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Waves

There are three primary categories of waves: mechanical, electromagnetic, and matter.

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Waves and their propagation can be described by certain parameters.

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Waves can interact with mediums and boundaries between mediums.

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Different types of waves with different properties are useful for different types of NDT.

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Introduction to Waves

After reading this section you will be able to do the following:

- Name the three categories of waves.
- Provide examples of mechanical and electromagnetic waves.

There are three primary categories of waves:

1. Mechanical
2. Electromagnetic
3. Matter

Each of these categories of waves breaks down into additional types of waves. In this module we'll discuss **mechanical waves** and **electromagnetic (EM) waves**. Matter waves are a part of quantum theory and are therefore beyond the scope of this material. Some examples of mechanical and electromagnetic waves are shown below. In the mechanical waves column, we see ripples in a pond and sound. Other examples of mechanical waves are waves on the ocean and seismic waves that occur from earthquakes. In general, mechanical waves are waves that require a medium to travel. In the electromagnetic waves column below we see the sun which produces ultraviolet radiation, a type of EM wave. We also see an antenna which produces EM waves at microwave frequencies. EM waves do not require a medium to travel. In the following pages we'll learn more about the different types of EM radiation, as well as other wave characteristics.

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Mechanical Waves



Electromagnetic Waves



Review:

1. There are 3 primary categories of waves: mechanical, electromagnetic (EM), and matter.
2. Mechanical waves require a medium to travel while EM waves do not.

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Types of Waves

After reading this section you will be able to do the following:

- Describe the different types of mechanical waves.
- Explain what electromagnetic waves are.

As previously discussed there are three primary categories of waves: mechanical, electromagnetic, and matter. Some more details on mechanical and electromagnetic waves will be discussed on this page. As a reminder, the big difference between mechanical waves and electromagnetic waves is that mechanical waves are disturbances that travel in a medium while electromagnetic waves do not require medium (they can travel in a vacuum!).

Mechanical Waves

While mechanical waves cause a disturbance in a medium, they do not transport matter as they travel. They only transport energy. Within the category of mechanical waves there are 3 primary types: **transverse,longitudinal, and surface**.

Transverse Waves

Imagine you have a long string. You tie one end to a tree and hold the other end so the string is under tension. You then move the end of the string you're holding up and down and you see this movement travel down the string towards the tree. In doing so, you're causing a displacement of the medium (the string) that is **perpendicular/transverse** to the direction of travel. In other words, you're causing a transverse wave!

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Longitudinal Waves

Longitudinal waves also called **compression waves** and **pressure waves**. In longitudinal waves the displacement of the medium is in the same direction as the wave travels. To visualize this, imagine liquid in a tube with a plunger or piston at one end of the tube and a rigid wall at the other end. When you push on the piston you're causing displacement and pressure fluctuations in the liquid (the medium) that travel down the tube. Another way to visualize this is

Surface Waves

Surface waves travel along the interface between two different mediums. Some examples are ocean waves or seismic waves that often occur as a result of an earthquake. In surface waves the molecules of the medium undergo circular motion and are therefore neither transverse nor longitudinal. However, they can be described as having transverse and longitudinal components. **Ground waves** are an electromagnetic version of surface waves, but are beyond the scope of this material.

Electromagnetic Waves

In the electricity and magnetism modules we discussed electric fields and magnetic fields, respectively. We also briefly discussed how a changing magnetic field can produce an electric field and vice versa. It is these linked changing electric and magnetic fields that form **electromagnetic (EM) waves**. As previously mentioned, these waves do not require a medium to travel. This means that while they can travel through a medium like air or a wall, they can also travel through a vacuum like outer space. Electromagnetic waves are used a lot in communications systems, such as those used to talk to satellites in space. It should be noted that electromagnetic waves and electromagnetic radiation refer to the same phenomenon.

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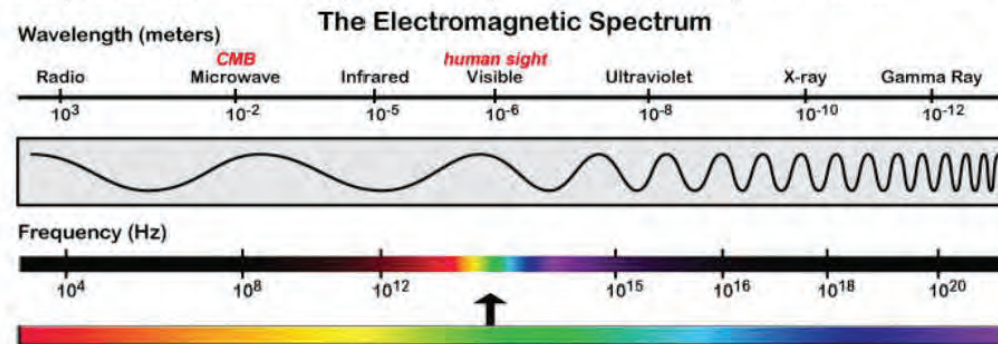
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One defining characteristic of an electromagnetic wave is its frequency, which is related to its wavelength and its energy. These concepts will be discussed more in a following page. The electromagnetic spectrum, which encompasses the full range of frequencies electromagnetic waves can have, is shown below.



Review:

1. The three main types of mechanical waves are transverse, mechanical, and surface.
2. Mechanical waves only transport energy as they travel. They do not transport matter.
3. Electromagnetic waves are formed from linked changing electric and magnetic fields.

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Mechanical Wave Characteristics

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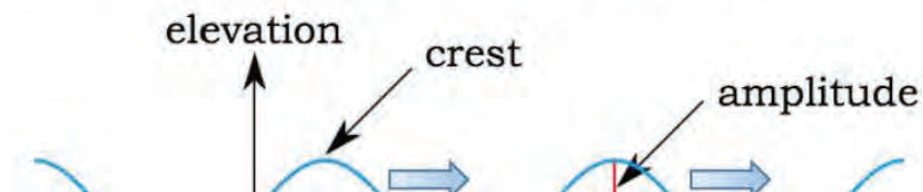
- Define periodic wave parameters like wavelength and period.
- Visualize periodic transverse waves and periodic longitudinal waves.

When the disturbance causing the transverse or longitudinal wave is repetitive (periodic), a **periodic wave** occurs.

Periodic Transverse Wave

When periodic waves have simple harmonic motion they can also be called **sinusoidal waves** and any periodic wave can be described by a combination of sinusoidal waves.

As a sinusoidal wave travels each particle undergoes simple harmonic motion with the same frequency, but does not travel with the wave. It is important to distinguish between the particle motion and the wave motion since waves transport energy, but not matter. The figure below illustrates a traveling periodic transverse wave and points out different features of the wave like its wavelength and amplitude.



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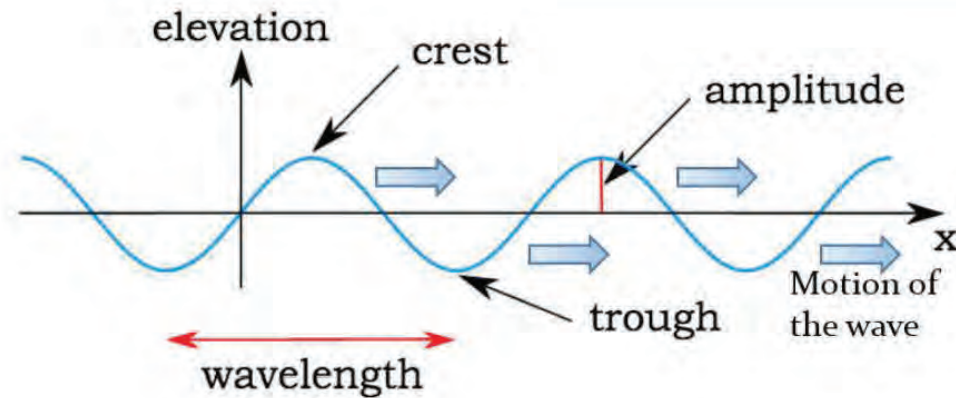
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The **wavelength** (represented by the Greek letter lambda) of a periodic wave is the physical distance between two same points in the pattern (e.g., the distance between two crests or the distance between two troughs). Since **wavelength** is a distance it is measured in distance units, typically meters. As a wave travels at a constant speed it advances 1 **wavelength** in the time of 1 **period**. The period of a wave, which is denoted by **T**, is measured in seconds and the wave speed, which is the speed the wave travels at in its medium denoted by **v**, is measured in meters per second. **Frequency** is the number of wave cycles that will pass a point in 1 second. It is measured in the unit **Hertz (Hz)**.

