probe movement. To aid the identification of defects, there are four basic probe movements:

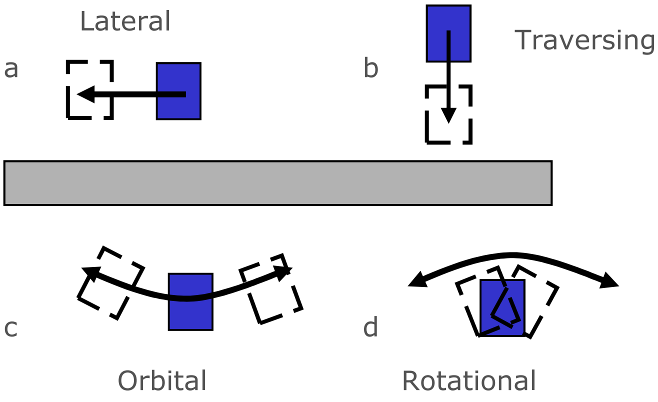
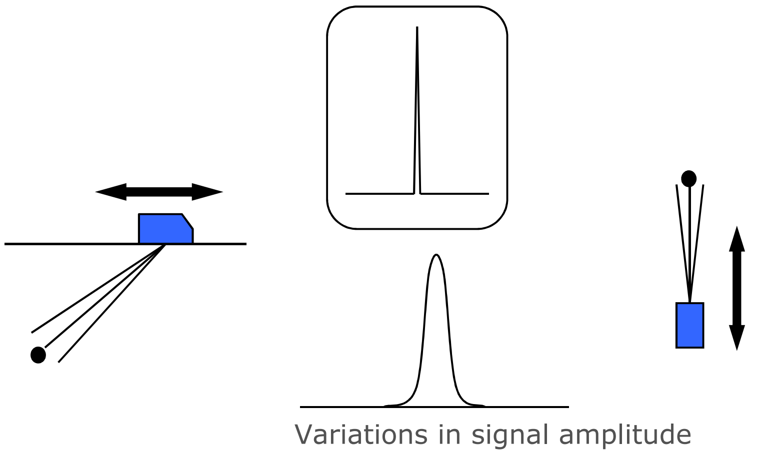
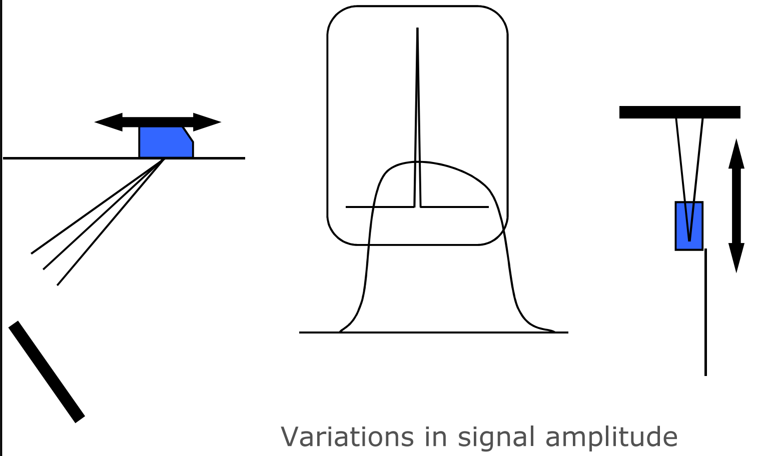


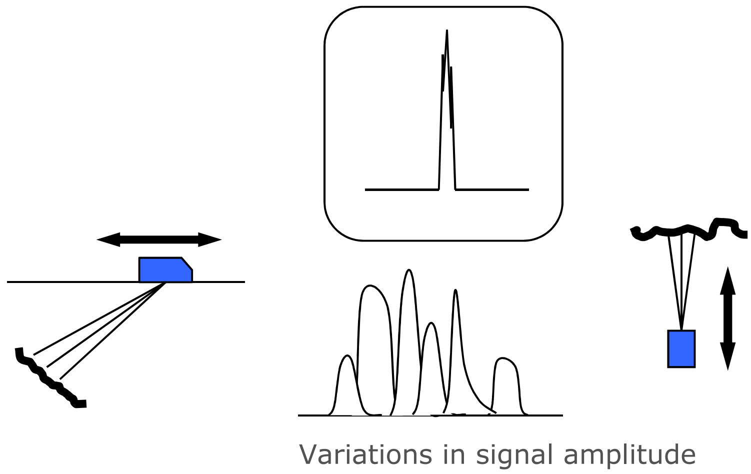
Figure 17.2 Probe movements to determine echodynamic patterns:
a Lateral probe movement;
b Traversing probe movement;
c Orbital probe movement;
d Rotational probe movement.



Pattern 1



Pattern 2



Pattern 3a

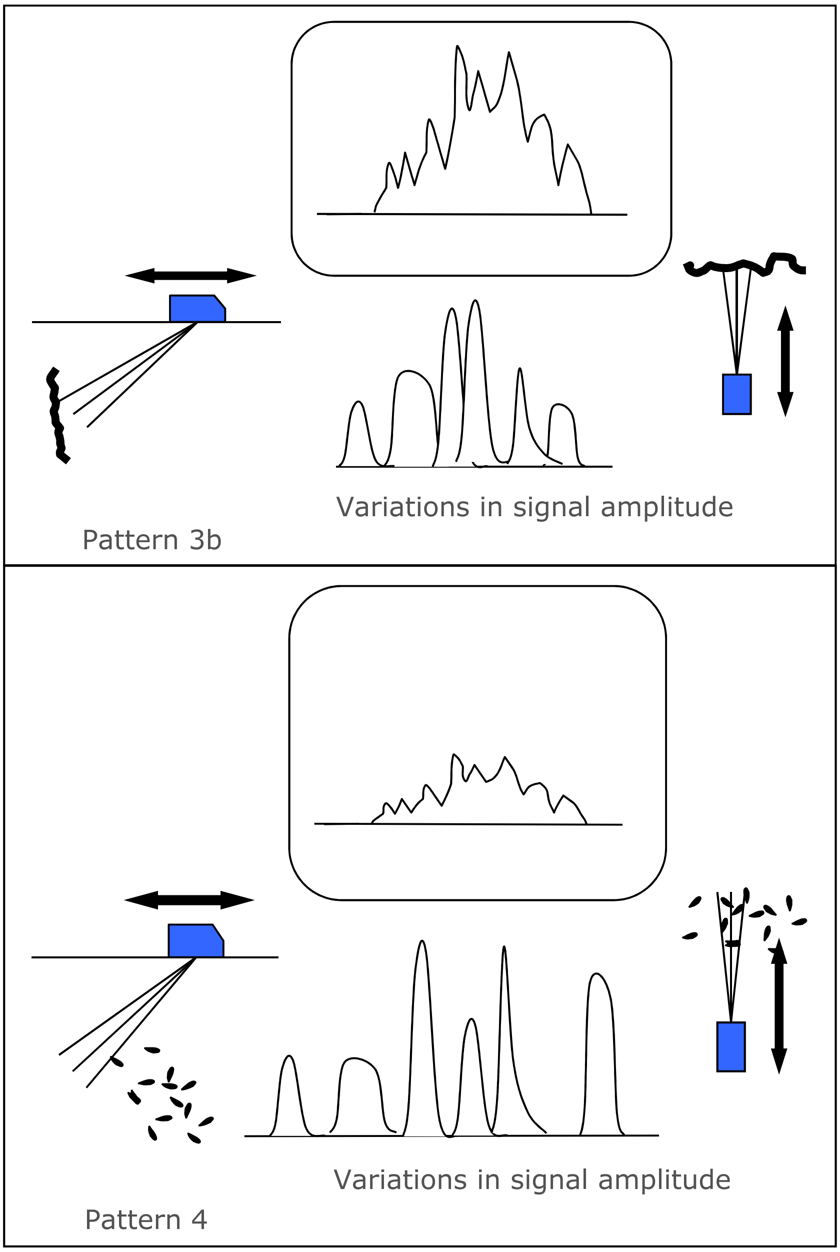


Figure 17.3 The five echodynamic patterns.

Section 18
Root Flaws

18 Root Flaws

The signal from a root flaw will appear on the time base while you are scanning laterally along a straight edge, at a fixed position from the root. Once the signal is maximised by getting the best reflection from the flaw, it can be assumed that the centre of the beam is hitting the bottom of the flaw. Fine adjustment of the straight edge will perhaps be necessary.

18.1 Excess penetration

- Echo amplitude between 10-90%, dependent on depth and probe angle.
- Multi-range signal - echo falls rapidly when traversed with 70° probe; also the range increases.
- Probe movement - echo falls rapidly when angle probe traverses forward.
- Measurement - it is not possible to measure the depth with an angle probe. Length measurement is difficult (usually 6dB).

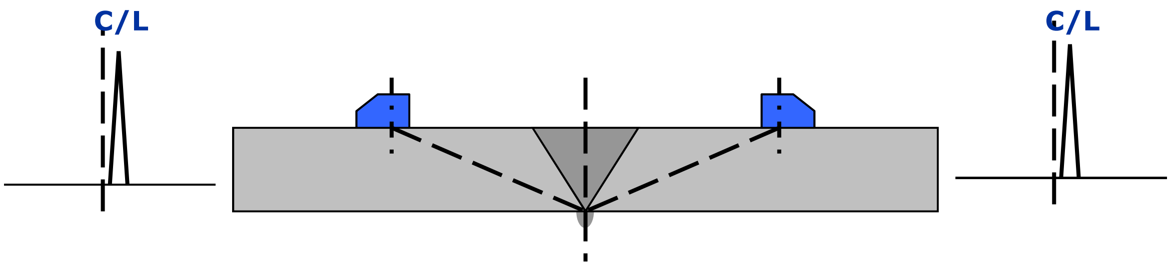


Figure 18.1 Excess penetration.

18.2 Root concavity

- Echo sharp and large, with reduced range. Often mode conversion with 60° probe.
- Probe movement - traversing backwards, the echo falls more rapidly than the lack of penetration.
- Measurement - use centre of beam and 20dB drop (trailing edge) for height. Not always possible to measure height.

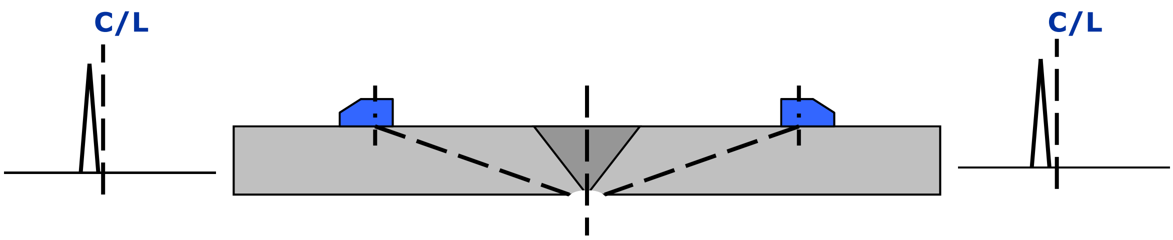


Figure 18.2 Root concavity.

18.3 Root crack

- Usually high amplitude response with fir tree appearance.
- Probe movement - orbit, echo held over large angle.
- Lateral, echo held with multi-range signals and variations on time base.
- Measurement - 6dB for length. Traverse forward with 20dB for height.

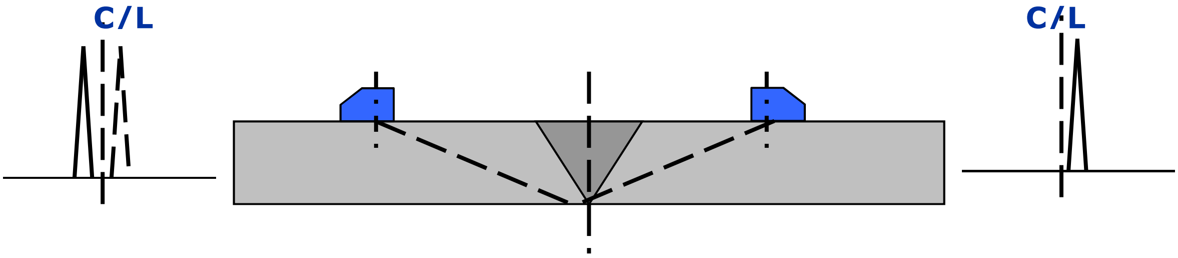


Figure 18.3 Root crack.

18.4 Lack of root fusion

- Similar to corner reflector with large, narrow echo from both sides.
- Probe movement - confirm with 70° probe, when traversed.
- Large movement for 20dB drop. Orbit: echo falls rapidly.
- Measurement - lateral use 6 or 20dB drop. Traverse use 20 or 10dB for 70° probe.

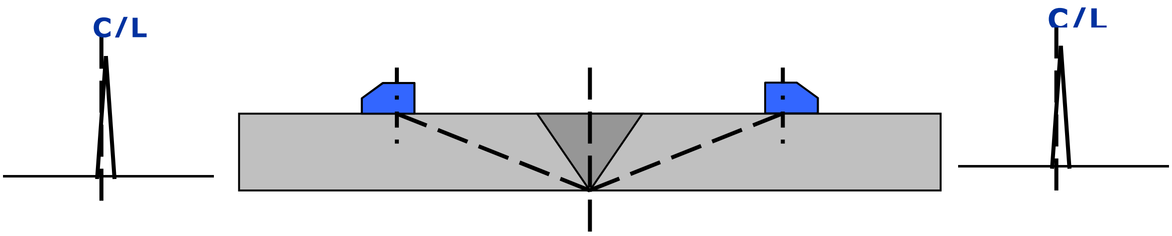


Figure 18.4 Lack of root fusion.

18.5 Misalignment

- Large single echo from one side. No echo from opposite side.
- Probe movement - traverse back echo falls rapidly.
- Measurement - lateral for 6dB drop.

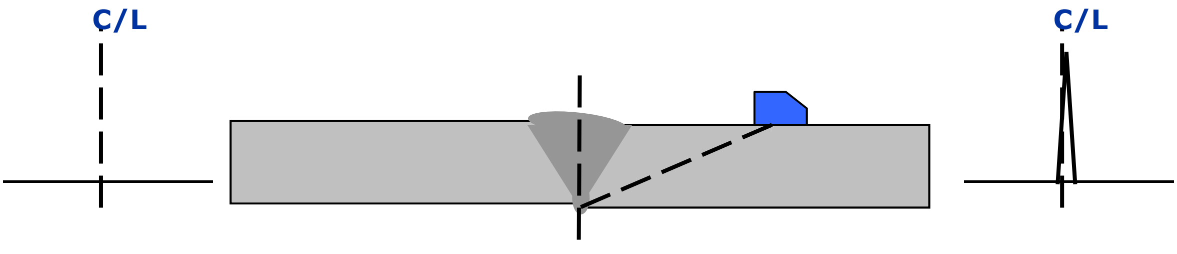


Figure 18.5 Mismatch.

Section 19
Face and Body Flaws

19 Face and Body Flaws

A degree of additional flexibility can be applied when flaws are located at the face or in the body of a weld. The diagrams below illustrate the characteristic shape of the screen presentation, but they are ideal rather an actual.

19.1 Lack of fusion

Echo large, single, narrow at time base when on the sidewall. Poor echo from opposite side. Confirm by skip scan.

- Probe movement:
  Rotate or orbit - echo falls rapidly.
  Lateral or traversing - echo height held.
- Measurement: For depth use 20dB. For length use 6 or 20dB.

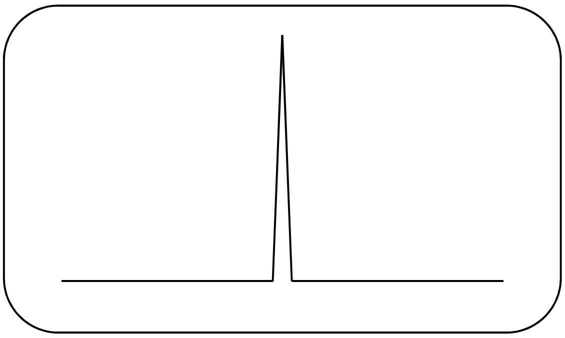


Figure 19.1 Lack of fusion.

19.2 Crack

- Multiple peak reflector: usually high amplitude, but dependent on type of crack and size; echo with fir tree appearance.
- Probe movement:
  Orbit - echo over larger angle than with fusion defects.
  Lateral - signal held with varying height.
- Measurement: For length use 6 or 20dB. For depth use 20dB.

Figure 19.2 Crack.

19.3 Gas pore

- Spherical even reflector: single peak echo, narrow profile, similar to drilled hole or radius of calibration block intensity (approximately 50% CRT).
- Probe movement:
  Rotate, lateral and traversing - echo falls rapidly.
  Orbit - echo height remains.
- Measurement: Impractical to measure height and length. Report as isolated reflector. Equate reflectivity against disc area or DGS.

