Ultrasonic Inspection (UT)

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Definitions

- *Ultrasonic Testing (UT)* - A nondestructive test method that uses high frequency sound energy to conduct examinations and make measurements.
- *Sound* - The mechanical vibration of particles in a medium.
- Pulser/receiver - electronic device that produces high voltage electrical pulses
- *Transducer* - converts the electrical pulses to mechanical vibrations (acoustic energy) by a phenomenon known as piezoelectric effect
- *Ultrasonic Wave Frequency* occur at a frequency of >20,000 Hz (20 kHz)
  - Humans are incapable of hearing sounds at this frequency
  - Bats emit ultrasonic waves (they listen to the echoes to locate objects)

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Uses for UT

- Flaw detection/ evaluation
- Dimensional measurements (ex. part thickness)
- Material characterization

UT Inspection System Components

- Pulser/receiver – electronic device that produces high voltage electrical pulses
- Transducer – converts the electrical pulses to mechanical vibrations (acoustic energy) by a phenomenon known as piezoelectric effect

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UT Inspection System Components - Continued

- Display screen – monitor that shows an A-scan, B-scan, and/or C-scan presentation of the sound reflection

Piezoelectric Element

- A crystal or polycrystalline material, which, when mechanically deformed, produces electrical charges, and conversely, when intermittently charged, will deform and produce mechanical vibrations

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Some examples of UT equipment

DM4 thickness gauges (with digital thickness readout)

DMS2 thickness gauges (with A-scan presentation)

USN 58L Flaw detectors

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Some examples of UT equipment

Phased-array flaw detector

USM Go Flaw Detector

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Propagation of Sound

- Sound energy introduced in the part propagates (travels) through the material in the form of waves
- A discontinuity, such as a crack, will reflect some of the sound wave back to the transducer
- Size of reflected signal depends on both the size of the discontinuity and its distance from the sound source
  - Smaller discontinuities and greater distances result in smaller signals
  - Larger discontinuities and nearer distances result in larger signals

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Some Advantages of UT

- Only single-sided part access is required (with pulse-echo technique)
- Results are instantaneous
- Highly accurate in locating flaws and assessing flaw size and shape
- Depth of penetration superior to other NDT methods

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Some Disadvantages of UT

- Requires more highly skilled operators than some other methods (leads to higher cost)
- Requires a coupling medium
- Difficult to inspect materials that are rough, irregular in shape, or nonhomogeneous
- Cast iron and coarse-grained materials difficult to inspect due to low sound transmission and high signal noise
- Reference standards are required for equipment calibration and characterization of discontinuities

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Brief History of UT

- Development of sonar – technique of sending sound waves through water and observing returning echoes to locate submerged objects
- Early 1940s – Dr. F.A. Firestone developed first pulse-echo instrument to detect deep-seated flaws
- 1950s – Japan used ultrasound to detect gallstones and tumors; later expanded to moving objects such as blood moving through the circulatory system
- U.S. produced the earliest “contact” scanner for clinical use

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Wave Propagation

- All materials composed of atoms
- Sound travels through solids in four principle wave modes
  - Longitudinal waves
  - Shear waves
  - Surface waves
  - Plate waves

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Longitudinal and Shear Waves

- Longitudinal waves also called compression or pressure waves
  - Oscillate in *direction* of wave propagation as in the movement of a spring
  - Can travel in both liquids and solids
- Shear waves also called transverse waves
  - Oscillate *perpendicular to the direction* of wave propagation as in the movement of a wave along a rope
  - Can only travel in solids