$$v = \frac{\lambda}{T} = \lambda f$$

λ : wavelength

Periodic Longitudinal Wave

Longitudinal waves can also be periodic. As a longitudinal wave travels there are regions of high particle density

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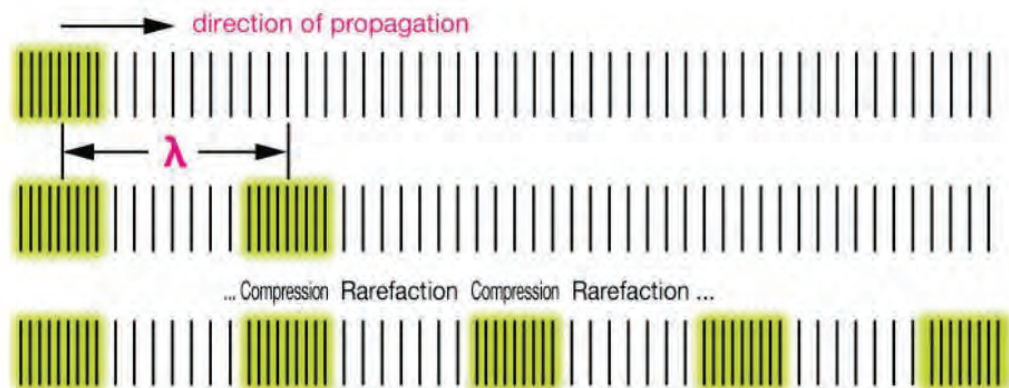
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or pressure and regions of low particle density or pressure. These regions are called **compression** and **rarefaction**, respectively, and are shown in the figure below. Just like with a transverse periodic wave, a periodic longitudinal wave has a **wavelength** that is the physical distance between two same points in the pattern. In this case the wavelength can be defined as the distance between two compression regions or two rarefaction regions.



Review:

1. When periodic waves have simple harmonic motion they can also be called **sinusoidal waves**.
2. Frequency is the inverse of the wave period and vice versa.
3. The wave speed is related to the wavelength and frequency of the wave.

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Characteristics of EM Radiation

After reading this section you will be able to do the following:

- Explain what the electromagnetic spectrum is and how scientists use it.

So far we have learned about the [atom](#), [electricity](#), and [magnetism](#), and have touched on electromagnetism. Two key points to remember about the characteristics of EM radiation (e.g., microwaves, X-rays, and gamma rays) are that EM radiation is not bits of matter, they are electromagnetic wave forms possessing no charge and no mass, and they can be characterized by **frequency**, **wavelength**, and **velocity**. Let's take a closer look at the characteristics of these wave forms so that we may better understand the nature of them.

Electromagnetic (EM) Waves

X- and gamma rays are part of what scientists refer to as the **electromagnetic (EM) spectrum**. They are waveforms that are part of a family in which some of the relatives are very familiar to us, such as light rays, infrared heat rays, and radio waves. However, X- and gamma rays cannot be seen, felt, or heard. In other words, our normal senses cannot detect them. Since X- and gamma rays have no mass and no electrical charge, they are not influenced by electrical and magnetic fields and will travel in straight lines.

Radiation possesses a dual character. Acting somewhat like a particle at times and like a wave at other times. The name that has been given to the small "packets" of energy with these characteristics is "**photon**." It is said that the radiation photon is a wave that is both electric and magnetic in nature. Electromagnetic radiation has also

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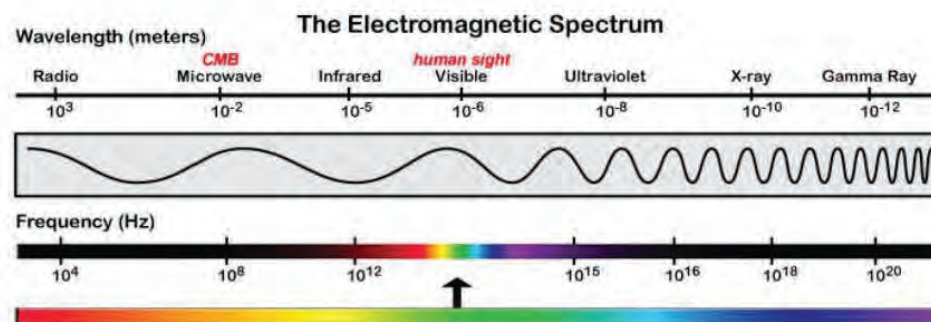
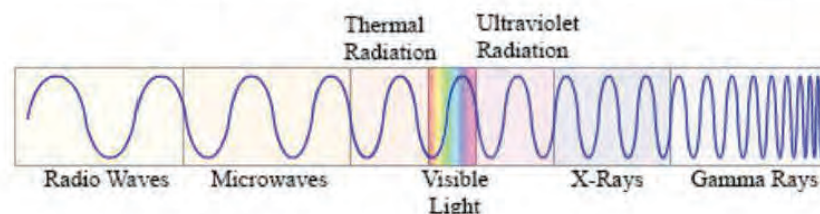
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been described in terms of a stream of photons (massless particles) each traveling in a wave-like pattern and moving at the speed of light.

This diagram shows the electromagnetic spectrum. Notice the changes in wavelengths of the various wave forms.



Every point across the spectrum represents a wave form of differing wavelength. It should be noted that the lines between the groupings are not precise, and that each group phases into the next.

Wave forms may be graphically represented as following:

x-position

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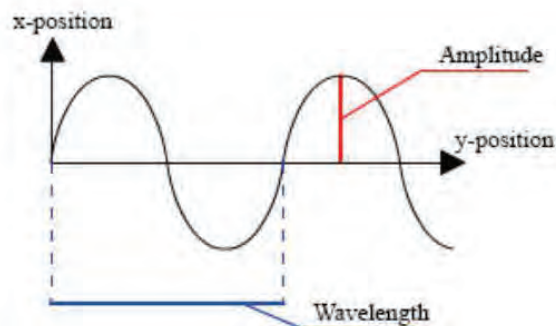
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Wavelength

Just as with mechanical waves on the previous page, the distance between the peaks or the distance between the troughs of the waves is the length of one wave, or more precisely the wavelength. Note that the electromagnetic waves vary in length from one end of the spectrum to the other. Some radio waves may be several miles long, while X and gamma rays are measured in angstroms, and fractions of angstrom. An angstrom unit is equivalent to 0.00000001 centimeters (100 millionths cm). If you want to compare this to an inch, a centimeter is equal to 0.394 inch. You can see that the wavelength as measured in angstrom units is extremely small.

Frequency

Another term used to describe a wave is **frequency**. Since waves are moving, we define frequency as the number of waves that pass a given point in a specified unit of time. The unit commonly used is Hertz which is the number

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of wave cycles pass a point in one second. So one cycle per second equals one Hertz. The frequency of a wave is indirectly proportional to the wavelength of the radiation. This means that as one value goes up, the other goes down. You can see that as the wavelength increases, it takes longer for one complete wave to pass a point and, therefore, the frequency goes down.

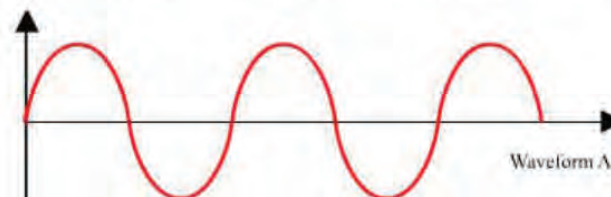
Frequency vs. Velocity

Don't confuse the frequency of a wave with the speed of travel or velocity of a wave; they are not the same or even related. X and gamma rays and all other members of the electromagnetic spectrum, travel at the same speed, 186,000 miles per second (3×10^8 meters per second). This speed is known as the speed of light, or actually the speed of electromagnetic radiation. Frequency describes how many complete wave cycles go flying by in one second.

Let's pause for a quick check of understanding

Now would be a good time to apply what we have learned about the characteristics of electromagnetic waves. Lets look at some specific examples and see if we understand.

Here are two wave forms (wave A, and wave B) with different wavelength. Which one has the greater wavelength and which one has the greater frequency? If wave A has a frequency of 1 Hertz, what is the frequency of wave B?