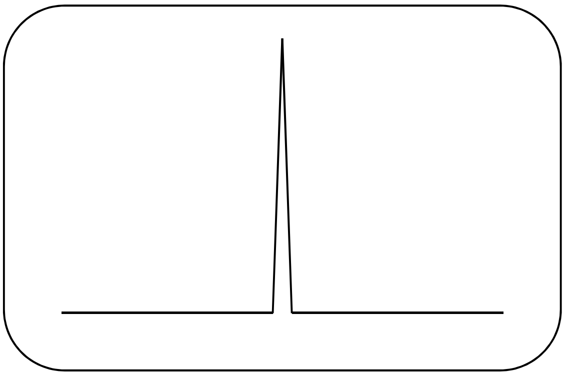


Figure 19.3 Gas pore.

19.4 Porosity

- Multiple peak echo: Low intensity (20% CRT), broad at time base due to numerous ranges.
- Probe movement: Orbit - echoes held with amplitude variations.
- Measurement: Indicate area by pinpointing last maximum signal from traversing and lateral scans.

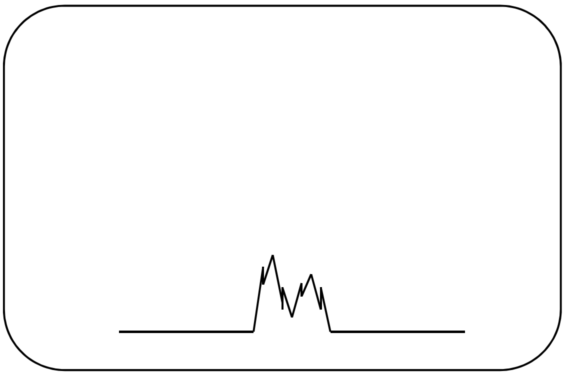


Figure 19.4 Porosity.

19.5 Linear inclusion (slag)

Echo may be wide at time base and will be multi-faceted, due to having more than a single range. Height will vary between 20-90%.

- Probe movement:
  Orbit (traversing is similar) - echo held with various maxima and minima.
  Rotational - echo will drop quickly.
  Lateral - will produce large variations in height, perhaps with total loss of signal for distances shorter than the beam width.

Figure 19.5 Linear inclusion (slag).

Section 20
Plate Inspection

20 Plate Inspection

EN 10160 describes methods for inspecting uncoated steel plates between 6 and 200mm in thickness for internal discontinuities. It details:

a Three quality classes.
b Equipment to be used.
c Calibration requirements (two BWEs).
d Coupling (normally with water but oil and paste are also acceptable).
e Scanning plan - 200 or 150mm grids, dependent upon the quality class.
f Sensitivity setting.
g Sizing techniques for defects (6dB).
h Acceptance criteria.
i Reporting requirements.

Section 21
Inspection Procedure

21 Inspection Procedure

BS EN ISO 17640 (NDT of welds – Ultrasonic testing – Techniques, testing, levels and assessment) describes the procedure for examining welds and details beam paths to be used for welds of different configurations, eg plates, pipes, nozzles and nodes. To standardise methods of examination, BS EN ISO 17640 and EN ISO 16811 (NDT - Ultrasonic testing – Sensitivity and range setting) recommend the use of DACs and different sensitivity settings to match the criticality of different examinations. The sensitivity is set higher for examining, say, a high-pressure steam pipe in a chemical plant than it is for a comparatively low-pressure line in a refinery.

Different procedures are followed in different projects. Usually, the test procedure is formulated before the job starts so the technicians know exactly what is expected of them.

The following is the procedure laid down in BS EN ISO 17640, recommended for the inspection of examination test pieces:

- **Compression scan** to check the parent metal on either side of the weld for laminations and to check through-thickness dimensions.
- **Root scan** to check the root for longitudinal defects such as lack of penetration, lack of root fusion, cracking or mismatch.
- **Weld body scan** with shear probes to check the sides of the weld and the weld body for longitudinal defects like lack of fusion, cracks, slag and porosity.
- **Transverse weld scan** to check the weld for transverse and chevron cracking.
- **Reporting**.

21.1 Information required prior to testing

BS EN ISO 17640 specifies that the following information should be specified before commencing an inspection:

- Method for setting the reference level.
- Method to be used for evaluation of indications.
- Acceptance levels.
- Testing levels.
- Manufacturing and operating stage at which inspection is to be performed.
- Qualification of personnel.
- Extent of testing for transverse indications.
- Requirements for tandem testing.
- Parent metal testing prior to and/or after welding.
- Whether or not a written test procedure is required.
- Requirements for written testing procedure.

EN 17640 also states that it is essential that the operator performing an inspection on a welded joint shall have access to the following:

- Written test procedure.
- Types of parent material and product form.
- Manufacturing and operating stage at which inspection is to be performed.
- Time and extent of post-weld heat treatment.
- Joint preparation and dimensions.
- Requirements for surface conditions.
- Welding procedure or relevant information on the welding process.
- Reporting requirements.
- Acceptance requirements.
- Extent of testing including requirements for transverse defects if relevant.
- Personnel qualification level.
- Procedures for corrective action when unacceptable indications are revealed.

EN 17640 itself would, in many cases, satisfy the requirement for a written test procedure.

21.2 Compression scan

Make a visual examination of the weld. Note if there is any spatter, rust or inaccessible areas. Look for surface defects, lack of fill, undercut and gross misalignment, cracks or surface porosity.

Find the centre of the weld. The stand-off must be measured from there. If the root is detectable, find the root from both sides with a 60° probe. Mark where the index point falls on both sides of the weld when the root signal is maximised; the weld centre is midway between these two marks. Note the thickness of the parent metal on either side of the weld and ensure there is no counter boring.

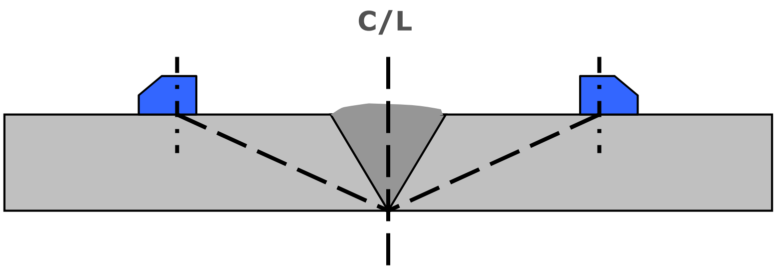


Figure 21.1 Weld root detection.

Examine the parent metal on either side of the weld with a 0° compression probe with sensitivity set at either 2nd BWE to FSH or the sensitivity given in the procedure. Look for changes in thickness and lamination. You should cover the parent metal on either side of the weld to full skip distance for the highest angle probe, that is for a 60° or 70° probe. Mark any discontinuities found in the parent metal.

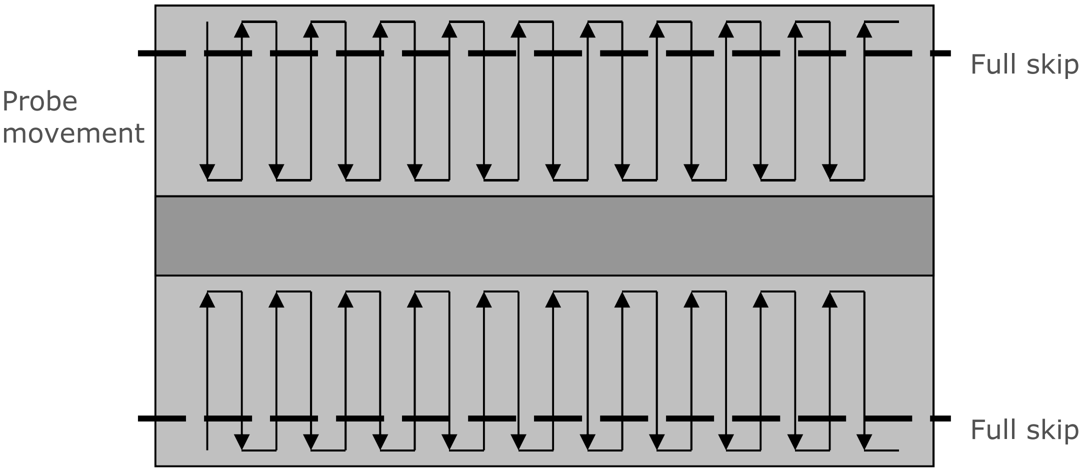


Figure 21.2 Parent material comparison probe scan.

Draw a cross section of the weld on the slide of your beam plotting chart once you are sure of the weld dimensions.

If the cap of the weld has been dressed ground flush with the parent metal, examine the body of the weld with the 0° probe. If a backing bar has been used, check bonding at the root if possible. Check the root on a double sided weld if the cap has been ground flush. Lack of penetration at the root will sometimes show with a 0° probe.

If you are examining a single V weld with a dressed cap, a 0° probe scan of the weld can reveal lack of inter-run fusion and large pockets of slag.

21.3 Root scan

Use a 70° probe for the root scan if possible. Work out the half skip distance for a 70° probe to put the beam centre exactly through the centre of the root.

Measure out the half skip distance on the parent metal on either side of the weld, measuring from the centre line of the weld. Draw lines on either side of the weld at this distance. Note the range of the root centre along the main beam.

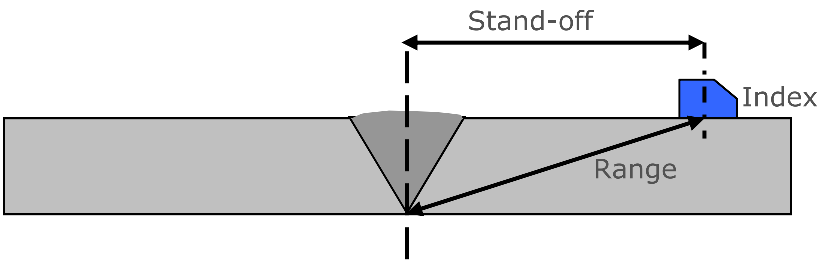


Figure 21.3 Root Scan using an angle probe at a fixed 'stand-off'

Set the gain from an IOW block so that a hole at the depth of the root will give an echo to FSH. (Or set the gain according to the set procedure.)

Place the probe index point on the line and put a magnetic ruler or strip behind it as a guide. Move the probe laterally along the weld. Signals from a good root should be small, while defects will give large signals. Signals from a fully penetrated root will usually appear just beyond the range of the root centre.

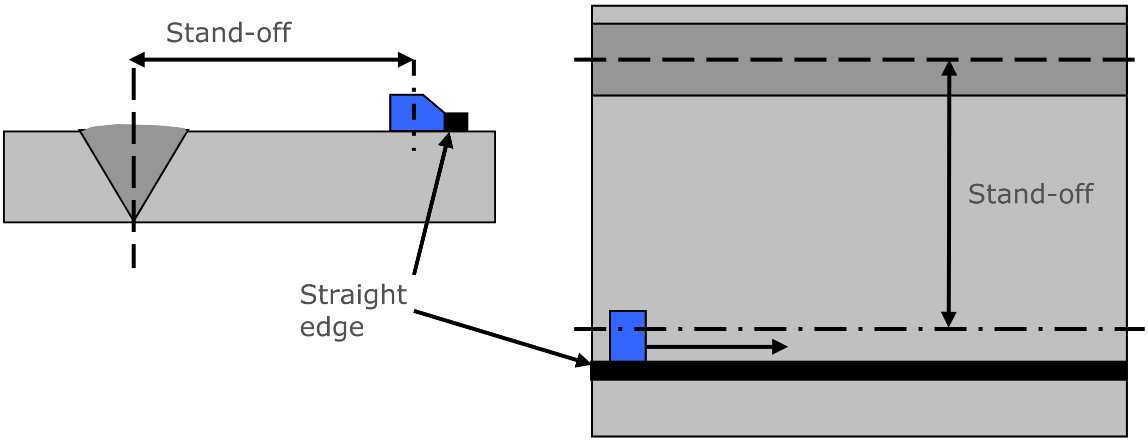


Figure 21.4 Fixed 'stand-off' scan using a straight edge.

Mark any defects on the parent metal or the magnetic guide behind your probe. Find the height of the defect using a 20dB drop on the trailing edge of your beam. Record the defect on a sketch and note the stand-off distance and range.

21.4 Weld scan

Many standards and procedures demand that the first weld scan be done with a probe beam which meets the joint face at as near to 90° as possible. This has almost always meant a 60° probe, although probe angles have become steeper lately and 70° probes are increasingly used.

If a 60° probe is used first, follow up with a 70° probe if the plate thickness is less than 25mm and a 45° probe if it is over 20mm. There is a bit of an overlap.

Use your beam plot and flaw location slide to work out the half skip distance to the root centre and full skip distance plus half the weld width to the top of the weld. Mark these stand-off distances on the parent metal on either side of the weld. Note the range of the root can cap.

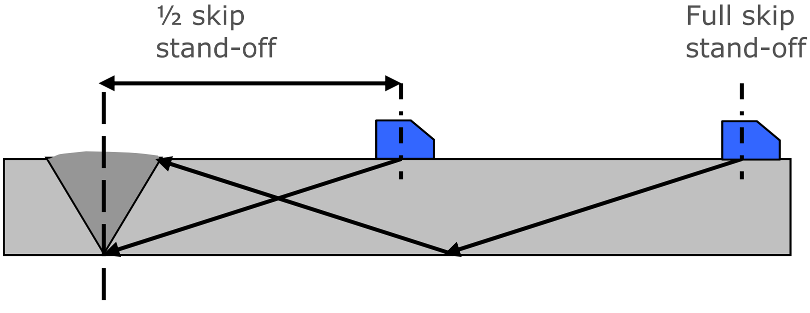


Figure 21.5 Angle probe raster scanning from the weld cap edge to the full skip position.

Set the gain relative to DAC according to the sensitivity setting given in the procedure.

Move the 60° probe backwards and forwards along the weld on either side so that the beam covers the sidewalls and centre body of the weld (see Figure 21.5). Defects should maximise between the root and cap signals. If any signal occurs near the cap, use a couplant-covered finger to damp any signal that may be coming from the cap, thus identifying its position.

Make a second scan of the weld body with a 45° probe for materials with more than 20mm thickness or a 70° probe for less than 25mm thickness.

Check the area just under the cap with a 45° probe if you are examining thicker materials. You may find porosity that the 60° probe has not revealed. Check any defect already noted and see if it is longer than shown with the 60° probe.

On thinner materials, a 70° probe will confirm defects already noted and may help you distinguish between signals from a defect and signals from, say, the weld cap or mode change.

21.5 Transverse scan

Place a 60° or 70° probe beside the weld cap angled slightly inwards (see Figure 21.6) and move the probe along the weld to find transverse cracking. Turn the probe round and check in the opposite direction. Examine the weld along the other side in both directions.

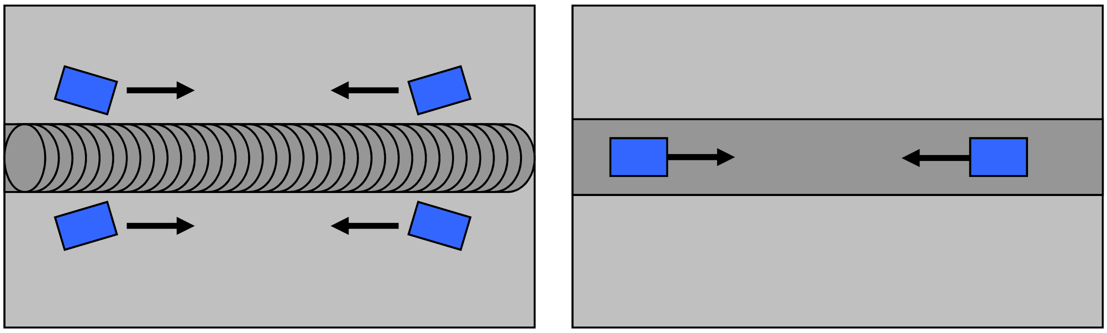


Figure 21.6 Shear wave angle probe scan to detect transverse defects.

If the weld has been dressed, push the probe along the centreline of the weld in both directions and then push it along both edges of the weld in both directions.

21.6 Double V welds

If a weld had been welded from both sides, it can be examined from both sides. The method for examining a double V weld is not much different from that used for a single V weld.

Examine the root with a 70° probe straight into the root at 1/4 skip (see Figure 21.7). Run the probe laterally along the weld with sensitivity set from a hole in the IOW block at a suitable range; this should show any lack of penetration at the root.

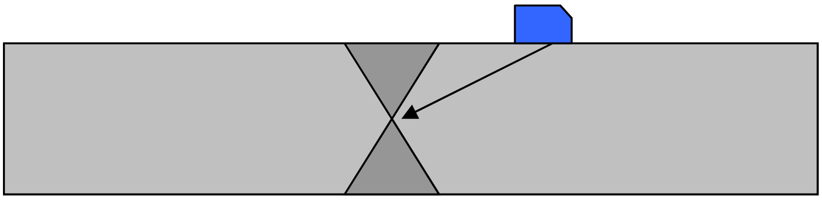


Figure 21.7 Double V weld root examination from ¼ skip.

Make body scans with 60° and 45° probes from both sides of the weld if the plate is thick (over 25mm) using ¼ to ½ skip stand-off.