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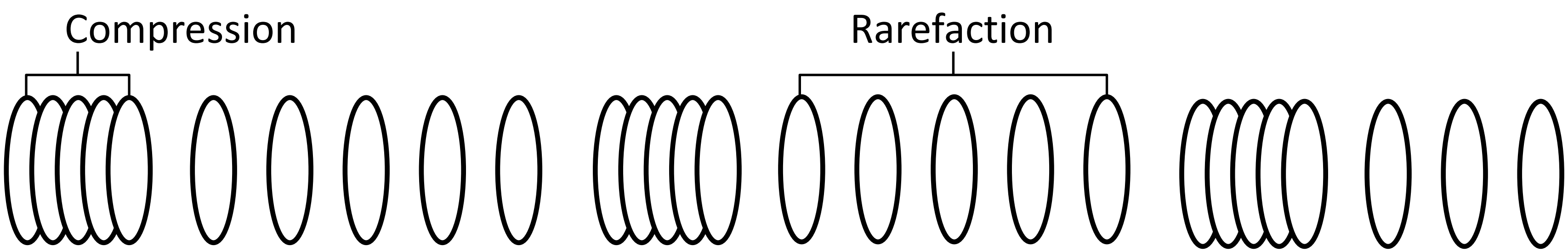
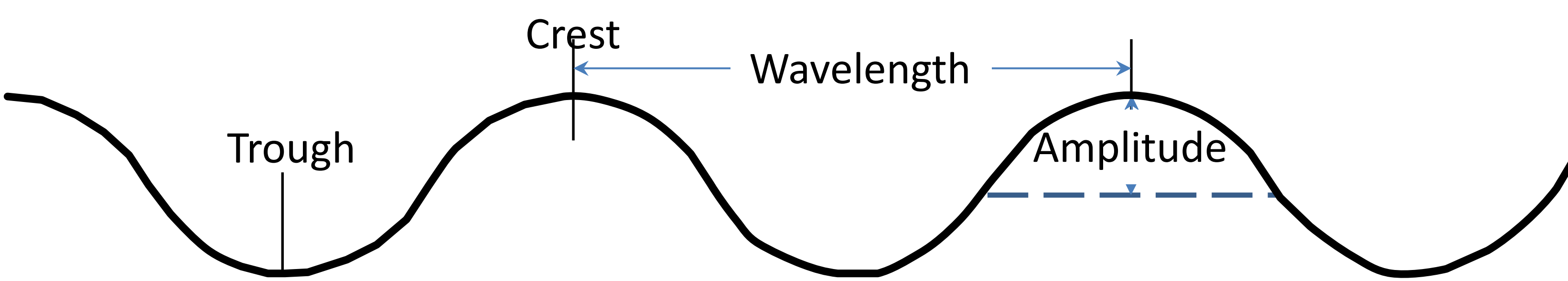
Longitudinal Vs. Shear Waves

Comparison of Longitudinal and Shear Waves



Longitudinal Waves



Shear Waves

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Surface Waves and Plate Waves

- Surface waves also called Rayleigh waves
  - Combine the motion of both longitudinal and shear waves
  - Follow the surface around curves and therefore are sensitive to surface defects
  - Travel at a depth of approximately one wavelength
- Plate waves also called Lamb waves
  - Similar to surface waves
  - Used for inspection of thin plates (only a few wavelengths in thickness)

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Properties of Waves (wavelength, frequency, and velocity)

Wavelength

- Wavelength (λ) – the distance in the direction of propagation of a wave for the wave to complete one cycle example, the distance from trough to trough or crest to crest

Frequency

- Frequency (f) – the number of complete cycles of a wave passing a given point in a unit time
  - 1 cycle/second = 1 Hz
  - 10^6 cycles/second = 1 MHz

  *In UT, frequency is dependent on the frequency rating of the transducer (usually specified in kHz or MHz)

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Properties of Waves (continued)
Velocity

- Velocity (v) – the speed at which sound waves travel through a medium
  - Typically given in cm/microsecond

  *Is a function of the material being tested

Relationship Between Wave Properties: $\lambda = v/f$

- Wavelength is directly proportional to the velocity of sound in the material and inversely proportional to the frequency of the sound wave

  *Rule of Thumb: A discontinuity must be >1/2 the wavelength to be detected (influences transducer frequency selected)

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Example Problem #1

- You are given the longitudinal velocity in aluminum is 0.25 in/µs (0.65 cm/µs). Using a 2.25 MHz transducer, what is the wavelength of sound produced in the material?

Problem #1 Solution

$$\lambda = \frac{V}{f} = \frac{0.25\ in/\mu sec}{2.25 * 10^6\ cycles/sec} * \frac{10^6\ \mu sec}{sec}$$

$$\lambda = 0.111 \text{ in/cycle}$$

Using the rule of thumb, a 2.25 MHz transducer can be used to detect flaws of greater than 0.0556” (0.141 cm) in aluminum.

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Example Problem #2

- Given a 1 MHz transducer, find the wavelength (λ) of a transverse sound wave in carbon steel. $V_{st,t}$ =0.13 in/µsec.

$$\lambda = \frac{V}{f} = \frac{0.13\ in/\mu sec}{1.00*10^6\ cycles/sec} * \frac{10^6\ \mu sec}{sec}$$

λ = 0.13 in/cycle

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Sensitivity

- The ability of a system (or method) to detect small discontinuities
- Increases with higher frequencies and shorter wavelengths

Resolution

- Resolution (resolving power) – the measure of the capability of a system to separate two discontinuities that are close together in the part of near the part surface
  - * As with sensitivity, resolution increases with an increase in frequency and decrease in wavelength