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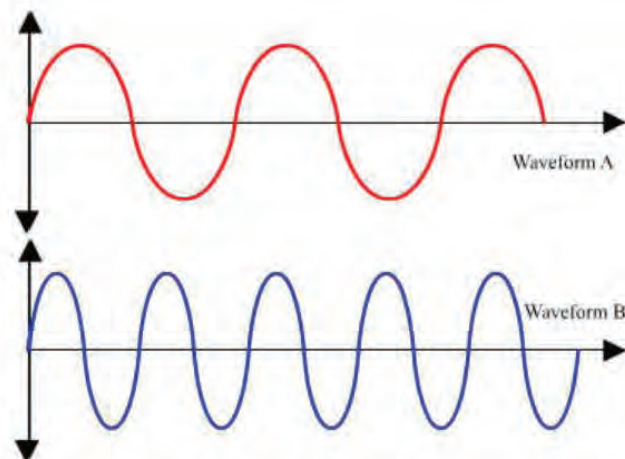
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You should have concluded that Wave A has a longer wavelength; therefore it will have a lower frequency than Wave B. Remember wavelength and frequency is inversely proportional; meaning that as one increases, the other decreases by a proportional amount. You should have also concluded that Wave B has a frequency of 2 Hertz. For every complete cycle of Wave A, Wave B completes 2 cycles.

Importance of Wavelength and Frequency

Not only are the wavelength and frequency of the wave linked, but they are also linked to the amount of energy of the wave. If two waves have that same amplitude then they each have the same amount of energy in one complete a cycle. Since waves with short wavelengths complete more cycles per second, you can see that they can transfer more energy than waves with longer wavelengths can in the same amount of time. Therefore, shorter wavelengths and higher frequency equates to more energy. If you refer back to the electromagnetic

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spectrum, you will note that the shorter wavelength rays posses more energy.

Importance of the Energy of Radiation

It is important to know the energy of the radiation because the energy controls the penetrating power of the radiation. Higher energy radiation can penetrate more amounts of material and harder to penetrate materials. This is important for a doctor taking x-rays so that there is not too much energy which can harm their patient. In NDT it's important so that we can properly penetrate the material or structure we want to inspect.

Measuring Radiation

It is common practice to measure x and gamma rays in one of two units, which are thousand **electron volts** (Kev), or million electron volts (Mev). What is an electron volt, you might ask? An electron volt is an amount of energy equal to the energy gained by one electron when it is accelerated by one volt. For example, if one electron was accelerated by a potential of 10 thousand volts (10 Kv), then the electron would have an energy of 10 thousand electron volts (10 Kev). If all of the accelerating energy were converted to electromagnetic energy, it would result in a 10 Kev x-ray.

Review:

1. Radiation is an electromagnetic (EM) wave that has no charge and no mass.
2. EM radiation can be characterized by frequency, wavelength, and energy.

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Properties of Plane Waves

After reading this section you will be able to do the following:

- Describe properties of waves.
- Explain what a plane wave is.

Wavelength, Frequency and Velocity

As previously discussed, for mechanical waves among the properties of waves propagating in isotropic solid materials are **wavelength**, **frequency**, and **velocity**. The wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave. This relationship is shown by the following equation.

$$\text{Wavelength}(\lambda) = \frac{\text{Velocity}(v)}{\text{Frequency}(f)}$$

The applet below shows a longitudinal and transverse wave. The direction of wave propagation is from left to right and the movement of the lines indicate the direction of particle oscillation. The equation relating ultrasonic wavelength, frequency, and propagation velocity is included at the bottom of the applet in a reorganized form. The values for the wavelength, frequency, and wave velocity can be adjusted in the dialog boxes to see their effects on the

Velocity: The distance covered by the wave in unit time.

Frequency: The number of complete disturbances (cycles) in unit time. Usually expressed in Hertz.

Wavelength: The distance between successive points of equal phase in a wave.

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wave. Note that the frequency value must be kept between 0.1 to 1 MHz (one million cycles per second) and the wave velocity must be between 0.1 and 0.7 cm/us.

Longitude Wave



Wavelength: 2.000 cm

Velocity: 0.600 cm/us

Frequency: 0.300 mHz

Time acceleration: 1x

Shear Wave



wavelength * frequency = velocity

Frequency: Wavelength:
Velocity: Time Acceleration:

Change the settings for the applet and observe how the waveforms change.

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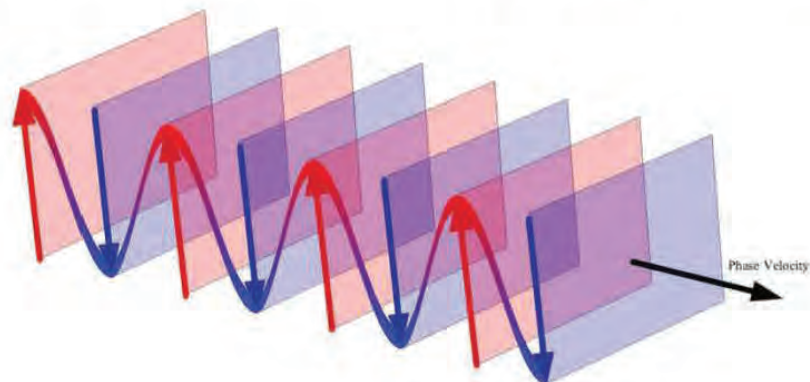
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As can be noted by the equation, a change in frequency will result in a change in wavelength. Change the frequency in the applet and view the resultant wavelength. At a frequency of .2 and a material velocity of 0.585 (longitudinal wave in steel) note the resulting wavelength. Adjust the material velocity to 0.480 (longitudinal wave in cast iron) and note the resulting wavelength. Increase the frequency to 0.8 and note the shortened wavelength in each material.

In ultrasonic testing, the shorter wavelength resulting from an increase in frequency will usually provide for the detection of smaller discontinuities. This will be discussed more in following sections.

Plane Wave

Plane waves are a special case of waves where a physical quantity, such as phase, is constant over a plane that is perpendicular to the direction of wave travel. There can be mechanical (both transverse and longitudinal) as well as EM plane waves. It should be noted that EM plane waves are only transverse. A visualization of a plane wave is shown below. Just like periodic waves, plane waves have a wavelength, frequency, and wave speed.



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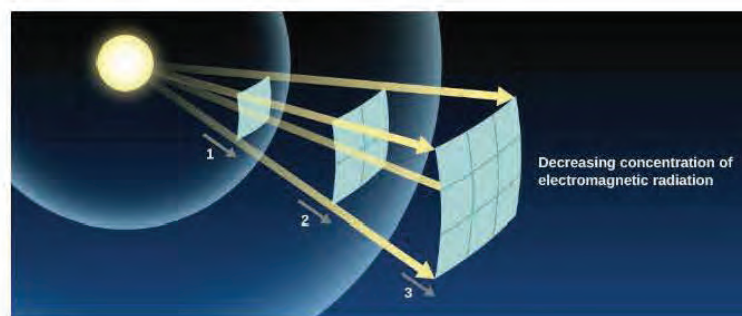
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When EM waves radiate from a source, such as an antenna, they radiate as spherical waves (see the figure below). As the waves move farther from the source, their energy gets spread out over a bigger spherical surface area. At big distances, which we call the **far-field**, a spherical wave front can be approximated as a uniform plane wave over a defined area.



Review:

1. **Plane waves** are a special case of waves where a physical quantity, such as phase, is constant over a plane that is perpendicular to the direction of wave travel.
2. Just like periodic waves, plane waves have a wavelength, frequency, and wave speed.

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Wave Number and Impedance

After reading this section you will be able to do the following:

- Describe different wave parameters that are related to the material the wave is in.

Refractive Index

Refractive index is a material property that determines how much light (or a wave at other frequencies) is bent and how much is reflected/transmitted when it travels from one material to another. The refractive index is related to the [complex dielectric constant](#) by the following equation:

$$n = \sqrt{\epsilon_r}$$

As a reminder:

$$\epsilon = \epsilon_r \epsilon_0$$

$$\mu = \mu_r \mu_0$$

Wave Speed and Speed of Light

In free space an EM waves travels at the [speed of light](#), which is approximately 3×10^8 m/s. In a material, an EM wave travels more slowly as a function of the dielectric constant of the material. In general, the wave speed (v_p) is related to the permeability and the permittivity by the following equation:

$$v_p = \frac{1}{\mu \epsilon}$$

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$$v_p = \frac{1}{\sqrt{\mu\epsilon}}$$

When the wave is traveling in free space this equation works out such that v_p equals the speed of light. You can test this yourself by plugging in the following values:

$$\mu = \mu_0 \mu_r = (4\pi \times 10^{-7})(1) = 4\pi \times 10^{-7} H / m$$

$$\epsilon = \epsilon_0 \epsilon_r = (8.854 \times 10^{-12})(1) = 8.854 \times 10^{-12} F / m$$

You should get close to 3×10^8 m/s!