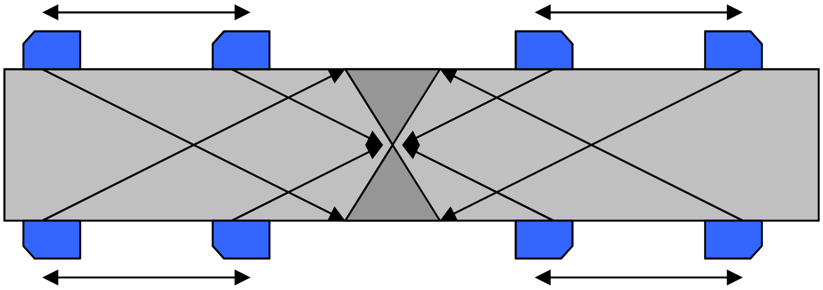


Figure 21.8 Weld body scan between a ¼ and ½ skip stand-off using 45° and 60° probes.

On thinner plates, use a 60° and a 70° probe from one side of the weld only between ¼ and full skip and ½ weld thickness stand-off positions. Take great care in locating the defects and reporting, as you will have to use a mirror image on your plotting chart and this can lead to confusion. You may find a defect and place it on the wrong side of the weld.

21.7 Pipes

Circumferential pipe welds can be examined in the same way as butt welds in plates are examined, that is:

- **Compression scan** to check the parent metal on either side of the weld for laminations and to check through-thickness dimensions.
- **Root scan** using a flexible strip at the back of the probe will help to ensure that the centre of intensity of the beam goes into the centre of the root.
- **Weld body scan** with shear probes to check the sides of the weld and the weld body for longitudinal defects like lack of fusion, cracks, slag and porosity.
- **Transverse weld scan** - difficulty may arise here as you must be sure that the beam reaches the bore of the pipe.

This flexible guide is convenient for marking defects. All defects must be measured from a datum point. The button at the top of the weld is a convenient datum point. When examining a longitudinal weld on a pipe or when doing a transverse check on a circumferential weld, you must choose a probe angle that will reach the bore of the pipe (see Figure 21.8). The formula below provides this angle.

$$\frac{\text{Inside diameter of pipe}}{\text{Outside diameter of pipe}} = \text{Sine of max probe angle}$$

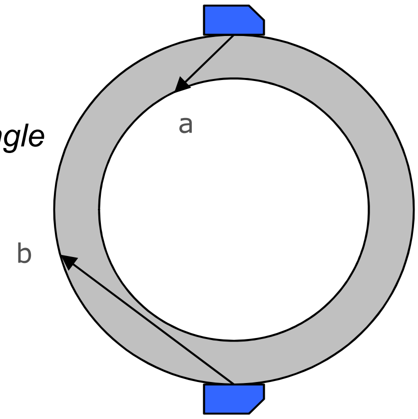


Figure 21.9 Ultrasonic beam:
a at the inside surface of the pipe;
b with its centre axis not reaching the inside pipe surface.

So a 12cm OD pipe with a 1cm wall will need what probe angle?

$\frac{10}{12}$ = 0.8333 which is the sine of 56°.

A 60° probe will not reach the bore of this pipe, so a 45° probe is advised.

21.8 Reporting

A detailed test report will normally be produced for each item of test and will cover all of the salient parameters that affect the quality and integrity of the test as laid out in the test procedure, which must be made available to the test technician/operator prior to starting the test along with written instructions detailing the components to be tested, the specific test procedure, specifications/standards and acceptance criteria to be applied along with any special instructions that might apply (eg PPE to be used, use of photographs etc.). The test report will normally include an assessment of the condition of the component against the specified acceptance criteria.

Specific details that may be included in the test procedure are as follows:

- Title of the test procedure.
- Description (including sketch/drawing if relevant) of components including materials and surface condition.
- Scope detailing general requirements of the test (eg type of ultrasonic instrument and settings together with probe and scanning details).
- Reference documents (eg codes, standards, client requirements, personnel qualifications).
- Definitions and abbreviations used.
- Responsibilities (personnel involved in the test sequence including identification of test component, carrying out the test and making the area of testing safe).
- Personnel qualifications (technician undertaking the test, evaluating the results/indications and procedure preparation).
- Technique procedure, equipment and settings (if applicable), initial cleaning, surface preparation and access requirements.
- Examination details, diagnostic area and scan overlap.
- Interpretation of results and evaluation of indications against the acceptance criteria with a sketch showing the positions of indications if required.

What follows is a sample NDT report. The headings within it are taken from BS EN ISO 17640, (Ultrasonic Testing – Techniques, testing levels and assessment) which specifies these as the minimum content.

Ultrasonic Test Report

Name of inspector		***Date of report***	
Reference standard			

Item Inspected

Material	
Product form	
Dimensions	
Location of weld	
Specification	
Operator certification	

Configuration	
Stage of manufacture	
Surface condition	
Date of test	

Equipment

Flaw Detector

Maker	***Type***	***Serial number***

Ultrasonic Probes

Maker	***Type***	***Frequency***	***Serial number***
Couplant			

Technique	
Testing levels	
Extent of test	
Location of scanning areas	
Reference point	
Identification of probe position	
Time base range	
Sensitivity level	
Reference level	
Parent metal	
Acceptance level	
Deviations from standard	

Results					
	Co-ordinates	***Maximum amplitude***	***Type***	***Length***	***Accept/ reject***

Figure 21.10 Ultrasonic Test Report conforming to BS EN ISO 17640.

Section 22
Ultrasonic Thickness Measurement

22 Ultrasonic Thickness Measurement

Standards to be used for reference include:

BS EN 14127. Non-destructive testing - Ultrasonic thickness measurement.

BS EN ISO 16811. Non-destructive testing – Ultrasonic testing. Sensitivity and Range setting.

BS EN 1330-4. Non-destructive testing – Terminology. Part 4, Terms used in ultrasonic testing.

22.1 Measurement modes

The precise thickness of a component part can be determined by accurately measuring the transit time for a short duration ultrasonic pulse generated by a transducer to travel through the material thickness once, twice or several times.

The material thickness can be calculated by multiplying the sound velocity of the material with the transit time and dividing the result by the number of times that the pulse has transited the material thickness.

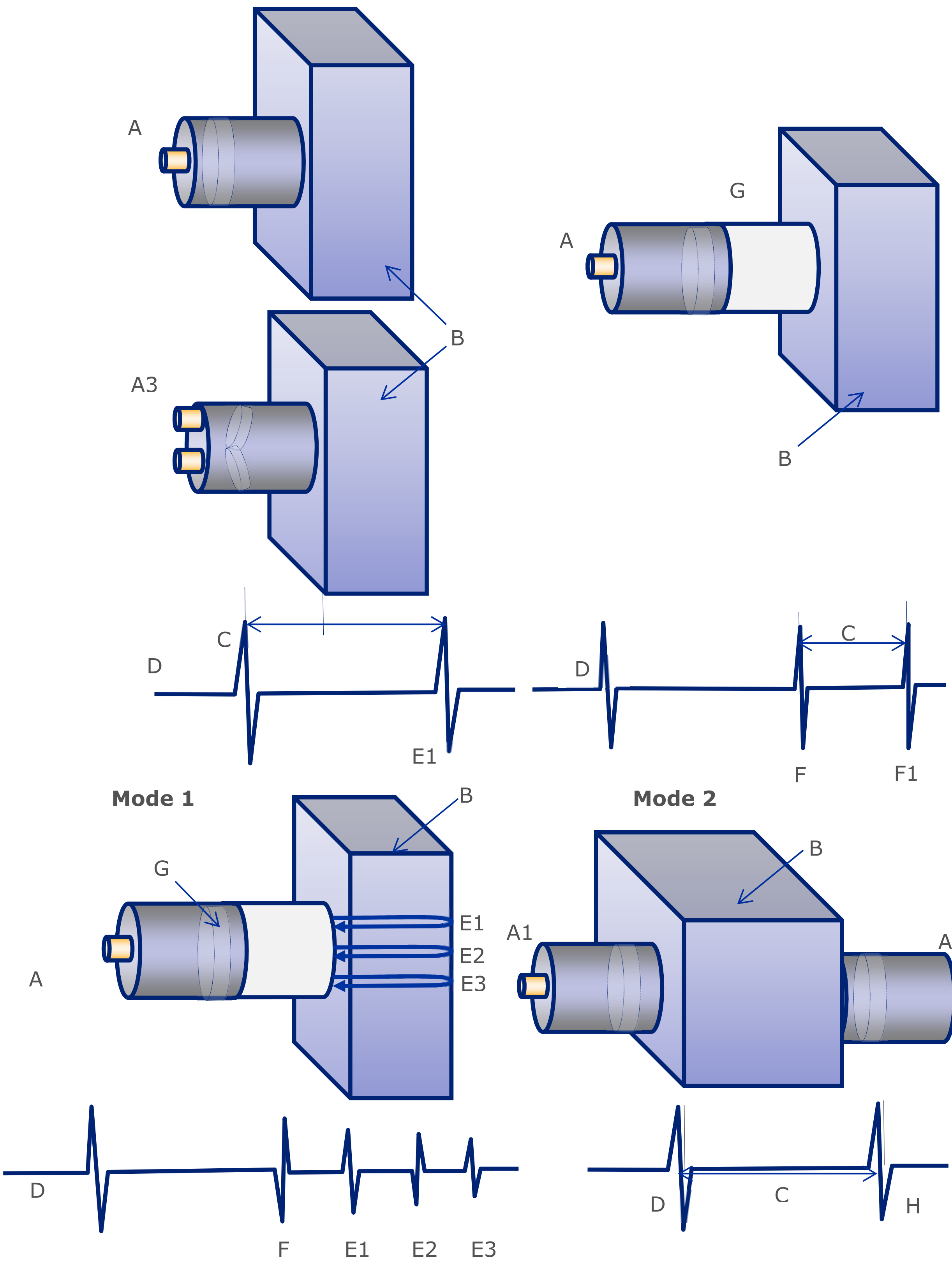
Four ultrasonic measurement modes are given below and illustrated in Figure 22.1:

a **Mode 1**: Measure the transit time from an initial excitation pulse to a first returning echo, minus a zero correction to account for the thickness of the transducer wear surface and the couplant layer (single echo mode).

b **Mode 2:** Measure the transit time from the end of a delay line to the first back wall echo (single echo delay line mode).

c **Mode 3:** Measure the transit time between back wall echoes (multiple echoes).

d **Mode 4:** Measure the transit time for a pulse travelling from the transmitter to a receiver in contact with the back wall (through transmission mode).



Key

A	transmit/receive probe (dual element probe)	B	test object	F	interface echo
A1	transmit probe	C	sound path travel time	G	delay path
A2	receive probe	D	transmission pulse indication	H	received pulse
		E1-E3	back wall echoes		

Figure 22.1 Ultrasonic Measurement Modes.

22.2 Requirements – test object, instruments, probes and reference blocks

a Test Object:

The object to be tested shall enable ultrasonic propagation/transmission and have access to apply the probe to the test surface that will be free of all dirt, grease, scale or any material that could interfere with the examination.

If the surface to be tested is coated, the coating will have tight adhesion to the base parent material, otherwise it must be removed.

When measuring through a coating, the coating thickness and sound velocity need to be known unless Mode 3 above is being used.

b Ultrasonic Instruments

The following Ultrasonic measurement instruments can be used:

- Dedicated ultrasonic thickness measurement instrument with a numerical display that shows the measured thickness.
- Dedicated ultrasonic thickness measurement instrument with a numerical display that shows the measured thickness and the 'A'-scan waveform presentation.
- 'A'-scan display instruments that are designed primarily for flaw detection and may also include a numerical display of measured thickness.

c Probes

Generally compression (longitudinal) wave probes are used based on either of the following configurations:

- Dual element probes (see Probe A3 in Figure 22.1)
- Single transducer probes (see Probe A in Figure 22.1)

d Reference Blocks

The ultrasonic measurement system (ie instrument and probe) must be calibrated on a sample(s) or reference block that closely represent the component whose thickness is to be measured in terms of dimensions, material and structure and the reference sample thickness range should cover the range of component thicknesses to be measured. Either the thickness or the sound velocity of the reference sample block shall be known.

Thickness calibration reference blocks are commercially available for steel and aluminium in the form of ladder step wedges and curved step wedges.

Glossary

Glossary

Acoustic emission (AE). Method of flaw detection which uses an array of accurately positioned transducers to listen to the structure under stress. The high-frequency sound given out by a growing crack would be detected by the transducer array.

Acoustic impedance matching. Coupling of two media together to provide optimum transfer of acoustical energy between them.

Acoustical shadow. Effect produced in a body by its geometry or by a discontinuity in it, whereby ultrasonic energy when travelling in a particular direction is prevented from reaching a certain region within the body.

Angle of incidence. Angle which the axis of an ultrasonic beam makes with the normal to a tangent plane of a surface at its point of impingement as it travels towards that surface.

Angle of reflection. Angle which the axis of an ultrasonic beam makes with the normal to the tangent plane of a reflecting interface, at the point of impingement of the incident wave, as it travels away from that interface in the same medium.

Angle of refraction. Angle which an ultrasonic beam makes with the normal to a tangent plane of an interface as it travels away from that interface into the second material. **Note:** A synonymous term is beam angle.

Angle of squint. Angle between the side edge of the probe and the projection of the beam axis on the plane of the probe face. **Note:** For angle probes this normally relates to deviation in the lateral direction.

Angle probe. Contact probe from which the main lobe of waves propagates at any angle other than 0° or 90° to the normal to the tangent plane of the surface at the place where the probe is positioned.

A-scan. Ultrasonic flaw detector display in which the pulse amplitude is represented as a displacement along one axis (usually the Y axis) and the travel time of the ultrasonic pulse is represented as a displacement along the other axis (usually the X axis).

ASME. Cross-drilled holes with diameter and position as required by the ASME pressure vessel code. **Note:** ASME = American Society of Mechanical Engineers.

Attenuation. Diminution in the level of acoustic energy as it propagates through material.

Attenuation coefficient. Factor determined by the diminution in the amplitude of a wave per unit distance travelled. **Note:** The attenuation coefficient is composed of two parts, one proportional to frequency (termed absorption), the other dependent on the ratio of grain size to wavelength and arising from scatter.

Attenuator. Electrical device by which the amplitude of an ultrasonic signal can be adjusted by calibrated increments.

Automatic scanning. Systematic relative displacement of the ultrasonic beam and the material under test by other than manual means.

AVG/DGS diagram. Series of curves which show the relationship between distance along the beam to gain in dB compared with a particular back wall echo and the size of a particular flat-bottom hole reflector.

Back wall echo (BWE). Pulse of ultrasonic energy reflected from the boundary of a body directly opposite to the surface on which the probe(s) is/are positioned and returned to that surface by the shortest possible path. **Note:** The term is generally restricted to normal compressional waves and is sometimes referred to as bottom echo (first).

Beam angle. See angle of refraction.

Beam axis. Locus of points of maximum intensity in the far field in a beam of ultrasonic waves, and its geometrical prolongation into the near field.

Beam index. Point on the surface of a body through which the beam axis passes (cf. probe index).

Beam spread. Divergence of the main lobe of an ultrasonic beam in the far field. **Note:** The beam spread is proportional to the ratio of the wavelength to the diameter of the ultrasonic crystal.

Bottom echo (first). See back wall echo (first).

Boundary echo (first). Pulse of ultrasonic energy reflected from any boundary of a body to the surface on which the probe(s) is/are positioned, and returned to that surface by the shortest possible path. **Note:** Term is generally restricted to shear or surface waves.

B-scan display. Two-dimensional graphical plot showing the apparent size and position of reflectors in the test piece on a cross-sectional plane which is normal to the test surface and contains the beam axis of the probe during a single line scan.

Calibration block. Piece of material of specified composition, heat treatment, geometric form and surface texture, by means of which the performance of ultrasonic flaw detection equipment can be assessed and calibrated for the examination of material of the same general composition. **Note:** For specification and use of calibration blocks, see BS EN ISO 2400 and BS EN ISO 7963, respectively.

Calibration reflector. Reflector of ultrasonic waves, such as a drilled hole, machined slot or the end face of a specimen representative of the material under test, which can be used to calibrate or set up equipment for inspection purposes.

Characteristic impedance. Complex ratio of sound pressure to particle velocity at a point in the path of a purely progressive sound wave. For a non-dissipative material it is equal to the product of density and velocity.

Combined double probe. See double crystal probe.

Compressional wave. Form of wave motion in which the particle displacement at each point in a material is parallel to the direction of propagation. **Note:** A synonymous term is longitudinal wave; also sometimes referred to as dilatational wave or irrotational wave.

Constructive interference. When two positive or negative sound waves from two sources (Huygens's Principle) meet at a point at the same instant, the wave is reinforced and assists the sound to propagate into the material under test. This is constructive interference and takes place in the near field. See also destructive interference.

Contact scan. Scanning carried out by means of ultrasonic probe(s) in contact with the body under examination.

Convergence point. Point of intersection of the axes of the transmitting and receiving sound fields in a double crystal probe.

Corner effect. Reflection of ultrasonic energy back to a point coincident with or very close to its point of origin, after impinging successfully on two or three orthogonal surfaces.