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More on Velocity

- Dependent on both the density of the material and its elastic properties
- Also dependent on the type of sound wave
  - Longitudinal waves travel at twice the speed of shear waves
  - Surface waves travel at 90% the speed of shear waves

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Attenuation

- The loss in acoustic energy which occurs between any two points of travel
- Primarily due to scattering and absorption
  - Scatter – dispersion of ultrasonic waves
  - Absorption – conversion of sound waves into another energy form (heat)
- Higher frequency produce more scatter so penetrating power is reduced (depth of penetration of the sound into the material)

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Acoustic Impedance of a Material (Z)

- The factor which controls the propagation of an ultrasonic wave at a boundary interface (its transmission and reflection)
- $Z=\rho*v$ (where ρ=density and v=velocity)
- An important factor in the calculation of acoustic transmission and reflection at the boundary of two different materials
- UT waves are reflected at boundaries where there is a difference in acoustic impedance (difference called “impedance mismatch”)
  - The greater the “mismatch” the greater the sound reflection (and therefore less penetration)

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Reflection Vs. Transmission

- Reflection coefficient, R – fraction of wave reflected
- Transmission coefficient, T- Fraction of wave transmitted on through the part
- $R = \frac{(z_2 - Z_1)^2}{(z_2 + Z_1)^2}$
- $R + T = 1$

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Acoustic Impedance Data

- Depends on type of material as well as type of wave (longitudinal vs. shear wave)
- Example impedance values:

Material	**Impedance (Z) $g/(cm^2\text{-}sec)*10^5$**
Water	1.48
Air	0.0004
Aluminum	17
Stainless Steel	45.4

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Reflection Calculation

- How much sound is reflected at the interface between water and stainless steel?
  - Solution: from previous table
  - Z_{water} = 1.48 g/(cm^2-sec)*10^5
  - $Z_{stainless\ steel}$ = 45.4 g/(cm^2-sec)*10^5
  - $R = \frac{(1.48-45.4)^2}{(1.48+45.4)^2} = 0.878$
  - Which means that 87.8% of the sound is reflected.

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Transmission Calculation

- How much sound is transmitted at the interface between air and aluminum?
  - Solution: from previous table Z_{air} = 0.0004 g/(cm^2-sec)*10^5 and $Z_{aluminum}$ = 17 g/(cm^2-sec)*10^5
  - $R = \frac{(0.0004 - 17)^2}{(0.0004 + 17)^2} = 0.9999$ Which means that 99.99% of the sound is reflected.
  - $R + T = 1 \rightarrow T = 1 - R = 1 - 0.9999 = 0.0001$
  - Which means that 0.01% of the sound is transmitted through the part
  - This is why a coupling medium is required at the interface between the transducer and the part.

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Snell's Law

- Describes the relationship between the angle and velocity of the waves.
- $\frac{\sin \theta_1}{V_{L1}} = \frac{\sin \theta_2}{V_{L2}}$
  - where V_{L1} = longitudinal velocity in material 1
    V_{L2} = longitudinal wave velocity in material 2,
    θ_1 = angle of incidence (angle at which the sound penetrates the material),
    θ_2 = angle of refraction

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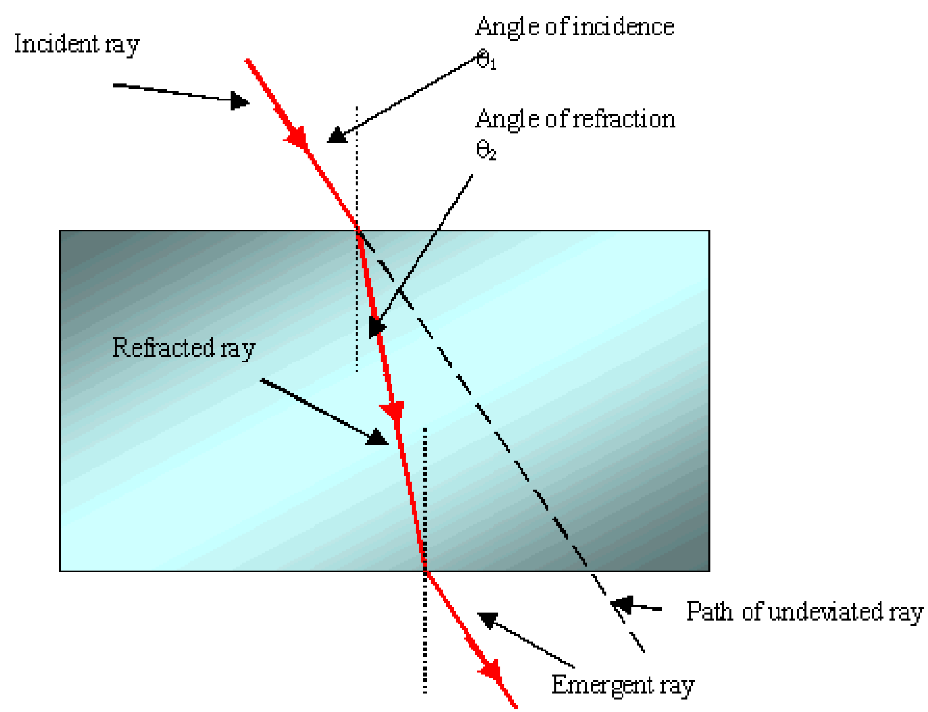
Refraction