Wavenumber

The **wavenumber**, also called the propagation number or propagation constant, can be thought of as a spatial frequency - how many wavelengths occur per unit distance. In free space it is the ratio of the angular frequency to the speed of light and in a material it is related to the refractive index.

Intrinsic Impedance

The **intrinsic impedance** is the impedance an EM wave faces as it travels through a medium. When the medium is homogeneous and the EM wave is a **transverse electromagnetic (TEM)** wave, then the intrinsic impedance is equal to the wave impedance. A TEM wave is simply a special case of EM waves where the linked electric fields and magnetic fields that make up the wave are orthogonal to each other and to the direction that the wave is traveling in. A visualization of a TEM wave is shown below.



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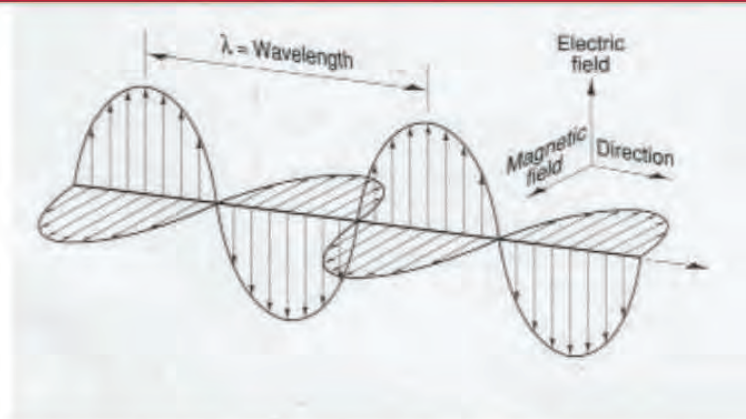
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When the wave is traveling in a dielectric then the intrinsic impedance (represented by the Greek letter eta) can be described with the following equation:

$$\eta = \sqrt{\frac{\mu}{\epsilon}}$$

The equation above shows that the intrinsic impedance is related to the permeability and the permittivity of the material.

Review:

1. Refractive index, wave speed, wave number, and intrinsic impedance are all interrelated quantities.
2. Changing the material properties changes how a wave will propagate through that material.

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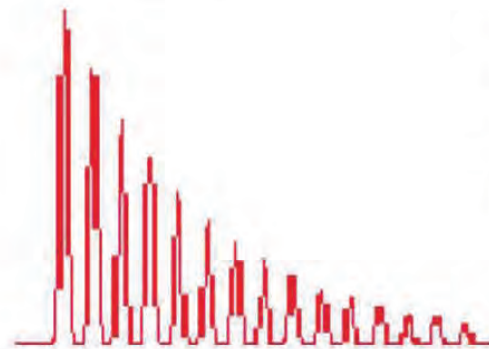
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Attenuation of Waves

After reading this section you will be able to do the following:

- Describe what attenuation is and what causes it.
- Use the decibel unit with ratios and absolute quantities.



When a wave travels through a medium, its intensity diminishes with distance. In idealized materials, the wave amplitude is only reduced by the spreading of the wave. Natural materials, however, all produce an effect which further weakens the wave. This further weakening results from scattering and absorption. Scattering is the reflection of the wave in directions other than its original direction of propagation. Absorption is the conversion of the wave energy to other forms of energy. The combined effect of scattering and absorption is called **attenuation**.

The amplitude change of a decaying/attenuating plane wave can be expressed as:

$$A = A_0 e^{-\alpha z}$$

In this expression **A_0** is the unattenuated amplitude of the propagating wave at some location. The amplitude **A** is the reduced amplitude after the wave has traveled a distance **z** from that initial location. The quantity **α** is the attenuation coefficient of the wave traveling in the **z** -direction. The dimensions of **α** are nepers/length, where a

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attenuation coefficient of the wave traveling in the z-direction. The dimensions of α are nepers/length, where a neper is a dimensionless quantity. The term e is the exponential (or Napier's constant) which is equal to approximately 2.71828.

The units of the attenuation value in **Nepers per meter (Np/m)** can be converted to **decibels/length** by dividing by 0.1151. **Decibels** is a more common unit when relating the amplitudes of two signals. More information about decibels is provided below.

The Decibel

The **decibel (dB)** is one tenth of a **Bel**, which is a unit of measure that was developed by engineers at Bell Telephone Laboratories and named for Alexander Graham Bell. The dB is a logarithmic unit that describes a ratio of two measurements. The basic equation that describes the difference in decibels between two measurements is:

$$\Delta X(dB) = 10 \log \frac{X_2}{X_1}$$

where: delta X is the difference in some quantity expressed in decibels, X_1 and X_2 are two different measured values of X, and the log is to base 10.

Why is the dB unit used?

Use of dB units allows ratios of various sizes to be described using easy to work with numbers. For example, consider the information in the table.

Ratio between Measurement 1 and 2	Equation	dB
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Ratio between Measurement 1 and 2

Equation

dB

1/2

$dB = 10 \log (1/2)$

-3 dB

1

$dB = 10 \log (1)$

0 dB

2

$dB = 10 \log (2)$

3 dB

10

$dB = 10 \log (10)$

10 dB

100

$dB = 10 \log (100)$

20 dB

1,000

$dB = 10 \log (1000)$

30 dB

10,000

$dB = 10 \log (10000)$

40 dB

100,000

$dB = 10 \log (100000)$

50 dB

1,000,000

$dB = 10 \log (1000000)$

60 dB

10,000,000

$dB = 10 \log (10000000)$

70 dB

100,000,000

$dB = 10 \log (100000000)$

80 dB

1,000,000,000

$dB = 10 \log (1000000000)$

90 dB

From this table it can be seen that ratios from one up to ten billion can be represented with a single or double digit number. Ease to work with numbers was particularly important in the days before the advent of the calculator or computer. The focus of this discussion is on using the dB in measuring sound levels, but it is also widely used when measuring power, pressure, voltage and a number of other things.

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Use of the dB in Sound Measurements

Sound intensity is defined as the sound power per unit area perpendicular to the wave. Units are typically in watts/m² or watts/cm². For sound intensity, the dB equation becomes:

$$\Delta I(dB) = 10 \log \frac{I_2}{I_1}$$

However, the power or intensity of sound is generally not measured directly. Since sound consists of pressure waves, one of the easiest ways to quantify sound is to measure variations in pressure (i.e. the amplitude of the pressure wave). When making ultrasound measurements, a transducer is used, which is basically a small microphone. Transducers like most other microphones produced a voltage that is approximately proportionally to the sound pressure (P). The power carried by a traveling wave is proportional to the square of the amplitude. Therefore, the equation used to quantify a difference in sound intensity based on a measured difference in sound pressure becomes:

$$\Delta I(dB) = 10 \log \frac{I_2}{I_1} = 10 \log \frac{P_2^2}{P_1^2} = 20 \log \frac{P_2}{P_1}$$

(The factor of 2 is added to the equation because the logarithm of the square of a quantity is equal to 2 times the logarithm of the quantity.)

Since transducers and microphones produce a voltage that is proportional to the sound pressure, the equation could also be written as:

$$\Delta I(dB) = 20 \log \frac{V_2}{V_1}$$

where delta I is the change in sound intensity incident on the transducer and V₁ and V₂ are two different transducer output voltages.

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Revising the table to reflect the relationship between the ratio of the measured sound pressure and the change in intensity expressed in dB produces:

Ratio between Measurement 1 and 2	Equation	dB
1/2	$\text{dB} = 20 \log (1/2)$	-6 dB
1	$\text{dB} = 20 \log (1)$	0 dB
2	$\text{dB} = 20 \log (2)$	6 dB
10	$\text{dB} = 20 \log (10)$	20 dB
100	$\text{dB} = 20 \log (100)$	40 dB
1,000	$\text{dB} = 20 \log (1000)$	60 dB
10,000	$\text{dB} = 20 \log (10000)$	80 dB
100,000	$\text{dB} = 20 \log (100000)$	100 dB
1,000,000	$\text{dB} = 20 \log (1000000)$	120 dB
10,000,000	$\text{dB} = 20 \log (10000000)$	140 dB
100,000,000	$\text{dB} = 20 \log (100000000)$	160 dB
1,000,000,000	$\text{dB} = 20 \log (1000000000)$	180 dB

From the table it can be seen that 6 dB equates to a doubling of the sound pressure. Alternately, reducing the

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sound pressure by 2, results in a – 6 dB change in intensity.