Couplant. Liquid or pliable medium interposed between two solids to assist the passage of ultrasonic waves between them. **Note:** In the majority of cases, the couplant is a liquid interposed between the probe and the body under examination. Synonymous terms are coupling film and coupling medium.

Coupling film. See couplant.

Coupling losses. Reduction in amplitude of ultrasonic waves as a result of their passage through the couplant.

Coupling medium. See couplant.

Coupling monitor. Probe operating in the receive mode and positioned such that it detects ultrasonic energy originating from a second probe or multiple probes, thereby monitoring that successful coupling is taking place between the second probe and the body.

Critical angle. Angle of incidence of a beam of ultrasound on an interface at which one of the refracted wave modes has an angle of refraction of 90^o.

Cross-drilled holes. Cylindrical holes drilled parallel to the test surface and at right angles to the vertical plane of the probe, the cylindrical surfaces of which form the ultrasonic reflectors.

Cross talk. Acoustical or electrical signal leakage across an intended barrier. **Note:** Sometimes referred to as cross noise.

Crystal (ultrasonic). Part of a single crystal or polycrystalline plate having piezo-electric properties, used for the generation and/or detection of ultrasonic waves.

Crystal array. Single housing containing an orderly assembly of crystals which may be energised together in groups, with or without time delay, to give directional effects, focused beams or variable angle beams.

Crystal backing. Material attached to the rear surface of a crystal to increase damping.

Crystal loading. Mechanical power per unit surface area delivered by a crystal to a medium acoustically coupled to it.

Crystal mosaic. Regular assembly of ultrasonic crystals, in which each crystal is of identical material and cut and mounted so that the assembly of crystals tends to behave as though it were a single crystal.

C-scan display. Two-dimensional graphical projection of the test surface showing in plan view the apparent size and position of reflectors in the volume inspected by scanning an area of test surface.

Curie point. Temperature above which a ferromagnetic material loses its polarisation.

Curved crystal. Non-planar crystal generally used to improve coupling or focusing.

Cylindrical reflector. Reflecting surface in the form of a circular cylinder.

Damped train. Wave train in which the amplitudes of successive waves diminish.

Dead zone. Region in a material adjoining the surface of entry from which no direct echoes from discontinuities can be detected due to the characteristics of the ultrasonic equipment in association with the material under test and its surface condition.

Decay technique. Technique of using ultrasonic waves to assess the quality of a material or a bond by studying the amplitudes of successive echoes.

Decibel (dB). Unit used to express the magnitude of change in the amplitude of an ultrasonic signal, defined by the equation: $dB = 20 \log_{10}(A_1/A_0)$, where A_0 is a reference amplitude.

Defect detection sensitivity. A particular level of sensitivity setting of an ultrasonic flaw detector for revealing the presence of defects in a given application.

Delayed time-base sweep. Cathode ray tube display in which the initial part of the time scale is not shown.

Depth scan. Manipulation of an ultrasonic shear wave probe over the surface of a body so as to cause an oblique beam to traverse a particular plane section of the body.

Destructive interference. When a positive sound wave from one point source (Huygens's Principle) passes a negative sound wave from a second point source at the same instant, the pressure sound wave is nullified at that point. This is destructive interference, which results in areas of maximum and minimum pressure giving spurious indications from any reflectors in this area. This area of interference is the near field. See also constructive interference.

Diffuse reflection. Reflection of an ultrasonic wave from a rough surface so that the reflected energy is detectable over a range of angles on either side of the theoretical angle of specular reflection, ie reflection in a non-specular manner.

Dilatational wave. See compressional wave.

Directional sensitivity. Relationship between the angle made with the normal to the surface of a reflector by a beam of ultrasonic waves and the amplitude to the resultant echo.

Direct scan. See single traverse technique and indirect scan.

Dispersive medium. Material in which the phase velocity of an ultrasonic wave varies with frequency.

Display. Form in which ultrasonic data is presented for interpretation, generally on a cathode ray tube. See A-scan, B-scan, C-scan and D-scan.

Distance amplitude correction (DAC). Change in amplification of ultrasonic signals to provide equal amplitude from equal reflectors at different distances in the same material.

Distance amplitude curve. Curve constructed from the peak amplitude responses from reflectors of equal area at different distances in the same material.

Distortional wave. See shear wave.

Double bounce technique. See triple traverse technique.

Double crystal probe. Probe comprising two separate crystals in a single housing, one acting as a transmitter and the other as a receiver. **Note:** Synonymous terms are twin crystal probe and combined double probe.

Double probe technique. Ultrasonic testing technique using one probe for transmission and the other for reception.

Double skip technique. Ultrasonic testing technique where the distance between the point where the waves enter the body and the region under examination is twice the skip distance.

Double transceiver technique. Ultrasonic testing technique involving the use of two probes, each used simultaneously as a transmitter and a receiver.

Double traverse technique. Testing technique in which a beam of ultrasonic waves is directed into a region of a body under examination after having been reflected by a surface of the body. **Note:** A synonymous term is single bounce technique.

D-scan. Two-dimensional graphical projection onto a plane normal to the test surface and to the projection of the beam direction on the test surface, showing the apparent size and position of reflectors in the volume inspected by scanning an area of test surface.

Dynamic range. Range of signal amplitude that can be handled by electronic or ultrasonic equipment without overloading or excessive distortion and without being too small for detection. **Note:** Usually expressed in decibels (dB).

Echo. Distinct pulse of ultrasonic energy reflected from any surface or discontinuity.

Electro-magnetic acoustic transducer (EMAT). Transducer in which eddy currents are produced at a conducting surface adjacent to the transducer in the presence of a static magnetic field, the interaction of the two fields producing a mechanical deformation of the surface thereby generating ultrasonic vibrations and vice versa. **Note:** Often referred to as an EMA transducer.

Electronic noise. Unwanted random signals that vary rapidly with time, caused by electronic pick-up and thermal noise in the amplifier of the flaw detector.

Expanded time-base sweep. Increased speed of time-base spot sweep which enables echoes from a selected region within the thickness or length of a body to be displayed in greater detail on the screen of the ultrasonic flaw detector.

Far field. Region in an ultrasonic beam where the intensity is inversely proportional to the square of the distance. **Note:** Sometimes referred to as the Fraunhofer region.

First critical angle. Angle of incidence of a longitudinal wave in one medium such that the refracted longitudinal wave is 90° in the second medium, ie along the surface, only the transverse wave being transmitted into the second medium.

Flat-bottom hole (FBH). Cylindrical blind hole with a flat bottom, the flat bottom being used as the ultrasonic reflector.

Flat-bottom hole equivalent. Size of flat-bottomed hole which gives an ultrasonic indication equal to that from the discontinuity, at the same range.

Flaw location scale. Specially graduated device that can be attached to a shear wave probe which, in conjunction with the position of the flaw echo on the screen of the cathode ray tube, gives a direct reading of the location of the discontinuity within the body.

Focused probe. Probe incorporating an acoustic lens or a suitably curved crystal, so as to produce focusing of the ultrasonic beam.

Frequency (f). Number of cycles or complete particle oscillations in one second, expressed in hertz (Hz).

Fresnel region. See near field.

Full-skip technique. Ultrasonic testing technique whereby the inspection of a surface region of a body is accomplished by using shear waves entering the same surface at a point one skip distance away.

Gap scanning. Form of scanning in which the probe carrier follows the contour of the material under examination but the probe, whilst not in direct contact with its surface, is coupled to it through a layer or jet of liquid which is maintained between the surfaces of the probe and the material.

Gate. Electronic means of monitoring a selected region of the cathode ray tube display of an ultrasonic flaw detector.

Ghost echo. Indication arising from an incorrectly matched combination of pulse repetition frequency and time base frequency.

Ghost images. See ghost echo.

Grass. Spatially random signals arising from the reflection of ultrasonic waves from grain boundaries and/or microscopic reflectors in a material.

Half skip technique. Ultrasonic testing technique in which the inspection of a surface region of a body is accomplished by using a shear wave beam entering from the opposite surface at a point corresponding to the half skip-distance.

Hard face probe. Probe in which the contact surface is of a hard material, such as steel or ceramic, to minimise wear.

Head wave. Shear wave generated by mode transformation when a compressed wave travels at a grazing angle on a free solid surface. **Note:** In steel, the head wave is at 33°.

Holography (ultrasonic). Ultrasonic image from two transducers, the beams of which are positioned to produce an interface pattern, usually on a liquid surface, which when illuminated by laser light produces a visible indication of ultrasonic wave intensity distribution.

Huygens's principle. States that any finite source of sound is considered to be constructed of an infinite number of point sources, with sound radiating out from each.

Immersion probe. Compressional wave probe designed to be used while immersed in a liquid.

Immersion testing. Ultrasonic testing technique in which the material under test and the probe(s) are immersed in a tank of water or other liquid.

Indexing. Automatic measuring of probe position, usually electrically, to generate probe position data that can be recorded.

Indirect scan. Use of surface(s) of a body to direct an ultrasonic beam into a particular region of the body.

Interface. Transition region between two materials of different characteristic impedance in acoustical contact.

Interface signal. Displayed ultrasonic signal arising from the part reflection of an incident pulse at an interface.

Interface trigger. Interface signal used as the initiating point from which other timing sequences (eg gate position) are referenced.

Internal echoes. Unwanted signals generated within an ultrasonic probe.

Irrotational wave. See compressional wave.

Lamb wave. Term applied to those modes of vibration which propagate in a plate. **Note 1:** A synonymous term is plate wave. **Note 2:** In general, both compressional and shear elasticity are involved, together with plate thickness and frequency; also, the propagation shows dispersion.

Lateral resolution. Ability of an ultrasonic flaw detection system to give separate indications from two reflectors having the same range within the sound beam. See also range resolution.

Logarithmic amplifier. Amplifier where the output is related logarithmically to the amplitude of the input signal.

Logarithmic decrement. For a damped train, the natural logarithm of the ratio of the peak values of the amplitudes of two successive cycles.

Longitudinal wave. See compressional wave.

Love wave. Acoustical wave which propagates along a stratum bounded on both sides by layers of material which differ from the stratum in their elastic properties. **Note:** The particle displacement of the wave is parallel to the wave front and to the stratum.

Magnetostrictive effect/transducer. Transducer in which the application of a magnetic field on the active element of the transducer produces mechanical deformation of the active element, thereby generating ultrasonic vibrations and vice versa.

Maximum working range. Total distance over which a probe will transmit sufficient energy to find the smallest reflector to be detected.

Mode conversion. See mode transformation.

Mode transformation. Process by which a wave of a given mode of propagation is caused to generate waves of other modes by reflection or refraction at a surface boundary.

Multiple echo. Repeated reflection of an ultrasonic pulse between two or more surfaces or discontinuities in a body.

Multiplexer. Device for electrically connecting probes to channels in sequence.

N-distance. Distance from the probe to the N-point (see BS M36).

N-point. Position in an ultrasonic beam where the intensity of sound on the beam axis reaches a final maximum before beginning a uniform reduction with distance (ie far zone; see BS M36).

Near field. Region in an ultrasonic beam subject to variations in intensity due to diffraction effects, extending from the source of radiation to the last axial maximum in intensity. **Note:** Synonymous terms are near zone and Fresnel region.

Near zone. See near field.

Normal probe. Probe from which waves propagate at 90° to its contact surface.

Opacity technique. Ultrasonic shear wave technique for the examination of thin plate which makes use of the principle that if the plate thickness is less than a minimum value, ultrasonic waves at a fixed angle and frequency are unable to propagate.

Operating frequency. Centre frequency of a pulse spectrum generated by an ultrasonic probe. **Note:** The frequency is determined by a number of factors including the electrical circuit connected to the probe, the thickness of the piezo-electric material and its backing.

Parasitic echo. See spurious echo.

Piezo-electric effect/transducer. Transducer in which the application of an electric field across the active element produces mechanical deformation of the active element thereby generating ultrasonic vibrations and vice versa.

Pitch and catch technique. Ultrasonic testing technique involving the use of two separate probes, one being used to transmit the ultrasonic energy into the body and the other positioned so as to receive the reflected energy from a discontinuity. **Note:** In variations of the technique, more than two probes may be used.

Plane wave. Wave in which points of the same phase lie on parallel plane surfaces.

Plate waves. See Lamb waves.

Poisson's ratio. Ratio of transverse strain to tensile strain.

Primary scan axis. Major direction of probe scanning movement.

Probe. Electromechanical device, usually incorporating one or more ultrasonic crystals, and functioning as a generator and/or receiver of ultrasonic waves.

Probe array. Array of probes which may comprise: **(1)** Probes in a mechanical holder which scan together and are used sequentially, individually and/or in pairs. **(2)** A single unit comprising probes used as in (1).

Probe face. Part of a probe through which ultrasonic waves are transmitted and received.

Probe index. Point on a shear wave or surface wave probe through which the emergent beam axis passes. **Note:** The index can vary slightly depending on the method of measurement.

Probe shoe. Shaped piece of solid material interposed between the probe and the material under examination for the purpose of improving acoustical contact.

Probe shoe delay. Time taken for the transmitted ultrasonic wave to traverse the probe shoe and to be reflected back to the ultrasonic crystal.

Proportional output. Output signal from ultrasonic or electronic equipment which is proportional to the peak amplitude of an input ultrasonic pulse, such as a defect echo.

Pulse. Short electrical or acoustical wave train.

Pulse amplitude. Pulse height of a signal, usually base to peak, when displayed in an A-scan.

Pulse duration. See pulse length.

Pulse echo technique. Technique in which the presence of a discontinuity in a material is indicated by a reflection of pulses from it.

Pulse energy. Total energy associated with a single pulse.

Pulse envelope. Outline of a pulse indication.

Pulse length. Time interval between the leading and trailing edges of a pulse, usually measured at the half-amplitude value. **Note:** Synonymous terms are pulse duration and pulse width.

Pulse repetition frequency (PRF). Number of pulses transmitted per second.

Pulse width. See pulse length.

Quadruple traverse technique. Technique in which a beam of ultrasonic waves is directed into a region of a body under examination, after having been reflected successfully three times by surfaces of the body. **Note:** A synonymous term is triple bounce technique.

Range resolution. Ability of an ultrasonic flaw detection system to give separate indications from two reflectors at similar range within the sound beam. See also lateral resolution.

Rayleigh waves. Particular type of surface wave which propagates on the surface of a body with effective penetration of less than a wavelength.

Reference piece. An aid to interpretation in the form of a test piece of the same nominal composition, significant dimensions and shape as a particular object under examination. **Note:** Such pieces may or may not contain natural or artificial imperfections.

Reference standard. Artificially produced imperfection of predetermined dimensions, usually a notch or hole, used for the sole purpose of establishing the test sensitivity of the ultrasonic equipment.

Reflecting surface. Interface at which the ultrasonic beam encounters a change in characteristic impedance.

Reflection coefficient. Ratio of reflected sound amplitude to incident sound amplitude at a reflecting surface. **Note:** A synonymous term is reflection factor.

Reflection factor. See reflection coefficient.

Reflection technique. Technique in which the presence of discontinuities in a material is indicated by receiving the reflected energy from them.

Refracting prism. A prism, usually of plastic material, which when placed in acoustical contact between an ultrasonic crystal and a body will cause ultrasonic waves to be refracted at a known angle into that body.

Refractive index. Ratio of the velocity of an incident wave in one material to the velocity of a refracted wave in a second material in acoustical contact with the first material.

Reject (rejection). Reduction of grass by the elimination of all signals below a predetermined amplitude. **Note:** A synonymous term is suppression.

Resolution. Ability of an ultrasonic flaw detection system to give separate indications of discontinuities having nearly the same range and/or lateral position with respect to the beam axis.

Resonance technique. Examination technique which involves varying the frequency of ultrasonic waves to excite a maximum amplitude of vibration in a body, or part of a body, generally for the purpose of determining thickness from one side only.

Reverberation time. Time required for the intensity of an unsustained vibration in a closed system to decrease to one millionth of its initial value, eg by 60dB.

Ringing time. Time during which the mechanical vibrations of a crystal continue after the electrical pulse has stopped.

Rotational wave. See shear wave.

Scale expansion. See expanded time-base sweep.

Scan pitch. Pitch or distance between lines of scan during passage of the probe(s) over the scan area.

Scanning. Systematic relative displacement of the ultrasonic beam and the material under test.

Scatter (ultrasonic). Energy reflected in a random way by small reflectors in the path of a beam of ultrasonic waves (eg grain boundaries).

Schlieren system. Optical system used to display an ultrasonic beam visually, by passing it through a transparent medium.

Screen marker. Small electronically generated pulses following one another at a preset time interval, presented on a time-base sweep to provide a calibration less dependent on the linearity of the time base.

Second critical angle. Angle of incidence of a longitudinal wave in one medium such that the refracted transverse wave is at 90^{o}, ie along the surface of the second medium.

Sensitivity. Ability of an ultrasonic system to identify a small reflector in the far distance.

Sequence number. In an automatic testing system, the order of connection of channels and probes required to perform defined scans.

Shadow technique. Technique in which a discontinuity in a material is revealed by the acoustical shadow it produces.

Shadow zone. Region in a body which cannot be reached by ultrasonic energy travelling in a given direction, because of the shape of the body or a discontinuity in it.

