SHEng
SMART HEALTHCARE ENGINEERING
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NDT TESTING IN HEALTHCARE INFRASTRUCTURES

Part 2

Class content material

This document is part of a training materials collection developed within the Erasmus+ project “Smart healthcare engineering”, SHEng, project No. 2023-1-RO01-KA220-HED-000159985.

The collection is intended for engineering students and professionals working in the healthcare sector. It covers technical subjects relevant to hospital infrastructure, equipment, materials and support services, helping readers understand how engineering contributes to safe patient care and the reliable operation of healthcare facilities.

These materials support classroom teaching and independent study. They should be used alongside the project handbook and the presentations, courses and other learning resources available on the project website. Each document addresses a specific subject, while the collection provides a broader understanding of the responsibilities and practical challenges of healthcare engineering.

The content is educational. Its application in practice requires consideration of the conditions of each healthcare facility, the applicable standards and the instructions provided by equipment manufacturers.

Project website: www.smarthealtheng.com

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ULTRASOUND TESTING

Introduction

Another non-destructive testing method, ultrasonic testing, is used in healthcare facilities to detect internal defects in welds and metal components and measure wall thickness in pipelines and tanks, helping monitor corrosion damage and prevent leaks or equipment failure.

Although advanced wave propagation physics can be intricate, the main principles of ultrasonic NDE remain straightforward. High-frequency sound waves – vibrating above the human audible threshold – propagate through solids, liquids and gases. As these waves travel through a solid medium, they interact with the internal structure in predictable, mathematically modellable ways. By generating controlled ultrasonic waves using a transducer, inspectors can evaluate material characteristics, including wall thickness, internal flaws and elastic properties. Consequently, ultrasonic testing is indispensable across diverse sectors such as aerospace, piping manufacturing, electronics, rail transport and power generation. This section serves as an introductory overview of UT, detailing wave propagation behavior, inspection techniques and historical development.

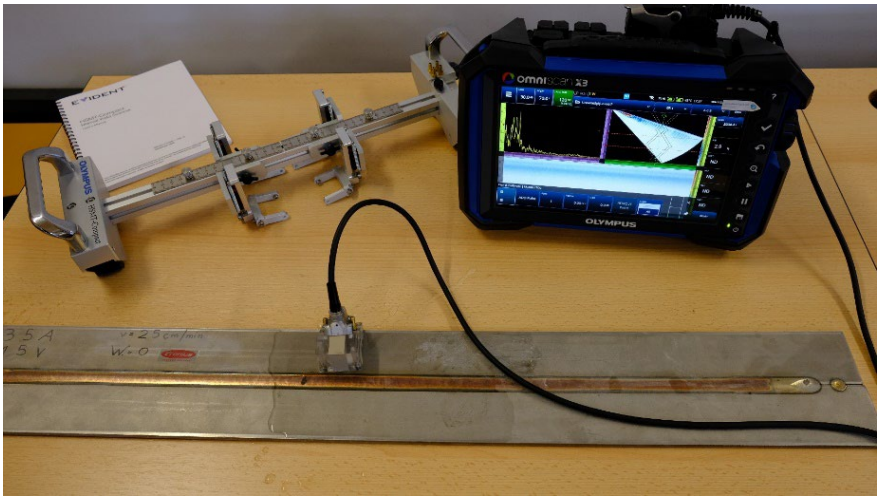

Fig. 1. Non-Destructive Evaluation of a welded plate via ultrasonic method [1]

The classic philosophical query regarding a tree falling unobserved in a forest hinges entirely on the definition of sound: whether it denotes auditory perception by an observer or the physical generation of acoustic waves by a source. When defined as acoustic wave generation, sound encompasses frequencies beyond the range of human hearing – giving rise to the concept of ultrasound.