- Refraction is the “bending” of the wave at the material interface
- If the angle of incidence is 0 (perpendicular to the material) there is no refraction



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Mode Conversion

- Definition: Change from one wave form to another, for example from a longitudinal wave to a shear wave.
- Occurs when a longitudinal wave hits an interface at an angle to surface (not perpendicular) – a shear wave is formed
- When the angle of refraction of the longitudinal wave becomes 90 degrees, the angle of incidence is called the 1^{st} critical angle
  - All energy form the reflected longitudinal wave converted into a surface-following longitudinal wave (called a creep wave)
  - Only a shear wave now propagates into the material

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Mode Conversion (continued)

- When the angle of refraction of the *shear* wave becomes 90 degrees, the angle of incidence is called the 2nd critical angle
  - All wave energy is converted into a surface-following shear wave (called a shear creep wave)
- At an angle of incidence > 2nd critical angle, surface waves are generated

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Transducers

- Active element of most acoustic transducers used today is a piezoelectric ceramic sometimes referred to as a crystal (quartz crystals were originally used as transducers)
  - Lead zirconate titanate most common transducer material
- Thickness of active element determines the transducer frequency
  - Thinner transducers – higher frequency but more fragile
  - Wavelength is ~ twice the thickness of the transducer – therefore transducers are cut to ½ the desired wavelength

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How does UT work?

- Piezoelectric element converts electrical signals into vibrations to transmit sound to the part; also converts the mechanical vibrations of the echoes back into electrical signals (acts as a receiver)
- Transducers have a wear plate to protect the active element from being scratched

More on Transducers

- A damping material is placed behind the active element
  - Damping improves resolution and sensitivity
- Sound originates from most of the surface of the piezoelectric element

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Near and Far Fields

- Transmitted sound waves are divided into regions designated as the "near field" and "far field"
- Extensive "noise" in the near field where sound originates – this makes it difficult to accurately evaluate flaws in this region
- Near field also called the Fresnel field; far field called the Fraunhofer field (Fresno is "nearer" to us than Fraunhofer, Germany!)

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Far Field

- The sound wave becomes more uniform at the start of the far field
  - Desire to have the detection area in the far field so no flaws are missed during an inspection
  - Smaller diameter transducers have shorter distances to travel before transition to the far field
  - Can also move start of far field to surface of part by adding a delay line

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Types of Transducers

- **Contact transducers**– used for direct contact inspections (hand manipulated)
  - A shoe can be added to contour a contact transducer to a given curvature
- **Immersion transducers** – do not contact the component (designed to operate in a liquid environment)
  - In immersion UT either or both the part and transducer are immersed in water
  - Air bubbles must be eliminated through use of a surfactant

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Single- Vs. Dual-Element Transducers

- **Single-element transducers** – transmits a signal, stops, then receives a signal
- **Dual-element transducers** – both transmits and receives a sound
  - No need for the element to stop transmitting to “listen” for a response
  - Better for detecting surface defects

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More Transducer Types

- **Angle-beam transducer** – introduces refracted shear waves into a part
  - Commonly used for inspection of welds
- **Paintbrush transducer** – a type of immersion transducer used for scanning wide areas
- **EMAT** – electromagnetic acoustic transducer – does not need couplant

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Couplant

- Material used to facilitate the transmission of ultrasonic energy from the transducer into the test specimen
- Needed due to high impedance mismatch between air and test materials
- Couplant displaces the air
- Usually made of oil, water, or glycerin

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Type of UT Presentations

- **A-scan:** Displays signal amplitude vs. distance or time
  - Must adjust the range as appropriate to thickness of the part
  - Signal amplitude can be increased by increasing the gain (does not change the actual echo, just its presentation)
- **B-scan:** Displays a profile (cross-sectional) view of the test specimen
  - Time of flight (travel time) displayed on the y-axis, linear position of transducer of the x-axis
- **C-scan:** Displays a plan view of the location and size of the test specimen
  - Likened to a radiograph