Shear wave. Form of wave motion in which the particle displacement at each point in a material is at right angles to the direction of propagation. **Note:** Synonymous terms are distortional wave, rotational wave and transverse wave.

Shear wave probe. Probe for generating or detecting shear waves.

Short pulse. Pulse which has few (usually less than 1.5) cycles in the time interval over which its amplitude exceeds half of its maximum amplitude.

Side lobe. Peak or pronounced shoulder in an ultrasonic beam lying to one side of the main beam.

Signal-to-noise ratio (SNR). Ratio of the amplitude of an ultrasonic echo arising from a discontinuity in a material to the amplitude of the average background noise.

Single bounce technique. See double traverse technique.

Single probe technique. Technique involving the use of a single crystal probe for both transmitting and detecting ultrasonic waves.

Single traverse technique. Examination technique in which a beam of ultrasonic waves is directed into a region of a body under examination without intermediate reflection. **Note:** A synonymous term is direct scan.

Sizing technique. Technique which enables an estimate of the size of a discontinuity to be made from its ultrasonic responses. **Note:** Examples of sizing techniques are 6dB drop (half maximum) technique, 20dB drop technique and maximum amplitude technique.

Skip distance. For a beam of shear waves entering a body, the distance measured over the surface of the body between the probe index and the point where the beam axis impinges on the surface after a single reflection from the opposite surface.

Snell's law. States that the angle of refraction is a function of the angle of the incident beam and the change in relative velocity between the two materials.

Soft-faced probe. Probe in which the contact surface is a flexible membrane and a space between the crystal and membrane is filled with a liquid couplant.

Soft-tipped probe. Probe in which a thick flexible medium forms the coupling between its crystal and the surface of the material under test.

Sound attenuation. Reduction in the level of sound intensity due to distortion, scatter and beam spread.

Specific acoustic impedance. Property of a medium which determines the amount of reflection that occurs at an interface with another medium. **Note:** It is defined mathematically as the product of the density of the medium and the velocity of the wave travelling through it.

Specular reflection. A mirror-like reflection of an ultrasonic beam such that the angle of incidence is equal to the angle of reflection.

Spherical reflector. Surface of spherical or near spherical form, separating two media of different characteristic impedance.

Spherical wave. Wave in which points of the same phase lie on the surfaces of concentric spheres.

Spurious echo. Term used for any indication not obviously associated with a discontinuity or boundary. **Note:** A synonymous term is parasitic echo.

Spurious indication. See spurious echo.

Stand-off. Block, usually of plastic material, which serves to separate the ultrasonic crystal(s) from the surface of the test piece. **Note:** The use of such blocks is generally confined to compression wave probes.

Stationary wave. Effect produced by the superposition of wave trains moving in opposite directions with the formation of stationary nodes and antinodes.

Subsidiary maxima. Irregular fluctuations in the response of a small reflector as an ultrasonic beam is scanned over it.

Suppression. See reject.

Surface noise. Unwanted signals at very short range, produced by ultrasonic waves being reflected within the coupling film and from irregularities of the surface.

Surface preparation. Processing of a surface necessary to render it suitable for providing good acoustical coupling for ultrasonic testing.

Surface wave. Ultrasonic wave which propagates on the surface of a body.

Surface wave probe. Probe for generating and/or detecting surface waves.

Swivel scan. Shear wave technique used to provide information about the form of a previously located discontinuity, the probe(s) being positioned at a constant distance from and directed at the discontinuity and rotated by an angle of up to 360°.

Tandem probe technique. Technique involving the use of two probes, one transmitting the ultrasonic energy into the body and the other positioned to pick up any energy reflected from a discontinuity. **Note:** The probes are usually scanned together at a fixed separation and the technique is mostly used for the detection of vertically oriented, through-wall, planar defects.

Test block. Piece of material capable of propagating ultrasonic waves and suitable for assessing particular features of ultrasonic equipment performance.

Test surface. Surface of a piece of material through which ultrasonic waves pass.

Threshold. Minimum signal amplitude that is regarded as significant in a particular ultrasonic examination.

Time base. Trace on the screen of a cathode ray tube which is generated in such a way that distance along it is proportional to time.

Time base range. Maximum ultrasonic path length that can be displayed on a particular time base.

Time corrected gain. Facility of flaw detectors to represent flaws of equal reflective size with the same screen amplitude, irrespective of their depth in the material.

Time marker. See screen marker.

Toe-in-semi-angle. Half the angle between the normals to the crystal faces in a twin crystal probe.

Total attenuation. Diminution of intensity of a particular mode, with travel range, of an ultrasonic beam of any form arising from the combined effects of absorption, scatter and geometric beam spread.

Total internal reflection. Reflection which occurs when the angle of incidence is greater than the critical angle and the reflection coefficient is unity.

Transceiver. Probe used to generate and detect ultrasonic energy.

Transducer. Electroacoustical device for converting electrical energy into acoustical energy and vice versa.

Transmission coefficient. Ratio of ultrasonic wave intensity transmitted across an interface to the total wave energy incident upon the interface.

Transmission point. Point on the time base which corresponds to the instant at which ultrasonic energy enters the material under examination.

Transmission technique. Technique in which the quality of a material is assessed by the intensity of the ultrasonic radiation incident on the receiving probe after the waves have travelled through the material.

Transverse wave. See shear wave.

Trigger/alarm condition. Condition where the equipment indicates that a piece of material is suspect.

Trigger/alarm level. Level at which the ultrasonic equipment is required to differentiate between acceptable and suspect material.

Triple bounce technique. See quadruple traverse technique.

Triple traverse technique. Technique in which a beam of ultrasonic waves is directed into a region of a body under examination after having been reflected successively by two surfaces of the body. **Note:** A synonymous term is double bounce technique.

Twin crystal probe. See double crystal probe.

Ultrasonic frequency. Any frequency of vibration greater than the range of audibility of the human ear, generally taken as greater than 20kHz.

Ultrasonic mode changer. Device which causes vibrations of a particular mode (eg compressional) in one body to produce vibrations of another mode (eg shear) in another body.

Wavelength (λ). Perpendicular distance between two wave fronts with a phase difference of one complete period.

Ultrasonic wave. Disturbance which travels through a material at ultrasonic frequency by virtue of the elastic properties of that material.

Wedge (ultrasonic). Device placed between the probe and the test surface for the purpose of causing ultrasonic waves to pass between the two at a particular angle.

Wetting Agent. Substance added to a coupling liquid to decrease its surface tension.

Young's modulus of elasticity. In an elastic material, the ratio of tensile stress to tensile strain.

TWI

Ultrasonic Testing (UT) - Welds

NDT4

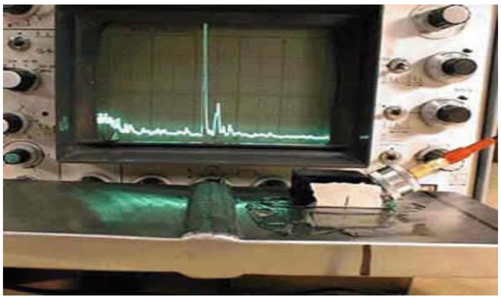
Materials Joining and Engineering Technologies

Training and Examination Services

NDT4-51015

TWI

Ultrasonic Inspection



Part 1 Principles of Sound

TWI

Course Objectives

- Explain the theoretical background of the techniques.
- Calibrate ultrasonic equipment.
- Measure the thickness of steel plates and determine levels of attenuation.
- Locate and evaluate laminations.
- Select the correct type of probe to examine welded butt joints in steel plate and aerospace components/structures.
- Report on the location and size of defects in typical welded butt joints.
- Interpret code requirements.
- Meet the syllabus requirements for PCN/CSWIP Levels 1 and 2.

TWI

History of Ultrasonic Testing

- From very early times castings were tested for soundness by tapping with a hammer.
- The piezo-electric effect was investigated by Jacques and Pierre Curie in 1880/81.
- Marine echo sounding for submarine and fish detection developed from 1912.
- In 1929 Sokolov developed the first ultrasonic test method for the detection of flaws in steel castings.
- Cathode ray tubes became available in the 1930s.
- Sproule designed and built the first pulse echo flaw detector in 1942.

TWI

What is Sound?

- A mechanical vibration.
- The vibrations create pressure waves.
- Sound travels faster in more elastic materials.
- Number of pressure waves per second is the frequency.
- Speed of travel is the sound velocity.

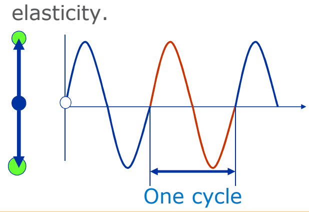
TWI

What is Sound?

Sound waves are the vibration of particles in solids, liquids or gases.

Particles vibrate about a mean position.

In order to vibrate they require mass and elasticity.



Properties of a Sound Wave

Velocity
How quickly a sound wave travels.

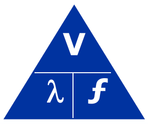
Frequency
How many vibrations per second.

Wavelength
How far a sound wave advances in completing one cycle.

Wavelength **Velocity**

$$\lambda = \frac{V}{f}$$

Frequency



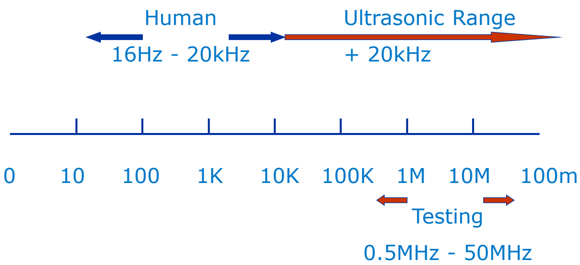
High Frequency Sound

$$\lambda = \frac{V}{f}$$

5MHz compression wave in steel

$$\lambda = \frac{5,900,000}{5,000,000} = 1.18mm$$

Acoustic Spectrum



Sound Travelling Through a Material

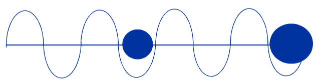
Velocity varies according to the material

Compression waves		Shear waves	
Steel	5960m/sec	Steel	3245m/sec
Water	1490m/sec	Water	NA
Air	344m/sec	Air	NA
Copper	4700m/sec	Copper	2330m/sec

Compression vs Shear

Frequency	Compression	Shear
0.5MHz	11.8mm	6.5mm
1 MHz	5.9mm	3.2mm
2MHz	2.95mm	1.6mm
4MHz	1.48mm	0.8mm
6MHZ	0.98mm	0.54mm

The smaller the wavelength the better the sensitivity
Minimum detectable defect taken as half the wavelength



Less than half wavelength – defect may not be detected

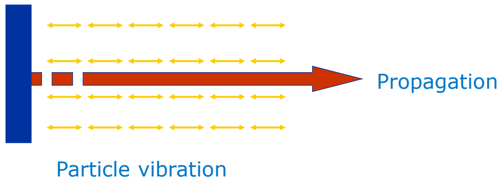
More than half wavelength – defect should be detected

Principal Waveforms Used in UT Inspections

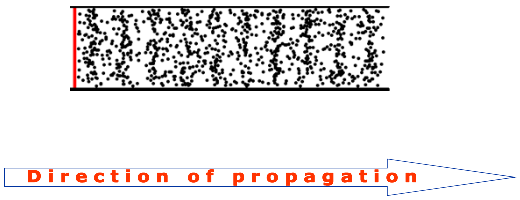
- Compression - also known as Longitudinal.
- Shear – also known as Transverse.
- Surface – also known as Rayleigh.
- Lamb – also known as Plate.

Compression Waves

- Vibration and propagation in the same direction.
- Travel in solids, liquids and gases.

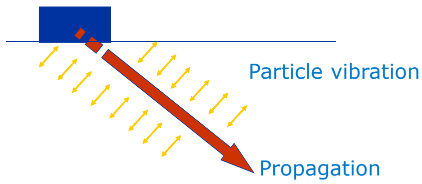


Compression Waves

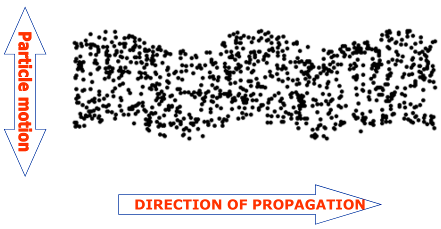


Shear Waves

- Vibration at right angles to direction of propagation.
- Travel in solids only.
- Velocity ≈ 1/2 compression (in same material).

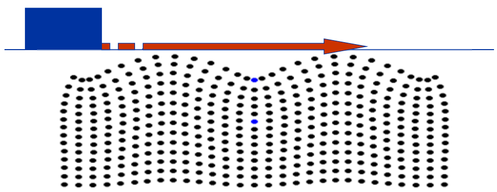


Shear Waves

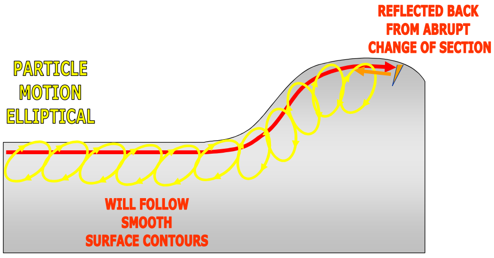


Surface Waves

- Elliptical vibration.
- Velocity 8% less than shear.
- Penetrate up to one wavelength deep.



Surface Waves

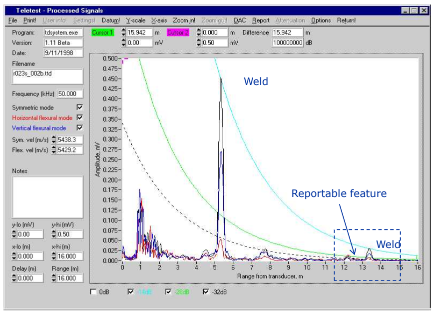


Lamb Waves

- Propagate in thin plate materials where plate thickness is equivalent to wavelength.
- Particle motion is a complex combination of symmetrical and non-symmetrical elliptical waves.
- Velocity varies with plate thickness and wavelength.

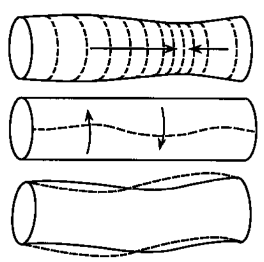
Long Range UT: Alaska 24" Road Crossing

Long Range UT: Alaska 24" Road Crossing



Long Range UT: Alaska 24" Road Crossing

Long Range UT: Wave Modes in Pipes



Longitudinal

Torsional

Flexural

Sound Intensity

Comparing the intensity of 2 signals

$$\frac{I_0}{I_1} = \frac{P_0}{P_1}$$

Electrical power proportional to the square of the voltage produced

$$\frac{P_0}{P_1} = \frac{(V_0)^2}{(V_1)^2} \qquad \text{Hence} \qquad \frac{I_0}{I_1} = \frac{(V_0)^2}{(V_1)^2}$$

Sound Intensity

$$\frac{I_0}{I_1} = \frac{(V_0)^2}{(V_1)^2}$$

Will lead to large ratios

Therefore:

$$Log_{10}\frac{I_0}{I_1} = Log_{10}\frac{(V_0)^2}{(V_1)^2}$$

$$Log_{10}\frac{I_0}{I_1} = 2Log_{10}\frac{V_0}{V_1}\ BELS$$

$$Log_{10}\frac{I_0}{I_1} = 20Log_{10}\frac{V_0}{V_1}\ dB$$

Take 2 Signals at 20% and 40% FSH

What is the difference between them in dB?

$$dB = 20\log_{10}\frac{H_0}{H_1}$$

$$dB = 20\log_{10}\frac{40}{20} = 20\log_{10}2$$

$$dB = 20 \times 0.3010$$

$$dB = 6dB$$

Take 2 Signals at 10% and 100% FSH

What is the difference between them in dB?

$$dB = 20\log_{10}\frac{H_0}{H_1}$$

$$dB = 20\log_{10}\frac{100}{10} = 20\log_{10}10$$

$$dB = 20 \times 1$$

$$dB = 20dB$$

Amplitude Ratios in Decibels

- 2 : 1 = 6bB = 50%
- 4 : 1 = 12dB = 25%
- 5 : 1 = 14dB = 20%
- 10 : 1 = 20dB = 10%
- 100 : 1 = 40dB = 1%

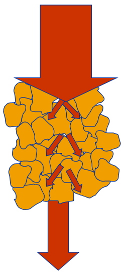
Sound Travelling Through a Material

Loses intensity due to

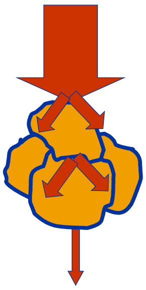
Beam spread
- Sound beam comparable to a torch beam.
- Reduction differs for small and large reflectors.

Attenuation
- Energy losses due to material.
- Made up of absorption and scatter.

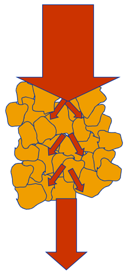
Scatter



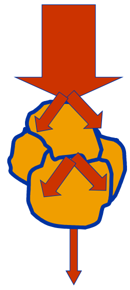
- The bigger the grain size the worse the problem.
- The higher the frequency of the probe the worse the problem.