Ultrasound refers to high-frequency mechanical waves vibrating above the nominal human hearing threshold of 20 kHz. While human hearing typically spans frequencies between 20 Hz and approximately 17 kHz, NDE applications utilize ultrasonic frequencies ranging from 50 kHz up to several gigahertz (GHz). Unlike electromagnetic radiation, which propagates optimally in a vacuum and experiences attenuation in dense matter, acoustic waves require a physical medium for transmission and cannot propagate through a vacuum. Furthermore, sound waves propagate through liquids and solids with significantly higher acoustic velocities and lower attenuation coefficients than in gases. For example, the acoustic wave velocity in structural steel exceeds that in air by more than fifteen times. The fundamental principle of ultrasonic NDE relies on this acoustic wave behavior in solid media. By analyzing wave propagation characteristics – specifically velocity and attenuation – researchers and engineers can determine a material's elastic moduli, density, microstructural features, internal flaws and geometric dimensions.

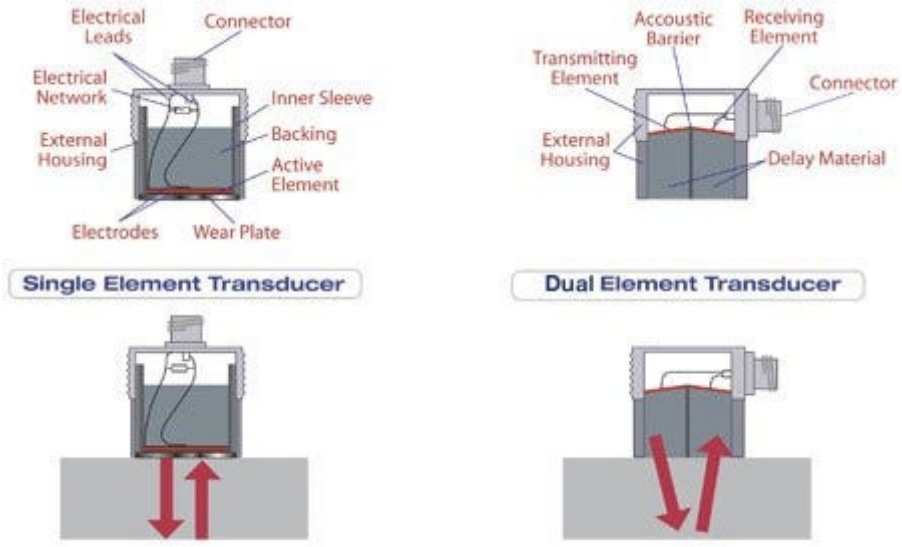

Fig. 2. Generating ultrasound and transducer configuration and component layout [2]

The operational principle of ultrasonic inspection consists of an electro-acoustic energy conversion: a transducer converts an applied electrical voltage pulse into a high frequency mechanical vibration

(ultrasonic wave). Once coupled to the test object, the acoustic wave propagates through the material, interacting with its geometric boundaries and elastic properties. Depending on the inspection setup, the signal is captured using one of two primary configurations:

1. Pulse-Echo method – a single transducer acts as both transmitter and receiver, capturing acoustic energy reflected from internal interfaces or defects.
2. Pitch-Catch method – separate transmitting and receiving transducers are positioned to measure the sound wave transmitted through the material.

The received acoustic signal is converted back into an electrical waveform for display and analysis on an oscilloscope or digital ultrasonic instrument.