"Absolute" Intensity Levels

Whenever the decibel unit is used, it always represents the ratio of two values. Therefore, in order to relate different intensities it is necessary to choose a standard reference level. The reference sound pressure (corresponding to a sound pressure level of 0 dB) commonly used is that at the threshold of human hearing, which is conventionally taken to be 2×10^{-5} Newton per square meter, or 20 micropascals (20 μPa). To avoid confusion with other decibel measures, the term dB(SPL) is used. Similarly for EM waves the quantities dBW and dBm have been defined where the reference is 1 Watt and 1 milliwatt, respectively.

Review:

1. When a wave travels through a medium, its intensity diminishes with distance due to spreading, scattering, and absorption.
2. The dB is a logarithmic unit that describes a ratio of two measurements.

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Wave Interaction or Interference

After reading this section you will be able to do the following:

- Explain what can happen to the energy of waves when the waves interact.
- Compare and contrast constructive interference and destructive interference.

Wave propagation has been discussed so far as if a single sinusoidal wave was propagating through the material. However, the sound that emanates from an ultrasonic transducer or the EM waves that radiate from an antenna do not originate from a single point, but instead originates from many points. This results in a **field** with many waves interacting or interfering with each other.

When waves **interact**, they superimpose on 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. First, let's consider two identical waves that originate from the same point. When they are *in phase* (so that the peaks and valleys of one are exactly aligned with those of the other), they combine to double the displacement of either wave acting alone. This is the case on the left and this is called **constructive interference**. When they are completely *out of phase* (so that the peaks of one wave are exactly aligned with the valleys of the other wave), they combine to cancel each other out. This is the case in the middle and this is a case of **destructive interference**. When the two waves are not completely *in phase* or *out of phase*, the resulting wave is the sum of the wave amplitudes for all points along the wave. This is the case on the right and in this case there is both constructive and destructive interference.



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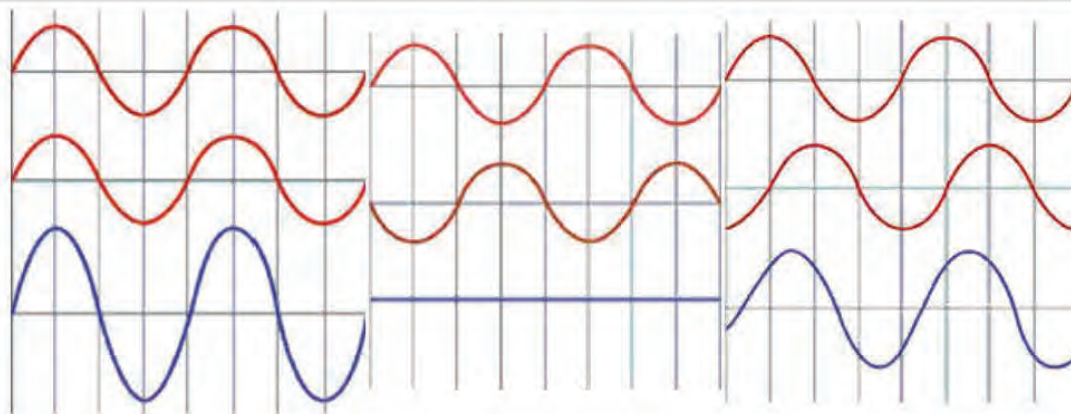
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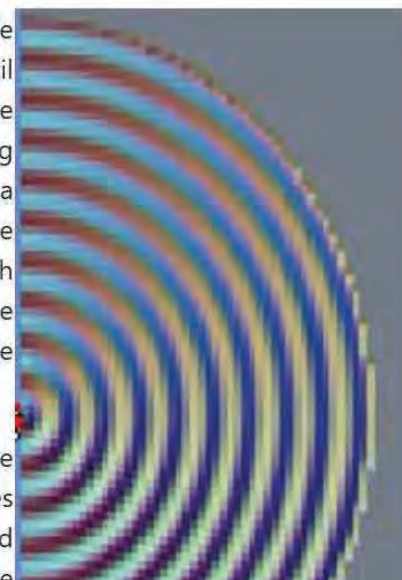
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When the origins of the two interacting waves are not the same, it is a little harder to picture the wave interaction, but the principles are the same. Up until now, we have primarily looked at waves in the form of a 2D plot of wave amplitude versus wave position. However, anyone that has dropped something in a pool of water can picture the waves radiating out from the source with a circular wave front. If two objects are dropped a short distance apart into the pool of water, their waves will radiate out from their sources and interact with each other. At every point where the waves interact, the amplitude of the particle displacement is the combined sum of the amplitudes of the particle displacement of the individual waves.

With an ultrasonic transducer or an antenna, the waves propagate out from the transducer face with a **circular wave front**. If it were possible to get the waves to propagate out from a single point on the transducer face, the field would appear as shown in the upper image to the right. Consider the light areas to be



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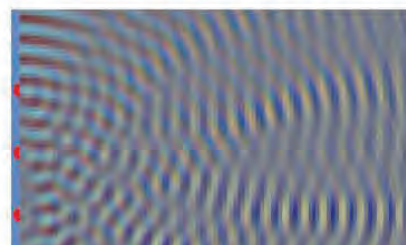
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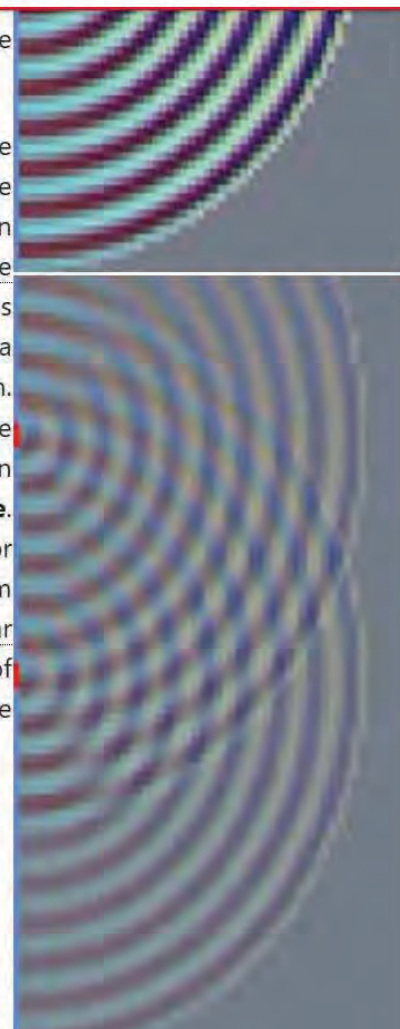
appear as shown in the upper image to the right. Consider the light areas to be areas of rarefaction and the dark areas to be areas of compression.

However, as stated previously, waves originate from multiple points along the face of the transducer or antenna. The lower image to the right shows what the field would look like if the waves originated from just two points. It can be seen that where the waves interact, there are areas of constructive and destructive interference. The points of constructive interference are often referred to as nodes. Of course, there are more than two points of origin along the face of a transducer or antenna. The image below shows five points of wave origination. It can be seen that near the face of the transducer, there are extensive fluctuations or nodes and the field is very uneven. In ultrasonic testing and in antenna theory, this is known as the **near field** (near zone) or **Fresnel zone**. The field is more uniform away from the transducer in the **far field**, or **Fraunhofer zone**, where the beam spreads out in a pattern originating from the center of the transducer/antenna. It should be noted that even in the far field, it is not a uniform wave front. However, at some distance from the face of the transducer and central to the face of the transducer, a uniform and intense wave field develops.



In the image to the left, multiple points of sound origination along the face of the transducer/antenna.