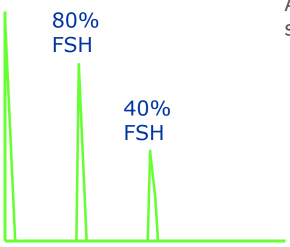
Scatter



- Scatter becomes significant as the average grain size exceeds about 1/10 of the wavelength.
- If the average grain size reaches 1/2 of the wavelength extremely high attenuation will occur.
- If the average grain size exceeds the wavelength ultrasonic testing will be impossible.

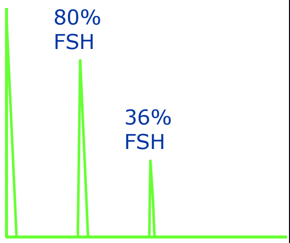


Beam Spread and Attenuation Combined



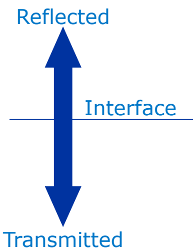
No attenuation, only beam spread. 6dB reduction.

Attenuation and beam spread. 6dB+ reduction.



Sound at an Interface

Sound will be either transmitted across or reflected back.



How much is reflected and transmitted depends upon the relative acoustic impedance of the two materials.

Acoustic Impedance

Definition

- Resistance to travel of sound waves within a material.

Measured in kg/m² x sec

Formula

- $Z = \rho \times V$

Is the product of density and velocity

- Steel 46.7 x 10^6
- Water 1.48 x 10^6
- Air 0.0041 x 10^6
- Perspex 3.2 x 10^6

% Sound Reflected at an Interface

$$\left[\frac{Z_1 - Z_2}{Z_1 + Z_2}\right]^2 \times 100 = \%\ reflected$$

% sound reflected + % sound transmitted = 100%.

Therefore:

% sound transmitted = 100% - % sound reflected.

TWI

How Much Sound is Reflected at a Steel to Water Interface?

- Z_1 (Steel) = 46.7 x 10^6
- Z_2 (Water) = 1.48 x 10^6

$$\left[\frac{46.7-1.48}{46.7+1.48}\right]^2 \times 100 = \%\ reflected$$

$$\left[\frac{45.22}{48.18}\right]^2 \times 100 = \%\ reflected$$

$0.93856^2 = 0.8809 \times 100$

$= 88.09\%$

TWI

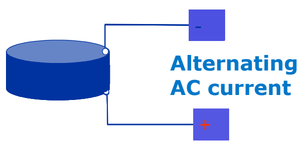
Sound Generation

- Hammers (Wheel tappers).
- Magnetostrictive.
- Lasers.
- Piezo-electric.

TWI

Piezo-Electric Effect

- When exposed to an alternating current a crystal expands and contracts.
- Converting electrical energy into mechanical.



TWI

Piezo-Electric Materials

Quartz
- Resistant to wear.
- Insoluble in water.
- Resists ageing.
- Inefficient converter of energy.
- Needs a relatively high voltage.

Lithium sulphate
- Efficient receiver.
- Low electrical impedance.
- Operates on low voltage.
- Water soluble.
- Low mechanical strength.
- Useable only up to 130ºC.

TWI

Polarised Crystals

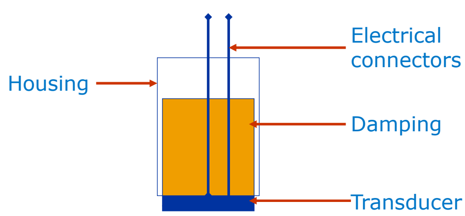
- Powders heated to high temperatures.
- Pressed into shape.
- Cooled in very strong electrical fields.

Examples:
- Barium titanate ($Ba\ Ti\ O_3$).
- Lead metaniobate ($Pb\ Nb_2\ O_6$).
- Lead zirconate titanate ($Pb\ Ti\ O_3$ or $Pb\ Zr\ O_3$).

TWI

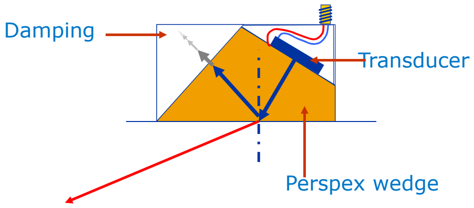
Probe Design

Compression wave



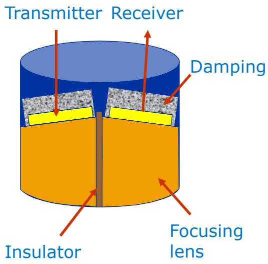
Probe Design

Shear wave



Probe Design

Twin crystal



Advantages:

- Can be focused.
- Measure thin plate.
- Near surface resolution.

Disadvantages:

- Difficult to use on curved surfaces.
- Sizing small defects.
- Signal amplitude/focal spot length.

Ultrasonic Testing
Part 2

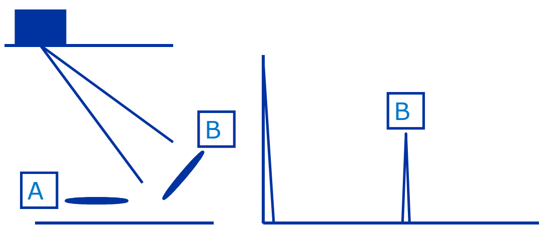
Ultrasonic Test Methods

- Pulse Echo.
- Through Transmission.
- Transmission with Reflection.

Pulse Echo Testing

- Single probe sends and receives sound.
- Gives an indication of defect depth and dimensions.
- Not fail safe.

Defect Position

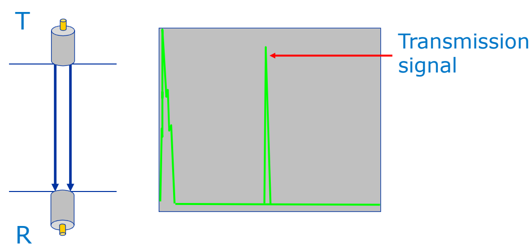


No indication from defect A (wrong orientation)

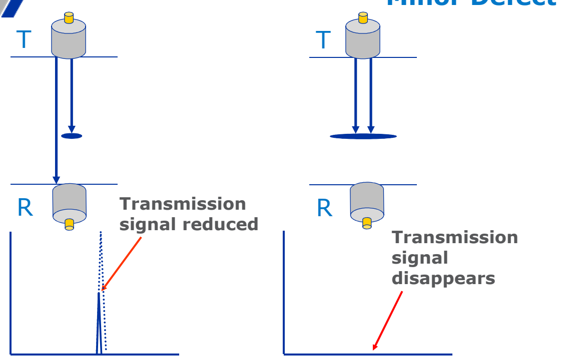
Through Transmission Testing

- Transmitting and receiving probes on opposite sides of the specimen.
- Presence of defect indicated by reduction in transmission signal.
- No indication of defect location.
- Fail safe method.

Through Transmission Testing



Minor Defect

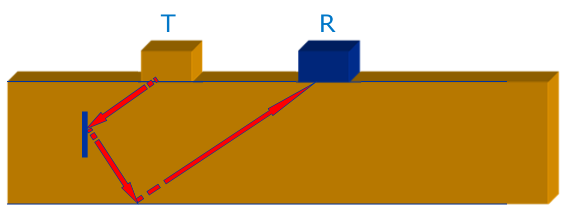


Through Transmission Testing

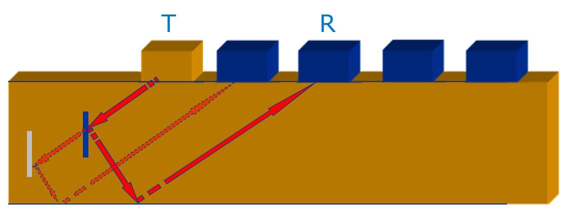
Advantages:
- Less attenuation.
- No probe ringing.
- No dead zone.
- Orientation does not matter.

Disadvantages:
- Defect not located.
- Defect can't be identified.
- Vertical defects don't show.
- Must be automated.
- Need access to both surfaces.

Transmission with Reflection

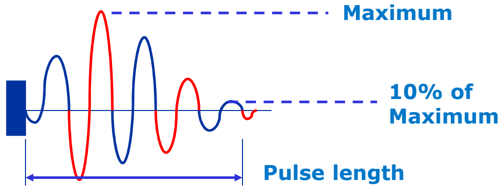


Transmission with Reflection



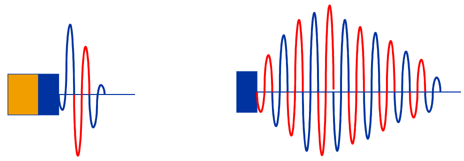
Pulse Length

- A short pulse of electricity is applied to a piezo-electric crystal.
- The crystal begins to vibrate, increases to maximum amplitude and then decays.



Pulse Length

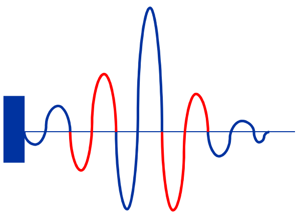
- The longer the pulse, the more penetrating the sound.
- The shorter the pulse, the better the sensitivity and resolution.



Short pulse, 1 or 2 cycles

Long pulse, 12 cycles

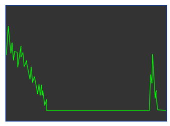
Ideal Pulse Length

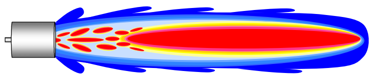


5 cycles for weld testing

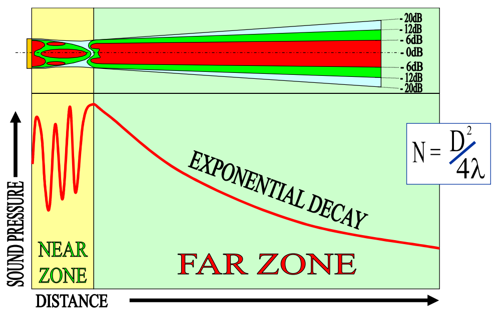
The Sound Beam

- Dead zone.
- Near zone or Fresnel.
- Far zone or Fraunhofer.





The Sound Beam



Sound Beam

Near zone:
- Thickness measurement.
- Detection of defects.
- Sizing of large defects only.

Far zone:
- Thickness measurement.
- Detection of defects.
- Sizing of all defects.

Near zone length as small as possible.

Near Zone

$$\text{Near Zone} = \frac{D^2}{4\lambda}$$

$$\lambda = \frac{V}{f}$$

$$\text{Near Zone} = \frac{D^2 f}{4V}$$

Near Zone

- What is the near zone length of a 5MHz compression probe with a crystal diameter of 10mm in steel?

$$\text{Near Zone} = \frac{D^2 f}{4V}$$

$$= \frac{10^2 \times 5,000,000}{4 \times 5,920,000}$$

$$= 21.1\,mm$$

Near Zone

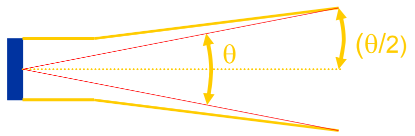
- The bigger the diameter the bigger the near zone.
- The higher the frequency the bigger the near zone.
- The lower the velocity the bigger the near zone.

$$\text{Near Zone} = \frac{D^2}{4\lambda} = \frac{D^2 f}{4V}$$

Should large diameter crystal probes have a high or low frequency?

Beam Spread

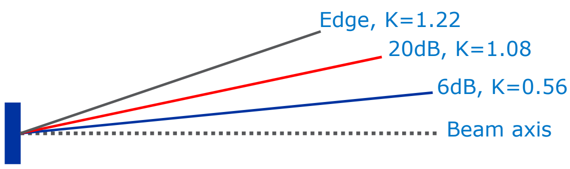
In the far zone sound pulses spread out as they move away from the crystal.



$$\sin\left(\frac{\theta}{2}\right) = \frac{K\lambda}{D} \text{ or } \frac{KV}{Df}$$

Beam Spread

$$\sin\left(\frac{\theta}{2}\right) = \frac{K\lambda}{D} \text{ or } \frac{KV}{Df}$$



Beam Spread

$$\sin\left(\frac{\theta}{2}\right) = \frac{K\lambda}{D} \text{ or } \frac{KV}{Df}$$

- The bigger the diameter the smaller the beam spread.
- The higher the frequency the smaller the beam spread.

Which has the larger beam spread, a compression or a shear wave probe?

TWI

Beam Spread

What is the half beam spread of a 10mm, 5MHz compression wave probe in steel to the 20dB point?

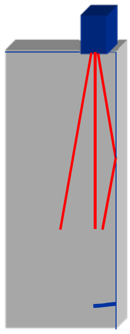
$$\sin\left(\frac{\theta}{2}\right) = \frac{KV}{Df}$$

$$= \frac{1.08 \times 5920}{5000 \times 10}$$

$$= 0.1278 \qquad = 7.35^{o}$$

TWI

Testing Close to Side Walls

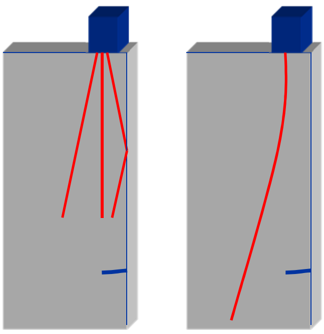


Remember!

The ultrasonic pulse is a pressure wave which can be diverted from its original path by other waves exerting pressure from the side.

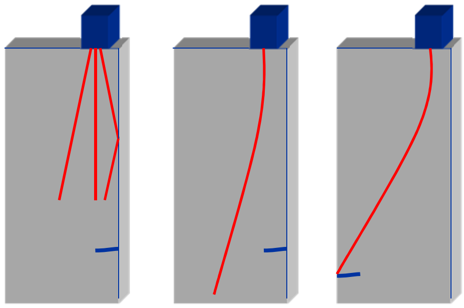
TWI

Testing Close to Side Walls



TWI

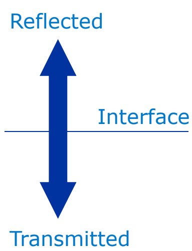
Testing Close to Side Walls



TWI

Sound at an Interface

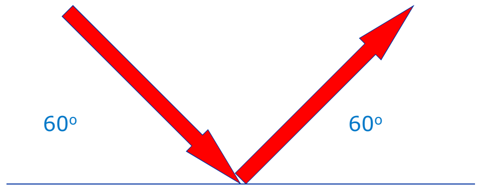
Sound will be either transmitted across or reflected back.



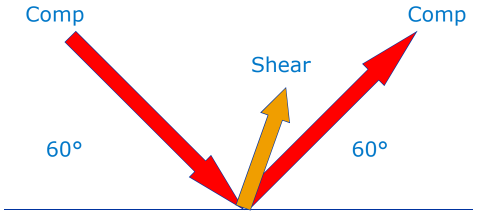
TWI

Inclined Incidence (not at 90°)

Angle of incidence = angle of reflection



Inclined Incidence (not at 90°)



Mode conversion

Ghost Echoes

- **Pulse repeat frequency (PRF)** is typically of the order of 1,000Hz.
- In 1/1,000 of a second a compression wave in steel travels about 5.96m.
- Using a PRF of 1,000Hz a steel slab up to 5.96/2 = 2.98m thick can be tested.
- If the slab exceeds 2.98m thick sound will arrive back at the probe **after** a second pulse of sound has been emitted.

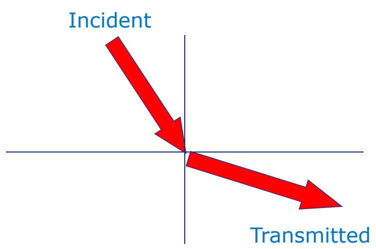
Ghost Echoes

- Thus the flaw detector will display an echo at a range equal to the actual range minus 2.98m.
- Such an echo is called a **ghost echo**.
- In the A-scan display the position of such echoes tends to oscillate slightly, even when the probe itself remains stationary.
- **Ghost echoes** can cause problems when testing bulky components that have low ultrasonic attenuation.

Ghost Echoes

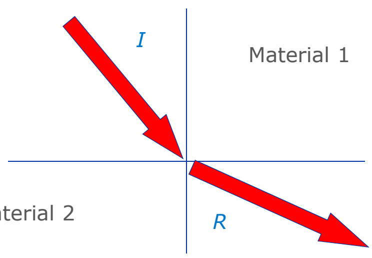
- **Ghost echoes** can be eliminated by reducing the PRF, on flaw detectors which provide the facility to do this.
- On many older portable flaw detectors it is not possible to adjust PRF.

Inclined Incidence(not at 90°)



The sound is refracted due to differences in sound velocity in the 2 materials.