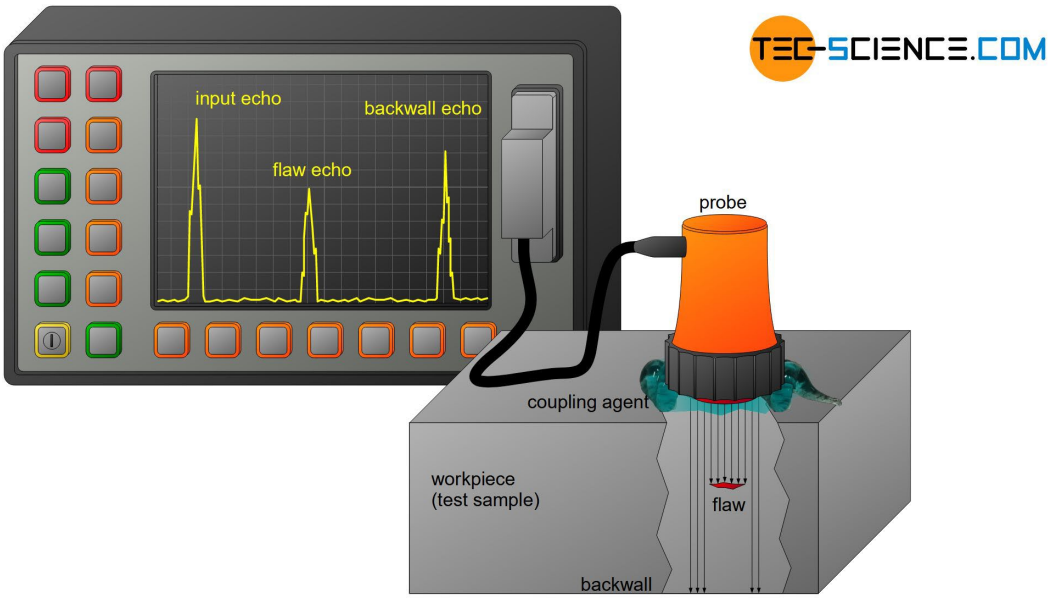

Fig. 3. Principle of ultrasonic defect detection with A-scan signal analysis [3]

Evaluating the signal's time-of-flight, amplitude and wave shape enables precise determination of:

- Wave velocity and thickness – material sound speed and accurate dimensional/wall thickness measurements
- Defect characterization – the presence, position, spatial orientation, geometry and nature of internal flaws or delaminations
- Mechanical and elastic properties – material density and elastic moduli
- Geometric and layered analysis – part profiles, interface conditions and multi-layer structural characteristics

Furthermore, raster-scanning the transducer across the component surface allows for two-dimensional (B-scan / C-scan) or three-dimensional structural imaging.

UT represents a flexible and robust non-destructive evaluation technique utilized across diverse industrial sectors. Along with radiography (X-ray testing), UT is one of only two volumetric NDE methods capable of detecting deep subsurface discontinuities (unlike electromagnetic methods such as eddy current or magnetic particle testing, which are limited to surface and near-surface regimes). Unlike X-ray methods, ultrasonic evaluation involves no ionizing radiation hazards, posing no environmental or health risks. While conventional UT relies on contact probes coupled via fluid media (water or gel), advanced non-contact approaches – such as laser-ultrasonics – permit non-contact inspection at standoff distances of several meters. Additionally, specialized transducer designs enable the inspection of complex component geometries across virtually all material classes, including metals, ceramics, polymers and biological tissues.

However, the technique presents specific operational limitations:

- Operator dependency and cost – requires highly qualified, experienced inspection personnel and often involves substantial capital equipment investment.
- Coupling requirements – most standard applications require direct surface contact using liquid or gel couplants
- Defect orientation sensitivity – ultrasonic waves generally fail to detect planar flaws aligned parallel to the direction of wave propagation.

WAVES PROPAGATION

A wave is defined as a local disturbance of a medium from its equilibrium state that propagates through space without transferring matter. When a stone is dropped into a body of water, the fluid particles oscillate locally while only the wave's energy and momentum propagate across the surface – a concept illustrated by a floating object that merely moves vertically as the wave passes. While particle motion versus energy transport can be counterintuitive in fluids, the distinction is clear in solid media, where lattice particles oscillate around equilibrium positions without changing their macroscopic spatial location.

In wave propagation theory, wave fronts originating from point sources exhibit curvature. However, for mathematical convenience and localized analysis, these front geometries are frequently approximated as planar over short distances – the plane wave approximation.

In UT, acoustic plane waves are categorized into two fundamental propagation modes based on particle motion relative to the energy propagation vector:

1. Transverse (Shear) Waves – particle displacement occurs perpendicular to the direction of wave propagation. Because transverse particle motion induces shear stresses, shear waves require a medium with shear stiffness and cannot propagate through low-viscosity fluids.
2. Longitudinal waves – particle displacement occurs parallel to the direction of wave propagation. As the wave travels, the medium experiences alternating zones of compression and rarefaction.

These modes can be conceptualized using a helical spring model: side-to-side displacement perpendicular to the spring axis simulates a transverse wave, whereas axial compression and tension along the spring axis model a longitudinal wave.