The curvature and the area over which the wave is being generated, the speed



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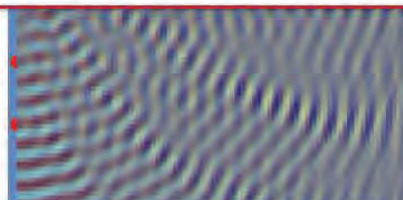
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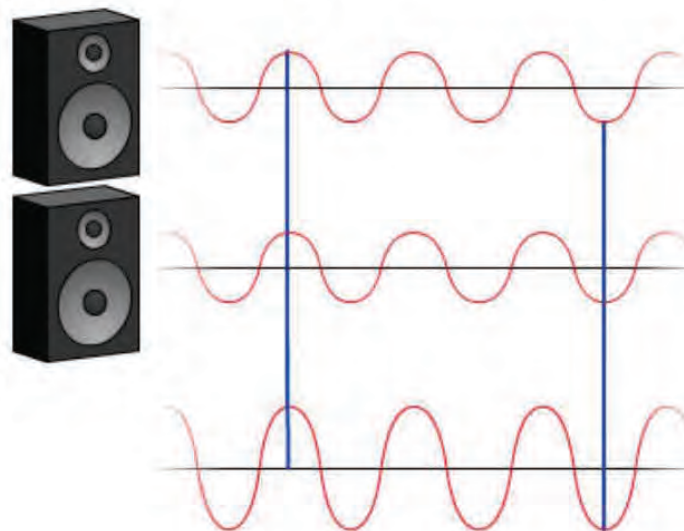
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Strong, uniform sound field.

In this experiment, there are two speakers next to each other and both are simultaneously playing a certain wave pattern. The very bottom wave is the sum of the other two waves.

The very bottom wave is produced by in two phase sound waves.



that the waves travel within a material and the frequency of the wave all affect the sound field. Use the Java applet below to experiment with these variables and see how the sound field is affected.

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The sound waves are in phase. The peaks and troughs of the wave are in line with each other.

The very bottom wave doubled the amplitude (loudness) compared to the other two waves. This is called **fully constructive interference**.

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Review:

1. Constructive interference is when two or more waves interact and their amplitudes add up to create a stronger wave.
2. Destructive interference is when two or more wave interact and their amplitudes subtract to create a dampened wave.
3. Constructive and destructive interference can happen at the same time if the waves are not completely in phase or out of phase.

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Refraction and Snell's Law

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After reading this section you will be able to the following:

- Describe what refraction and reflection is.
- Explain Snell's Law.



When an ultrasonic or EM wave passes through an interface between two materials at an **oblique angle**, and the materials have different indices of refraction, both **reflected** and **refracted** waves are produced. This also occurs with light, which is why objects seen across an interface appear to be shifted relative to where they really are. For example, if you look straight down at an object at the bottom of a glass of water, it looks closer than it really is. A good way to visualize how light and sound refract is to shine a flashlight into a bowl of slightly cloudy water noting the refraction angle with respect to the **incident angle**.

Refraction takes place at an interface due to the different velocities of the waves within the two materials. The velocity of the wave in each material is determined by the material properties (elastic modulus,

Oblique Angle: An angle that is not a right angle or a multiple of a right angle.

Refraction: A change in direction of a wave due to a change in its speed.

density, dielectric properties, refractive index) for that material. In the animation below, a series of plane waves are shown traveling in one material and entering a second material that has a higher wave speed. Therefore, when the wave encounters the interface between these two materials, the portion of the wave in the second material is moving faster than the portion of the wave in the first material. It can be seen that this causes the

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wave to bend.

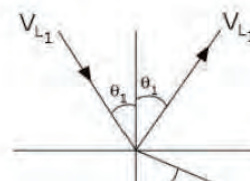


start



Snell's Law describes the relationship between the angles and the velocities of the waves. Snell's law equates the ratio of material velocities V_1 and V_2 to the ratio of the **sine's** of incident (Q_1) and refracted (Q_2) angles, as shown in the following equation.

$$\frac{\sin \theta_1}{V_{L1}} = \frac{\sin \theta_2}{V_{L2}}$$



Where:

V_{L1} is the longitudinal wave velocity in material 1

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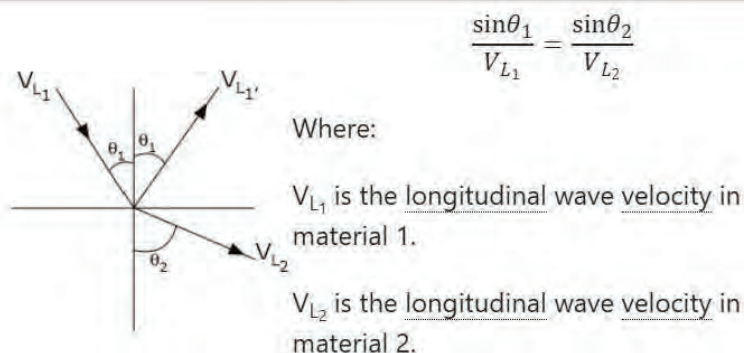
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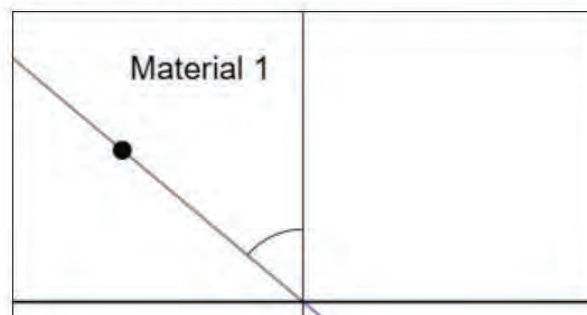
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Note that in the diagram above, there is a reflected longitudinal wave ($V_{L1'}$) shown. This wave is reflected at the same angle as the incident wave because the two waves are traveling in the same material, and hence have the same velocities. This reflected wave is unimportant in our explanation of Snell's Law, but it should be remembered that some of the wave energy is reflected at the interface. In the applet below, only the incident and refracted waves are shown. The angle of either wave can be adjusted by clicking and dragging the mouse in the region of the arrows. Values for the angles or wave velocities can also be entered in the dialog boxes so the that applet can be used as a Snell's Law calculator.



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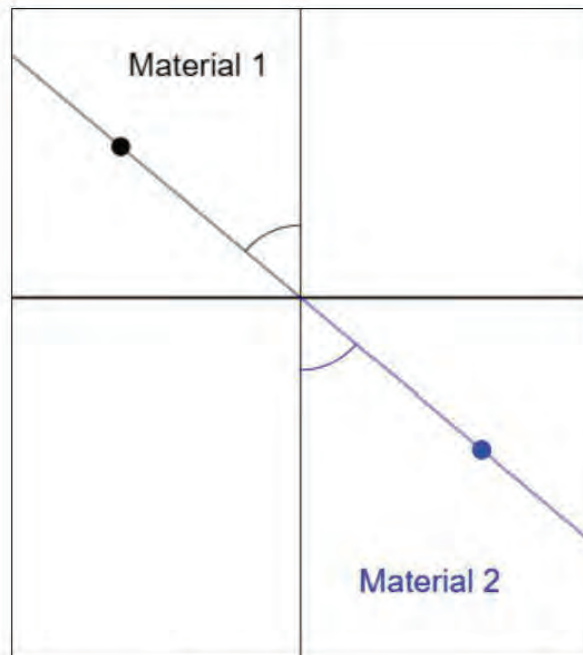
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Material 1 Sin

V1=

Material 2 Sin

V2=

$$\frac{\sin(50.000 \text{ degrees})}{\sin(31.5 \text{ degrees})} = \frac{0.635}{0.635}$$

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V2= 0.635

$$\frac{\sin(50.000 \text{ degrees})}{\sin(50.000 \text{ degrees})} = \frac{0.635}{0.635}$$

Sin >= 0 & Sin <= 90

V >= 0 & V <= 10

Units are in cm/us, but the user may assume other units.

Change the materials and incident angle. Observe how the angle of refraction changes.

When a wave moves from a slower to a faster material, there is an incident angle that makes the angle of refraction for the wave 90°. This is known as the first **critical angle**. The first critical angle can be found from Snell's law by putting in an angle of 90° for the angle of the refracted ray. In the case of acoustic waves, at the critical angle of incidence much of the acoustic energy is in the form of an inhomogeneous compression wave, which travels along the interface and decays exponentially with depth from the interface. This wave is sometimes referred to as a "creep wave." Because of their inhomogeneous nature and the fact that they decay rapidly, creep waves are not used as extensively as Rayleigh surface waves in NDT. However, creep waves are sometimes more useful than Rayleigh waves because they suffer less from surface irregularities and coarse material microstructure due to their longer wavelengths.

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1. Refraction is a change in direction of a wave due to a change in its speed, which occurs due to material differences.
2. Snell's Law describes the relationship between the angles and the velocities of the waves.

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Reflection and Transmission Coefficients

After reading this section you will be able to do the following:

- Understand how reflection and transmission varies based on materials.
- Calculate reflection and transmission coefficients.

Waves are reflected at boundaries where there is a difference in impedances (Z) of the materials on each side of the boundary. This difference in Z is commonly referred to as the **impedance mismatch**. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and another.