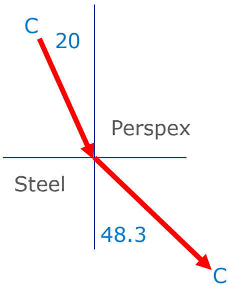
Snell's Law



$$\frac{\sin I}{\sin R} = \frac{V \text{ in Material } 1}{V \text{ in Material } 2}$$

TWI

Snell's Law



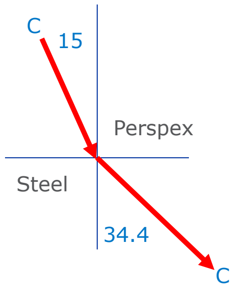
$$\frac{\sin I}{\sin R} = \frac{V \text{ in Material1}}{V \text{ in Material2}}$$

$$\frac{\sin(20)}{\sin(48.3)} = \frac{2730}{5960}$$

$$0.4580 = 0.4580$$

TWI

Snell's Law



$$\frac{\sin I}{\sin R} = \frac{V \text{ in Material1}}{V \text{ in Material2}}$$

$$\frac{\sin(15)}{\sin R} = \frac{2730}{5960}$$

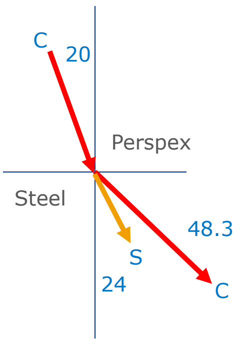
$$\sin R = \sin(15 \frac{5960}{2730})$$

$$\sin R = 0.565$$

$$R = 34.4$$

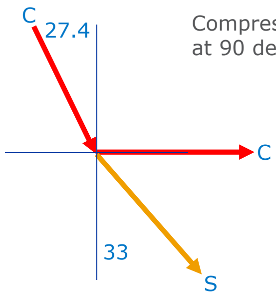
TWI

Snell's Law



TWI

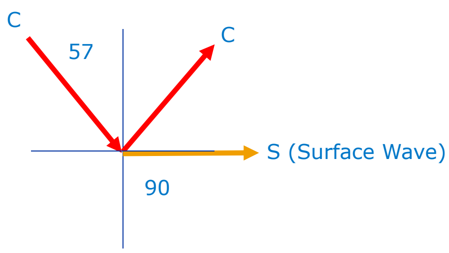
1st Critical Angle



Compression wave refracted at 90 degrees

TWI

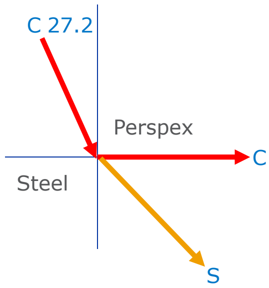
2nd Critical Angle



Shear wave refracted at 90 degrees.
Shear wave becomes a surface wave.

TWI

1st Critical Angle Calculation



$$\frac{\sin I}{\sin 90} = \frac{2730}{5960}$$

$$\sin(90) = 1$$

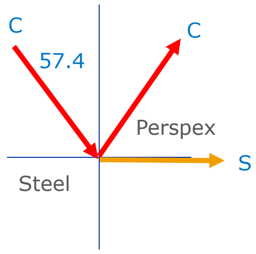
$$\sin I = \frac{2730}{5960}$$

$$\sin I = 0.458$$

$$I = 27.26$$

TWI

2nd Critical Angle Calculation



$$\frac{\sin I}{\sin(90)} = \frac{2730}{3240}$$

$$\sin(90) = 1$$

$$\sin I = \frac{2730}{3240}$$

$$\sin I = 0.8425$$

$$I = 57.4$$

TWI

Summary

- Standard angle probes between 1st and 2nd critical angles (45,60,70).
- Stated angle is refracted angle in steel.
- 1st critical angle: compression refracted at 90 degrees.
- 2nd critical angle: shear refracted at 90.
- 2nd critical angle produces surface waves.

TWI

Snell's Law

- Calculate the 1st critical angle for a perspex/copper interface.
- V Comp perspex: 2730m/sec.
- V Comp copper: 4700m/sec.

$$\sin I = \frac{2730}{4700} = 0.5808 = 35.5$$

TWI

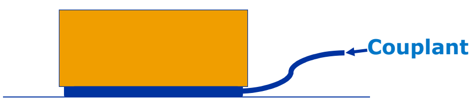
Automated Inspections

- Pulse echo.
- Through transmission.
- Transmission with reflection.
- Contact scanning.
- Gap scanning.
- Immersion testing.

TWI

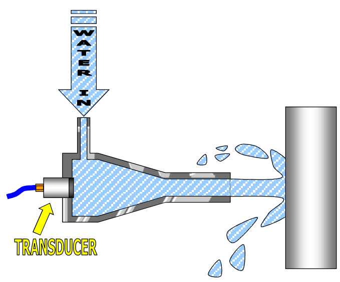
Gap Scanning

- Probe held a fixed distance above the surface (1 or 2mm).
- Couplant is fed into the gap.



TWI

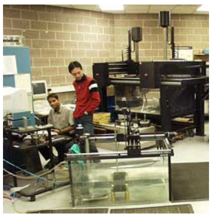
Bubblers and Squirters



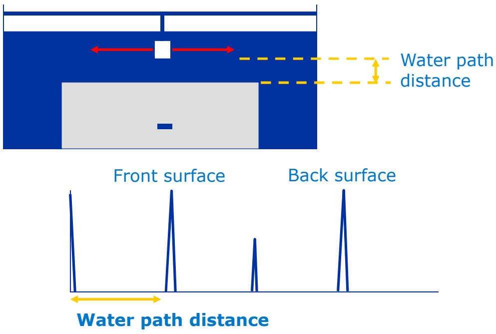
Bubblers and Squirters

Immersion Testing

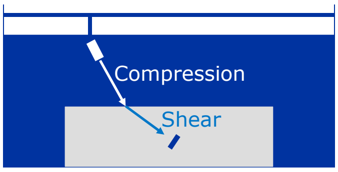
- Component is placed in a water filled tank.
- Item is scanned with a probe at a fixed distance above the surface.



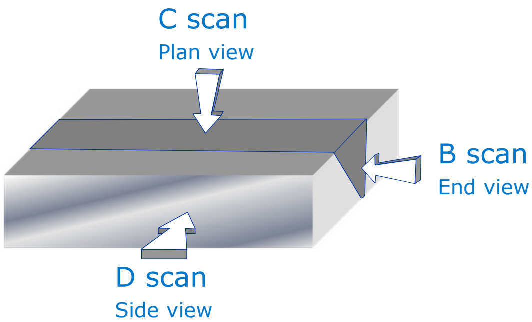
Immersion Testing



Immersion Testing Angulation

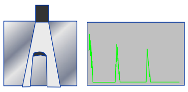


Ultrasonic Displays



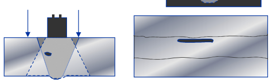
Ultrasonic Displays

A scan
- Time or distance along X axis.
- Returned echo amplitude Y axis.



B scan
End view

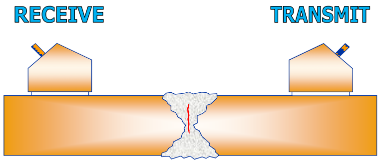
C scan
Plan view



D scan
Side view

TWI

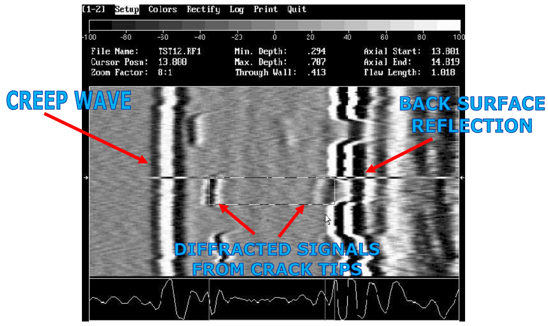
Time of Flight Diffraction



The probes are designed to flood the entire cross section with a wide range of compression and shear wave angles. The diffracted signals from the tips of non-planar defects permit extremely accurate sizing.

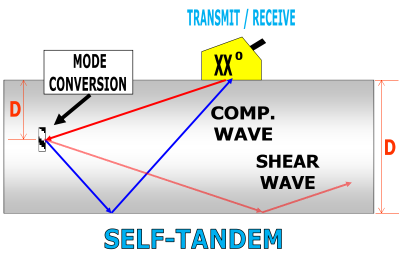
TWI

Time of Flight Diffraction



TWI

Other Special Techniques



TWI

Other Special Techniques

Self-tandem, ferritic steel, 100mm thick	
Shear wave angle	**Inspection depth (D, mm)**
62°	95
66°	67
70°	46
74°	29

TWI

Ultrasonic Testing
Part 3

TWI

Ultrasonic Inspection

- Sensitivity.
- Scanning procedure.
- Defect sizing.

Sensitivity

The ability of an ultrasonic system to find the smallest specified defect at the maximum testing range.

Depends upon

- Probe and flaw detector combination.
- Material properties.
- Probe frequency.
- Signal-to-noise ratio.

Methods of Setting Sensitivity

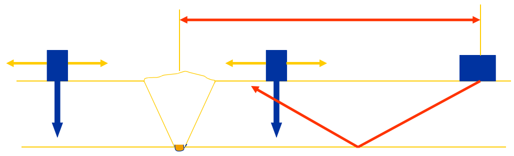
- Smallest defect at maximum test range.
- Back wall echo.
- Disc equivalent.
- Grass levels.
- Side-drilled holes, DAC curves.

Scanning Procedure

- Parent material.
- Root inspection.
- Side wall inspection.
- Weld body.
- Transverse scan.

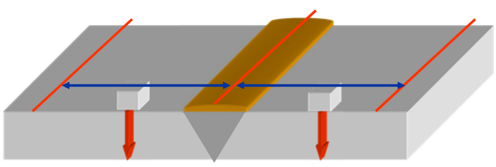
Scanning Procedure

Parent material
0 degree both sides



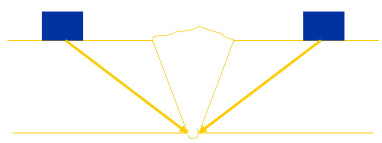
- To maximum range for angle probes.
- Full skip distance for 60° or 70° probes.

Parent Plate Inspection Using 00 Compression Probe

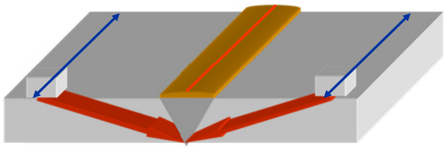


Scanning Procedure

- Weld root.
- Half skip from both sides.

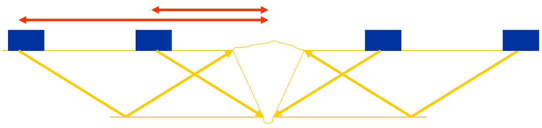


Fixed Root Scan



Scanning Procedure

Weld fusion faces
Half to full skip from both sides.

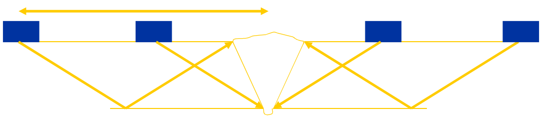


A probe which strikes fusion faces at 90 degrees.
Probe angle = 90 - (1/2 root angle).

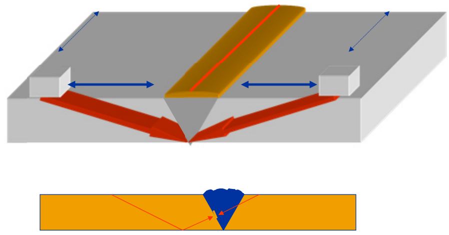
Scanning Procedure

Weld body
Half skip to full skip from both sides

Full skip 1/2 Skip



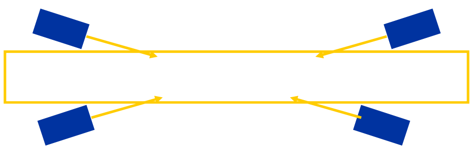
Scanning Procedure



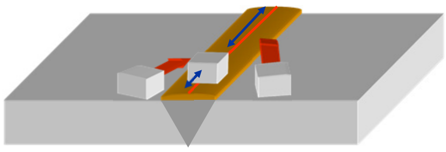
Fusion face and weld body inspection

Scanning Procedure

Transverse
70 degree



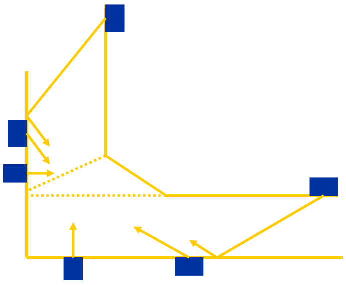
Scanning Procedure



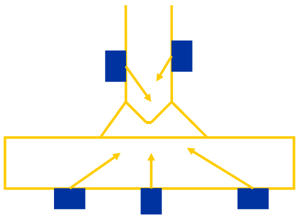
Transverse scan

Nozzle Welds

Scanning procedure



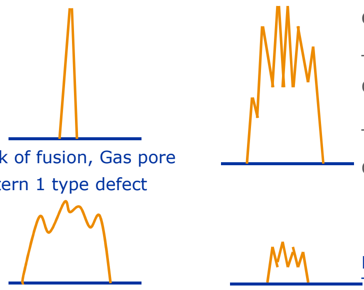
Tee Butt Welds



Defect Identification

- Echodynamics.
- Defect characterisation.

Echodynamics



Crack:

Type 3A defect
Crack at 90^0 to beam

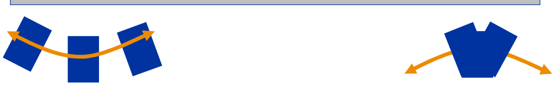
Type 3B defect
Crack oblique to beam

Defect Characterisation

Signal amplitude — Lateral

Probe manipulation — Depth

Orbital — Swivel



$$dB = 20\log_{10}\frac{H_0}{H_1}$$

$$\frac{\sin I}{\sin R} = \frac{V \text{ in Material1}}{V \text{ in Material2}}$$

$$\left[\frac{Z_1 - Z_2}{Z_1 + Z_2}\right]^2 \times 100 = \%\ reflected$$

$$t = \frac{V}{2f}$$

$$\sin\left(\tfrac{\theta}{2}\right) = \frac{K\lambda}{D} \text{ or } \frac{KV}{Df}$$

$$\lambda = \frac{V}{f}$$

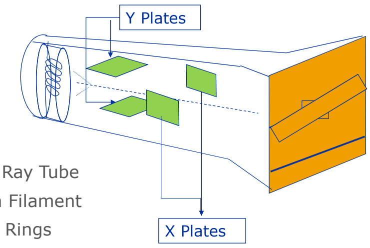
$$\text{Near Zone} = \frac{D^2}{4\lambda} = \frac{D^2 f}{4V}$$

TWI

Ultrasonic Testing
Part 4

TWI

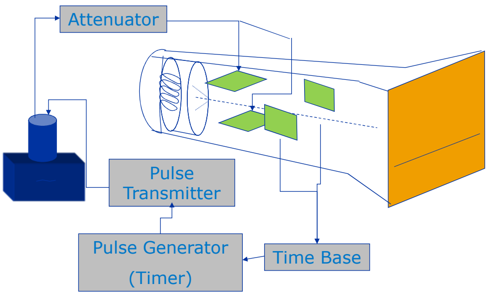
Ultrasonic Equipment



Cathode Ray Tube
Tungsten Filament
Focusing Rings
Electron Stream

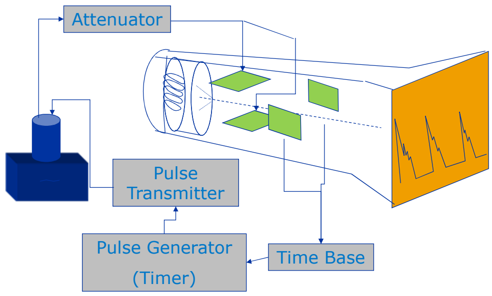
TWI

Ultrasonic Equipment



TWI

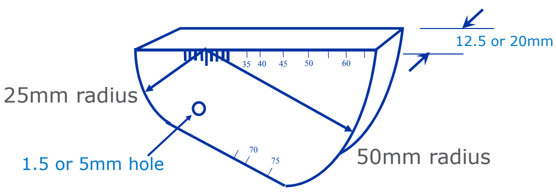
Ultrasonic Equipment



TWI

Calibration

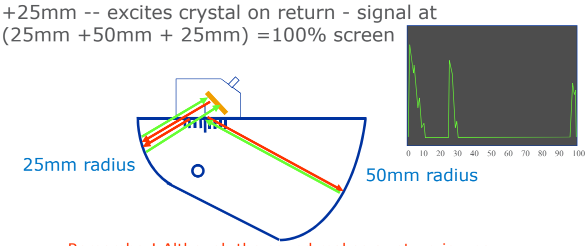
Using A4 block (also known as V2 or kidney block)



TWI

Calibration

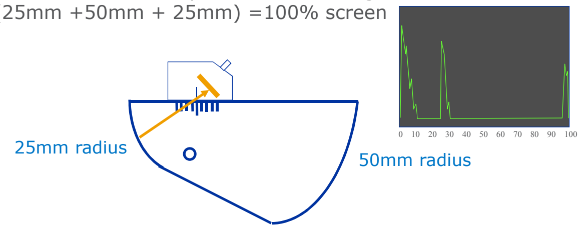
25mm -- excites crystal on return - signal at 25% screen.
+ 50mm -- does not excite crystal - no signal
+25mm -- excites crystal on return - signal at (25mm +50mm + 25mm) =100% screen



Remember! Although the sound makes a return journey, we only show a single journey on the CRT.