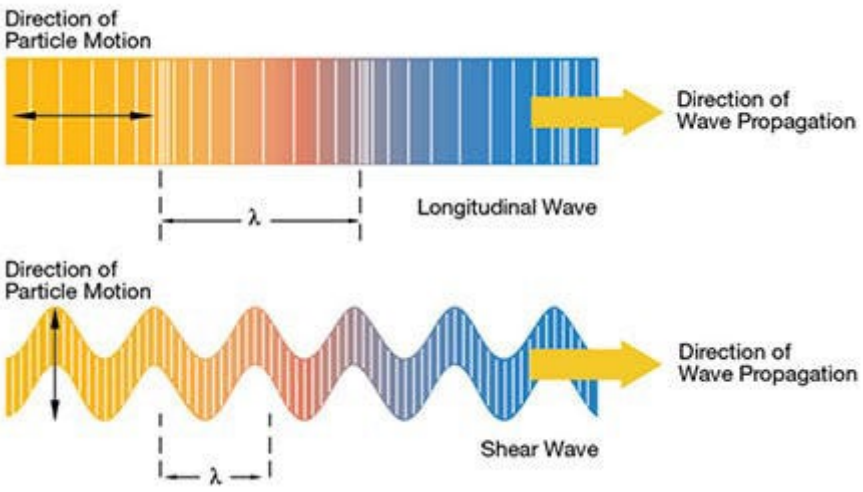

Fig. 4. Wave propagation and wavelength for acoustic modes [4]

INSPECTION PRINCIPLES

Carrying out an effective ultrasonic inspection involves establishing a precise testing configuration. The process begins by identifying the target variable to be measured, such as material thickness, elastic constants, or internal defect severity. Next, an appropriate transducer is selected to generate specific wave modes – including longitudinal, shear, surface or focused waves – configured in either a pulse-echo or pitch-catch arrangement. The system excitation must also be defined, utilizing spike pulses, tone bursts or continuous wave signals depending on the application. Finally,

inspectors must establish data processing and display methods, choosing whether time-amplitude presentations or spatial attenuation maps are best suited, while deciding if a localized point measurement or an automated area scan is required to fulfill inspection objectives.

Ultrasonic NDE relies on the direct measurement of four primary variables: time of flight, amplitude, phase and frequency. All secondary material characteristics – such as acoustic attenuation, elastic constants, structural homogeneity and microstructure – are derived from these fundamental parameters.

1. Time of flight – measures the transit duration of an ultrasonic pulse as it travels through a specimen and undergoes reflection or transmission.
    - When component thickness (d) is known, acoustic velocity (v) is determined by:

$$v = \frac{\text{Total Distance}}{\text{Time of Flight}}$$

      From this velocity data, material density and elastic constants can be calculated.
    - Conversely, when the acoustic velocity is known, time of flight locates internal discontinuities. For pulse-echo configurations, the measured time of flight corresponds to the complete round-trip distance (twice the path from transducer to reflector).
2. Amplitude and attenuation – Attenuation refers to the decay of signal amplitude caused by absorption, beam spreading, scattering or dispersion. It is quantified by analyzing the amplitude decay across successive echoes:

$$\alpha_l = \ln\left(\frac{A_{\text{final}}}{A_{\text{initial}}}\right)$$

$$\alpha_{\text{dB}} = 8.686 \ln\left(\frac{A_{\text{final}}}{A_{\text{initial}}}\right)$$

   where α represents the attenuation constant (in Nepers or decibels), l is the propagation distance and A is signal amplitude in volts. While displacement could theoretically be measured via amplitude changes, time of flight provides superior accuracy. Consequently, attenuation is primarily utilized to evaluate material homogeneity, dispersed particle volume fractions and scattering characteristics.
3. Phase analysis evaluates the relative shift in wave phase upon reflection. A wave reflecting off a boundary with a higher acoustic impedance experiences a 180° phase inversion. Phase measurements are typically combined with amplitude and time of flight data or utilized in

advanced techniques like ultrasonic interferometry to compare signal phase against a reference wave.