The fraction of the incident wave intensity that is reflected can be derived because particle velocity and local

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particle pressures must be continuous across the boundary. When the impedances of the materials on both sides of the boundary are known, the fraction of the incident wave intensity that is reflected can be calculated with the equations below. The values produced are known as **reflection coefficients**. Reflection coefficients can be in terms of amplitude or in terms of energy. The reflection coefficient is the fraction of incident energy or amplitude that is reflected as the incident wave reaches the boundary. Unlike energy reflection coefficients, amplitude reflection coefficients depend on what kind of quantity you are using to represent the wave amplitude and whether that quantity corresponds to the numerator or denominator of the impedance. The amplitude reflection coefficient for force, stress, voltage, or electric field waves is

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)$$

The amplitude reflection coefficient for displacement, velocity, current, or magnetic field waves is

$$R = \left(\frac{Z_1 - Z_2}{Z_2 + Z_1} \right)$$

The energy reflection coefficient does not depend on the type of wave and is

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

Transmission coefficients are likewise used to calculate the fraction of an incident wave that transmits across a boundary. For force, stress, voltage, or electric field wave representations, the amplitude transmission coefficient is

$$T = \left(\frac{2Z_2}{Z_1 + Z_2} \right)$$

Coefficients: A calculated measure of a physical property such as reflected or transmitted waves.

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For displacement, velocity, current, or magnetic field wave representations, the amplitude transmission coefficient is

$$T = \left(\frac{2Z_1}{Z_1 + Z_2} \right)$$

Interestingly, the amplitude reflection and transmission coefficients do not in general add up to 1.0 because amplitude is not conserved across the boundary. In contrast, since the amount of reflected energy plus the transmitted energy must equal the total amount of incident energy, the energy transmission coefficient is calculated by simply subtracting the reflection coefficient from one

$$T = 1 - \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2}$$

Formulations for energy reflection and transmission coefficients for elastic (mechanical) waves are shown in the interactive applet below. Different materials may be selected or the material velocity and density may be altered to change the acoustic impedance of one or both materials. The red arrow represents reflected sound and the blue arrow represents transmitted sound.

Energy Reflection and Transmission Coefficients (Mechanical Wave)

$$Z = P * V$$

Acoustic Impedance = Z, Density = P, Acoustic Velocity = V

Material 1

Z1 = 1.721 = *

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Material 1

Z1 = 1.721 = *

Material 2

Z2 = 1.721 = *

Bounds: 0.001 <= P <= 12 & 0.1 <= V <= 10

Formula

$$\left[\frac{Z2 - Z1}{Z2 + Z1} \right]^2$$

Reflection Energy

$$\left[\frac{1.721 - 1.721}{1.721 + 1.721} \right]^2$$

= Reflection Coefficient = 0
Decibels = 0dB

Transmission Energy

$$\left[1.721 - 1.721 \right]^2$$

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$$\text{Transmission Energy} = 1 - \left[\frac{1.721 - 1.721}{1.721 + 1.721} \right]^2$$

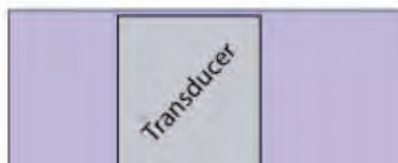
= Transmission Coefficient = 1.000

Decibels = 0dB

Change the settings for the applet and observe how the amounts of reflection and transmission change.

Note that the reflection and transmission coefficients are often expressed in decibels (dB) to allow for large changes in signal strength to be more easily compared.

Using the applet above, note that the energy reflected at a water-stainless steel interface is 0.88 or 88%. The amount of energy transmitted into the second material is 0.12 or 12%. The amount of reflection and transmission energy in dB terms are -1.1 dB and -18.2 dB respectively. The negative sign indicates that individually, the amount of reflected and transmitted energy is smaller than the incident energy.



If reflection and transmission at interfaces is followed through the component, only a small percentage of the original energy makes it back to the transducer, even when loss by attenuation is ignored. For example, consider an immersion inspection of a steel block, like the one

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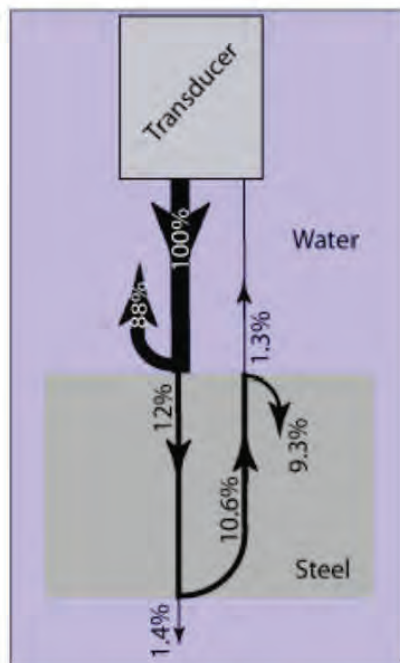
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If reflection and transmission at interfaces is followed through the component, only a small percentage of the original energy makes it back to the transducer, even when loss by attenuation is ignored. For example, consider an immersion inspection of a steel block, like the one on the left. The sound energy leaves the transducer, travels through the water, encounters the front surface of the steel, encounters the back surface of the steel and reflects back through the front surface on its way back to the transducer. At the water steel interface (front surface), 12% of the energy is transmitted. At the back surface, 88% of the 12% that made it through the front surface is reflected. This is 10.6% of the intensity of the initial incident wave. As the wave exits the part back through the front surface, only 12% of 10.6 or 1.3% of the original energy is transmitted back to the transducer.

Review:

1. Waves are reflected at boundaries where there is a difference in impedances (Z) of the materials on each side of the boundary.
2. Reflection and transmission coefficients are often expressed in dB.

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Mode Conversion

After reading this section you will be able to do the following:

- Explain what mode conversion is and what causes it.

When a wave travels in a solid material, one form of wave energy can be transformed into another form. For example, when a longitudinal waves hits an interface at an angle, some of the energy can cause particle movement in the transverse direction to start a shear (transverse) wave. **Mode conversion** occurs when a wave encounters an interface between materials of different impedances and the incident angle is not normal to the interface. From the ray tracing clip below, it can be seen that since mode conversion occurs every time a wave encounters an interface at an angle, signals can become confusing at times.

In the previous sections, it was pointed out that when waves pass through an interface between materials having different wave speeds, refraction takes place at the interface. The larger the difference in wave speeds between the two materials, the more the wave is **refracted**. Notice that the shear wave is not refracted as much as the longitudinal wave. This occurs because shear waves travel slower than longitudinal waves. Therefore, the velocity difference between the incident longitudinal wave and the shear wave is not as great as it is between the incident and refracted longitudinal

Material Properties:

Material strain is proportional to material stress.

Elastic Modulus : The ratio of the stress applied to a body to the strain produced.

waves. Also note that when a longitudinal wave is reflected

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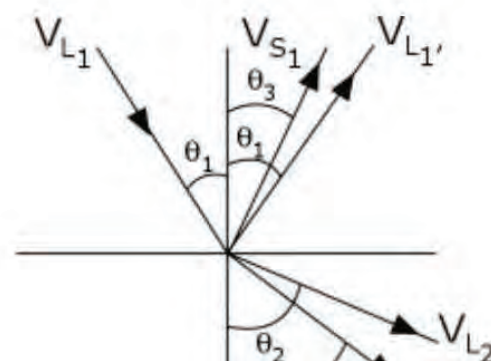
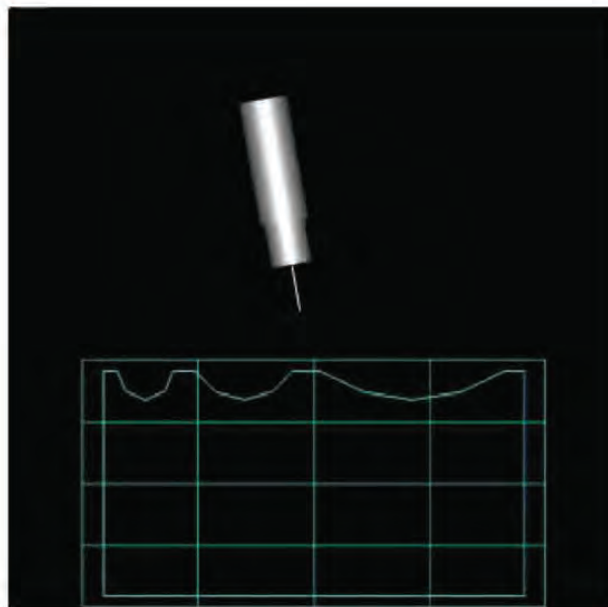
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longitudinal wave is reflected inside the material, the reflected shear wave is reflected at a smaller angle than the reflected longitudinal wave. This is also due to the fact that the shear velocity is less than the longitudinal velocity within a given material.