Calibration

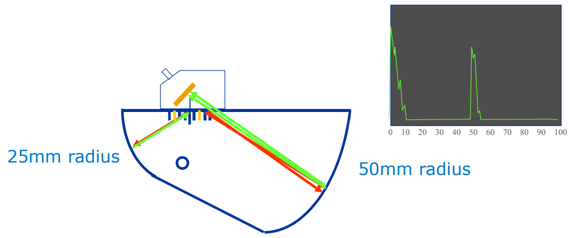
25mm -- excites crystal on return - signal at 25% screen.
+ 50mm -- does not excite crystal - no signal
+25mm -- excites crystal on return - signal at (25mm +50mm + 25mm) =100% screen



Calibration

50mm - excites crystal - signal at 50% screen

+25mm - does not excite crystal - no signal

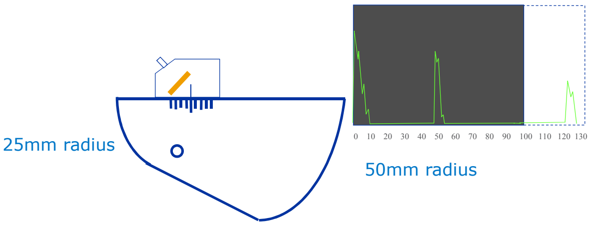


Calibration

50mm - excites crystal - signal at 50% screen

+25mm - does not excite crystal - no signal

+50mm - excites crystal - signal at 125% screen



Written Instruction

Ultrasonic Flaw Detection Written Instruction

Reference Number:	ABC01 Issue Number 001
Component:	Double V weld, Carbon Steel Plate, 25mm, MMA
Component I.D.:	Tag No. 13XX
Prepared By:	U.T. Tester Sign: Date:
Approved By:	Q.A. Mann Sign: Date:
Company:	Yahoo Technical International
Aim of Inspection:	100% examination to find defects in weld and HAZ, carried out in accordance with BSEN 1714:1998 Level D and PCN UT 001 Rev 0
Area of Test:	100% of weld body, HAZ and 10mm parent plate either side of weld
Stage of Manufacture:	As welded
Surface Condition:	Undressed, scanning surfaces to permit full and uniform coupling, Ra < 12.5μm
Couplant:	UCA 1, Ultragel or equivalent
Flaw Detector:	Krautkramer USM2 or equivalent
Probes:	Twin Crystal compression probe 10mm 5MHz 0^0 Single crystal shear wave probe 10mm 4MHz 45^0,60^0, 70^0
Calibration Blocks	A2, A4, A5 and A7
Scanning:	Scan 1 – compression scan of all plate to be scanned with angle probes. Scan 2 – Fixed root scan 70^0 Scan 3 – 45^0,60^0,70^0 scan of fusion face and weld body Scan 4 – 45^0 scan for transverse defects Maximum scanning speed 50mm/sec. With overlap of 10% probe diameter.
Timebase Calibration:	Scan 1 – 0 - 50mm Scan 2,3,4 0 – 100mm
Sensitivity Settings:	DAC from 3mm side drilled holes. Transfer correction to BS EN 583-2

Ultrasonic Flaw Detection Written Instruction

Evaluation of Indications:	All indications equal or exceeding DAC + correction factor and in excess of 5mm in any dimension to be evaluated using a beam geometry technique to establish maximum echo amplitude, length, through wall dimensions and defect characterisation. Correction factors to be :- 0^0 DAC + 8dB Shear wave DAC + 14dB. Transverse scan +14dB. Lamination scan at Full Screen Height 2nd Back Wall Echo
Safety:	Care to be taken when lifting specimens, Company and Statutory National Health and Safety procedures to be adhered to. Correct PPE to be worn.
Checks and Calibrations:	All equipment to be tested in accordance with BS EN 12668 parts 3 Records of all tests and calibrations to be kept.
Visual Inspection:	Carry out visual inspection of surface, report any irregularities or non-conformances to Supervisor.
Reporting Actions:	All inspections to be recorded on approved report format.
Reporting:	Identification of weld and following information to be recorded for each indication exceeding DAC + correction factors and 5mm length:- Length, depth, through wall dimension, position with respect to datum, maximum echo amplitude and defect characterisation.
Sketch:	Sketches to be produced for each indication evaluated giving:- through wall, length, depth and distance from centreline. An overall plan view shall be produced giving all indication positions in respect to datum.

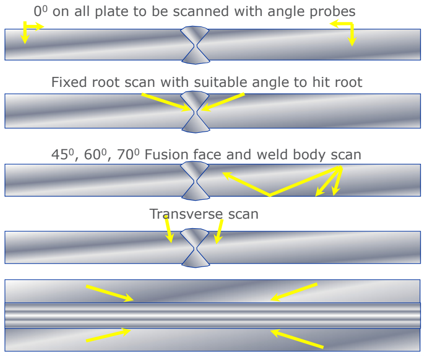
Ultrasonic Flaw Detection Written Instruction

Non-compliance: instruction — Any non-conformance in relation to this shall be brought to the Supervisor's attention immediately.

Minimum Operator Level: PCN level 1, Ultrasonic testing, with all indications checked by Supervisor or nominated Level 2 operator.

Post Examination: All traces of couplant to be removed.

Preservation: Plate to be free from all couplant, chinagraph or pencil marks, water and other contaminants are to be removed from the surface and a light covering of oil applied prior to storage.



Equipment Checks: Bs En 12668-3

- BS EN 12668-3 : 2000 Characterisation and Verification of Ultrasonic Examination Equipment Part 3: Combined Equipment.
- Prior to using an ultrasonic flaw detector and search unit combination it is important to ensure that this is performing adequately.
- BS EN 12668-3 describes the tests that should be used to ensure that ultrasonic flaw detectors and probes are in good working order.

Maintenance Checks

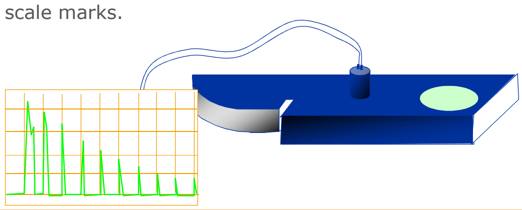
In line with BS EN 12668 Part 3 Combined equipment.

Linearity of flaw detector timebase.	Weekly.
Linearity of equipment gain.	Weekly.
Index point of each angle probe.	At least Daily.
Angle of probes.	At least Daily.
Physical state.	Daily.
Pulse duration.	Weekly.
Sensitivity/signal to noise ratio.	Weekly.

Calibration of timebase - **every time the probe is changed**

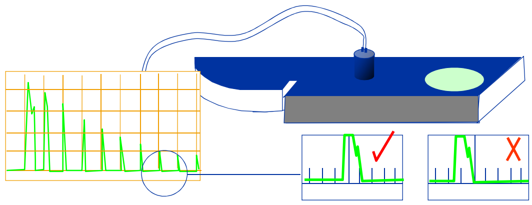
Maintenance Checks

Linearity of flaw detector timebase
Place a compression probe on the side of a V1 or V2 (A2, A4) block and adjust **range** and **delay** until you have 10 backwall echoes on the screen, making sure that the first and last echoes coincide with the correct scale marks.



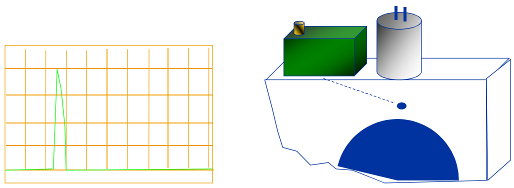
Maintenance Checks

Linearity of flaw detector timebase
Bring each successive backwall echo up to 80% screen height and check that the leading edge lines up with the appropriate graticule mark. Deviation should not be over 2% of full screen width.



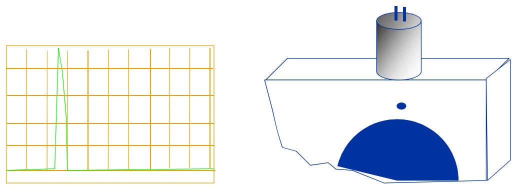
Maintenance Checks

Linearity of equipment gain
Obtain a signal from the 1.5 mm hole in V1 or V2 and set to <u>exactly</u> 80% FSH.



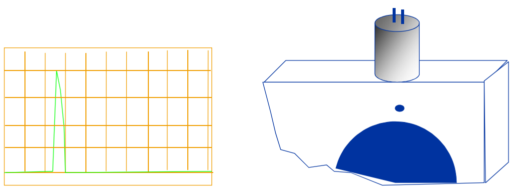
Maintenance Checks

Linearity of equipment gain
Increase the signal height using the gain control by 2dB and check the height increases to 100% FSH.



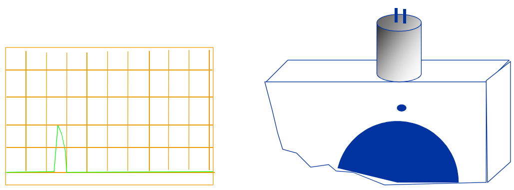
Maintenance Checks

Linearity of equipment gain
Reduce by 2 dB and check it goes back to 80% FSH.



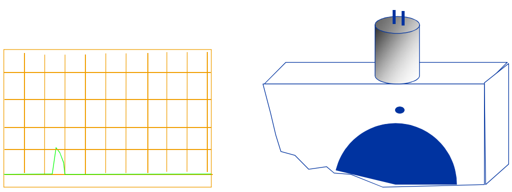
Maintenance Checks

Linearity of equipment gain
Reduce by a further 6 dB and check it goes down to 40% FSH.



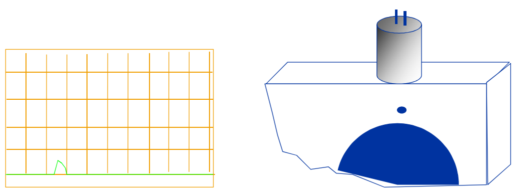
Maintenance Checks

Linearity of equipment gain
Reduce by a further 6 dB and check it goes down to 20% FSH.



Maintenance Checks

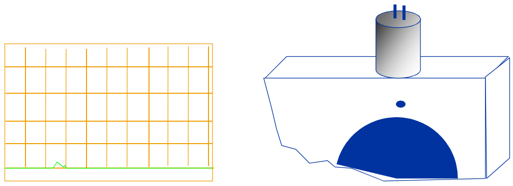
Linearity of equipment gain
Reduce as before by another 6 dB and check it goes down to 10% FSH.



Maintenance Checks

Linearity of equipment gain

Finally reduce by another 6 dB and the signal should fall to 5% FSH.



Maintenance Checks

Linearity of equipment gain

Decibels	Screen height	Deviation
0dB	80%	0
+2dB	100%	At least 95%
-2dB	80%	0
-6dB	40%	37 to 43%
-12dB	20%	17 to 23%
-18dB	10%	8 to 12%
-24dB	5%	visible, below 8%

Maintenance Checks

Probe index

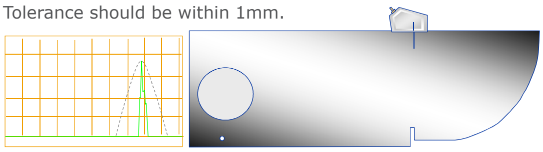
This check is for angle probes only.

Position probe on either a V1 or V2 block facing the quadrant.

Move probe backwards and forwards to maximise signal.

When signal is at maximum the index point will correspond with the engraved line on the block.

Tolerance should be within 1mm.



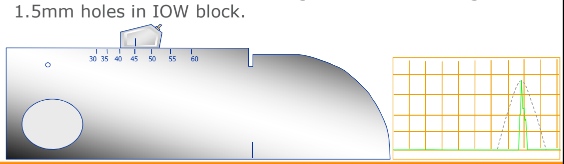
Maintenance Checks

Beam Angle

Quick method

- Place probe on calibration block.
- When signal is maximised, the beam angle can be read from the engraved scale.
- Accuracy should be approximately within 1.5° Tolerance within 2°.

This method is not accurate enough when weld testing – use 1.5mm holes in IOW block.

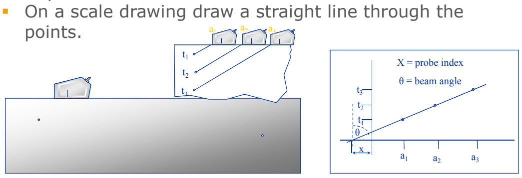


Maintenance Checks

Beam angle

More accurate method, (also able to check index point at same time).

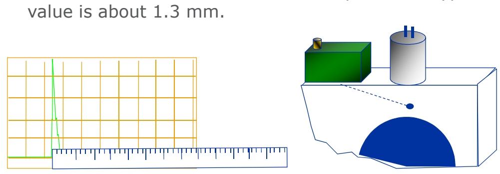
- Place probe on reference block (A5).
- Using at least 3, preferably 4 side drilled holes, maximise and measure depth and stand-off to **front of the probe** to plot hole location.
- On a scale drawing draw a straight line through the points.



Maintenance Checks

Pulse duration

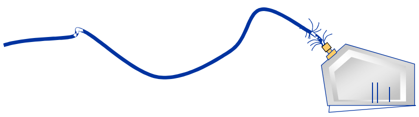
- Obtain a signal from the 1.5 mm hole in a V1 or V2 block.
- Maximise the signal to 100% FSH.
- Measure the width of the signal at 10% screen height.
- The typical pulse width for a 5 MHz compression probe is 2 mm whilst for a 4 MHz shear wave probe the typical value is about 1.3 mm.



Maintenance Checks

Physical state and external aspects

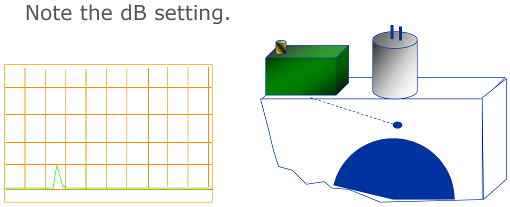
Visually inspect the outside of the ultrasonic unit, probes, cables and calibration blocks for physical damage or wear which could influence the reliability of the test .



Maintenance Checks

Sensitivity and signal to noise ratio

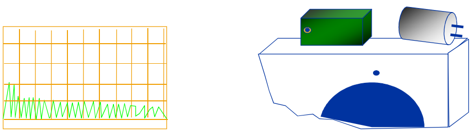
- Obtain a signal from the 1.5 mm hole in a V1 or V2 block.
- Maximise the signal to 20% FSH.
  Note the dB setting.



Maintenance Checks

Sensitivity and signal to noise ratio

- Remove probe from block and remove couplant from face.
- Place probe on its side.
- Increase signal height on the gain until the grass at the same range is up to 20% FSH.



The difference in dB is the signal to noise ratio

Maintenance Checks

Squint (Not required by BS EN 12668)

- Place the probe on the V1 block on the 100mm radius and maximise the signal.
- Check if the probe edge is parallel to the edge of the block.
- If the probe is not square then it will have squint.
- Note that the probe will give a return signal from not only the centre of the radius but also from the edges.

Maintenance Checks

Squint (To BS 4331)

Probe placed on 100mm radius

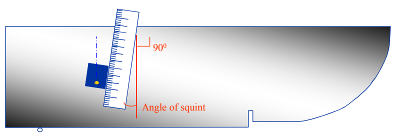
Probe getting return signal from corner of radius

Probe with squint

Maintenance Checks

Squint: Measurement of squint angle - Method 1

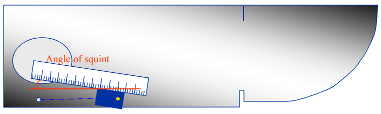
- Place probe on side of V1 and obtain signal from the edge of the block at half or full skip.
- Maximise the signal by swivelling the probe.
- Lay a ruler along the side of the probe - the ruler should meet the edge of the block at 90° when measured with a protractor.



Maintenance Checks

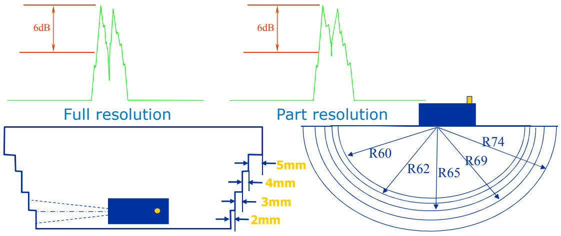
Squint: Measurement of squint angle - Method 2

- Place probe on side of V1 and obtain signal from the 1.5mm hole at half or full skip.
- Maximise the signal by swivelling the probe.
- Lay a ruler along the side of the probe - the ruler should stay a constant distance from the edge of the probe in relation to the hole .



Maintenance Checks

Resolving power (Resolution)
Using the A7 block, place the probe on the flat face of the block, at the centre of the radius.



Maintenance Checks

Resolving power (resolution)

- Good resolution is usually defined as distinguishing two echoes which are less than 2 to 2.5 wavelengths apart.
- Determine which are the appropriate steps on the A7 block, place the probe at the centre of the radii, on the flat surface with the beam giving echoes of equal height from either side of the step.
- The screen trace must show the two signals distinctly split to more than half their height ie >6dB.