4. Using continuous wave excitation, **frequency** tuning establishes standing waves within a component. System resonance occurs when harmonic wavelength (λ) equals twice the component thickness (d), defined as:

$$f_1 = \frac{v}{2d}$$

For higher harmonics, the frequency is expressed as:

$$f_n = \frac{nv}{2d} \quad (n = 1,2,3, \dots)$$

The frequency spacing between neighboring harmonics is constant:

$$f_{n+1} - f_n = \frac{v}{2d}$$

This relationship allows precise measurement of acoustic velocity or wall thickness, while internal defects alter local resonant frequencies accordingly.

Ultrasonic signals are conventionally displayed on an oscilloscope or digital flaw detector as voltage amplitude versus time, synchronized via a trigger signal from the pulser. Modern inspection systems process these waveforms to compute time of flight, attenuation, frequency content, phase shifts and threshold crossings in real time. In a standard pulse-echo setup, the raw waveform exhibits an initial high-amplitude excitation pulse (the "main bang" or front-surface echo) followed by subsequent back-wall reflections or flaw echoes.

Ultrasonic imaging converts point-by-point A-scan data gathered across a specimen into spatial 2D or 3D visual maps. During raster scanning, feature extraction algorithms isolate specific parameters – such as peak echo amplitude, signal decay rate or gate-bounded time of flight – and map them against spatial coordinates.

- A-scan: A localized point measurement displaying raw signal amplitude as a function of transit time (depth along the beam axis).
- B-scan: A cross-sectional view generated by moving the probe along a single linear axis. The spatial position is plotted against depth/time of flight or amplitude.

- C-scan: A plan-view representation of an interrogated area, typically generated via x-y raster scanning. The extracted gate parameter (amplitude, attenuation, time of flight or phase) is rendered in grayscale or color contrast along the z-axis.

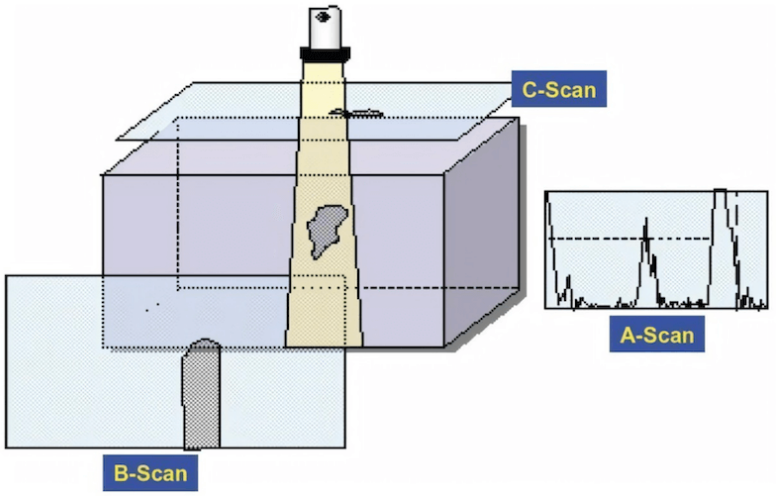

Fig. 5. UT A-Scan, B-Scan, C-Scan display modes [5]

By applying electronic time gates, C-scans can selectively interrogate specific depth zones within the specimen:

- Front-surface gating – accommodates minor surface profile variations or standoff distance fluctuations.
- Back-surface gating – captures reflections from the rear interface. Because the acoustic wave traverses the full thickness of the specimen, any near-surface or internal features are superimposed onto the back-surface image.

Industrial immersion testing typically submerges both the specimen and probe in a water tank to eliminate acoustic noise and turbulent interference. For high-speed or field applications, bubblers or water squirters establish a continuous fluid column between the transducer face and the part surface. By contrast, manual and medical scanning applications rely primarily on high-viscosity gels.

Ultrasonic non-destructive evaluation (UT) represents one of the most powerful, flexible and mathematically rigorous volumetric testing methodologies in modern engineering. Unlike surface bound inspection techniques – such as Liquid Penetrant Testing or Magnetic Particle Testing – UT penetrates the full volume of a component. By analyzing the interaction of acoustic energy with

internal interfaces, material microstructures and geometric boundaries, UT provides both qualitative defect identification and quantitative structural characterization.

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Acknowledgments

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