Snell's Law holds true for shear waves as well as longitudinal waves and can be written as follows.

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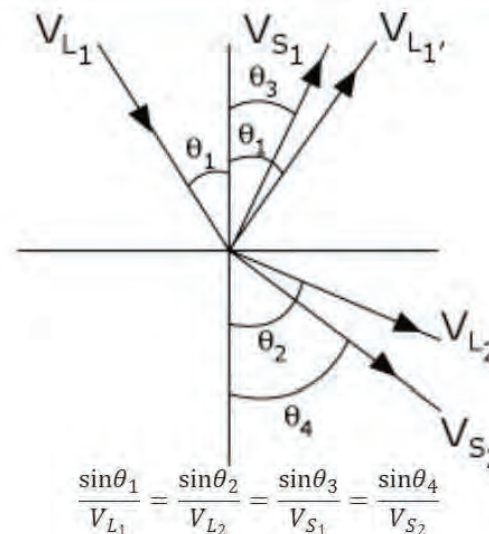
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Where:

V_{L1} is the longitudinal wave velocity in material 1.

V_{L2} is the longitudinal wave velocity in material 2.

V_{S1} is the shear wave velocity in material 1.

V_{S2} is the shear wave velocity in material 2.

In the applet below, the shear (transverse) wave ray path has been added. The ray paths of the waves can be adjusted by clicking and dragging in the vicinity of the arrows. Values for the angles or the wave velocities can also be entered into the dialog boxes. It can be seen from the applet that when a wave moves from a slower to a faster material, there is an incident angle which makes the angle of refraction for the longitudinal wave 90 degrees. As mentioned on the previous page, this is known as the **first critical angle** and all of the energy from

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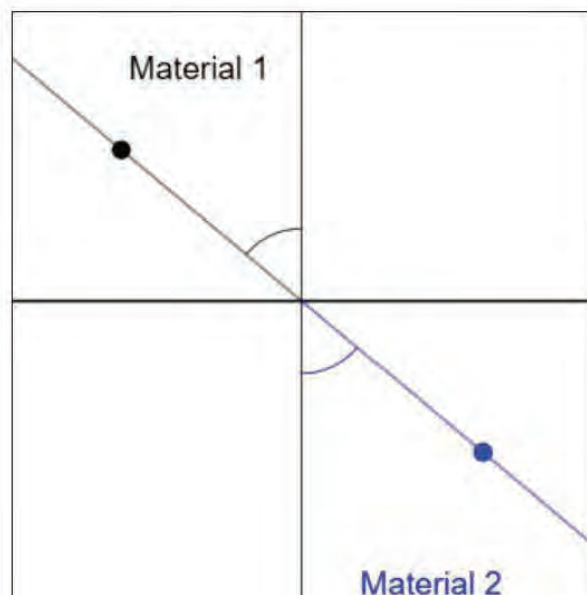
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the refracted longitudinal wave is now converted to a surface following longitudinal wave. This surface following wave is sometime referred to as a creep wave and it is not very useful in NDT because it dampens out very rapidly.

Beyond the first critical angle, only the shear wave propagates into the material. For this reason, most angle beam transducers use a shear wave so that the signal is not complicated by having two waves present. In many cases there is also an incident angle that makes the angle of refraction for the shear wave 90 degrees. This is known as the second critical angle and at this point, all of the wave energy is reflected or refracted into a surface following shear wave or shear creep wave. Slightly beyond the second critical angle, surface waves will be generated.



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Material 2

Material 1 Sin

V1=

Material 2 Sin

V2=

$$\frac{\sin(50.000 \text{ degrees})}{\sin(50.000 \text{ degrees})} = \frac{0.635}{0.635}$$

Sin >= 0 & Sin <= 90

V >= 0 & V <= 10

Units are in cm/us, but the user may assume other units.

Change the materials and incident angle. Observe how the angle of refraction changes.

Note that the applet defaults to compressional velocity in the second material. The refracted compressional wave angle will be generated for given materials and angles. To find the angle of incidence required to generate a shear wave at a given angle complete the following:

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1. Set V1 to the longitudinal wave velocity of material 1. This material could be the transducer wedge or the immersion liquid.
2. Set V2 to the shear wave velocity (approximately one-half its compressional velocity) of the material to be inspected.
3. Set Q2 to the desired shear wave angle.
4. Read Q1, the correct angle of incidence.

Review:

1. When a wave travels in a solid material, one form of wave energy can be transformed into another form.
2. When a wave moves from a slower to a faster material, there is an incident angle which makes the angle of refraction for the longitudinal wave 90 degrees. This is the critical angle.

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Wavelength and Defect Detection

After reading this section you will be able to do the following:

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- Define what sensitivity and resolution are.
- Describe how frequency choice can affect detection capabilities.

In ultrasonic and microwave NDT, the inspector must make a decision about the frequency of the transducer that will be used. As we learned on previously, changing the frequency when the wave velocity is fixed will result in a change in the wavelength of the sound. The wavelength used has a significant effect on the probability of detecting a discontinuity. A general rule of thumb is that a discontinuity must be larger than one-half the wavelength to stand a reasonable chance of being detected.

Sensitivity and resolution are two terms that are often used in ultrasonic inspection to describe a technique's ability to locate flaws. Sensitivity is the ability to locate small discontinuities. Sensitivity generally increases with higher frequency (shorter wavelengths). Resolution is the ability of the system to locate discontinuities that are close together and tell them apart within the material or located near the part surface. Resolution also generally improves as the frequency increases.

The wave frequency can also affect the capability of an inspection in adverse ways. Therefore, selecting the optimal inspection frequency often involves maintaining a balance between the favorable and unfavorable results of the selection. Before selecting an inspection frequency, the material's grain structure and thickness, and the discontinuity's type, size, and probable location should be considered. As frequency increases, waves tend to scatter from large or coarse grain structure and from small imperfections within a material. Cast materials often have coarse grains and other sound scatters that require lower frequencies to be used for evaluations of these products. Wrought and forged products with directional and refined grain structure can usually be inspected with higher frequency transducers.

Since more things in a material are likely to scatter a portion of the wave energy at higher frequencies, the penetrating power (or the maximum depth in a material that flaws can be located) is also reduced.

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Review:

1. Sensitivity generally increases with higher frequency (shorter wavelengths).
2. Before selecting an inspection frequency, the material's grain structure and thickness, and the discontinuity's type, size, and probable location should be considered.

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Signal-to-Noise Ratio

After reading this section you will be able to do the following:

- Define signal-to-noise ratio.
- Explain the role signal-to-noise ratio plays in defect detectability.

In a previous page, the effect that frequency and wavelength have on flaw detectability was discussed. However, the detection of a defect involves many factors other than the relationship of wavelength and flaw size. For example, the amount of the wave that reflects from a defect is also dependent on the impedance mismatch between the flaw and the surrounding material. A void is generally a better reflector than a metallic inclusion

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because the impedance mismatch is greater between air and metal than between two metals.

Often, the surrounding material has competing reflections. Microstructure grains in metals and the aggregate of concrete are a couple of examples. A good measure of detectability of a flaw is its **signal-to-noise ratio (S/N)**. The signal-to-noise ratio is a measure of how the signal from the defect compares to other background reflections (categorized as "noise"). A signal-to-noise ratio of 3 to 1 is often required as a minimum. The absolute noise level and the absolute strength of an echo from a "small" defect depends on a number of factors, which include:

- The probe size and focal properties.
- The probe frequency, bandwidth and efficiency.
- The inspection path and distance (water and/or solid).
- The interface (surface curvature and roughness).
- The flaw location with respect to the incident beam.
- The inherent noisiness of the metal microstructure.
- The 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.
- Multifaceted flaws will tend to scatter sound away from the transducer.

The following formula relates some of the variables affecting the signal-to-noise ratio (S/N) of a defect:

$$\frac{S}{N} = \sqrt{\frac{16}{\rho v_{metal} w_x w_y \Delta t} \frac{A_{flow}(f_0)}{FOM(f_0)}}$$

Where v_{metal} is the speed of sound in the metal, w_x and w_y are the lateral beam widths at the flaw depth, Δt is

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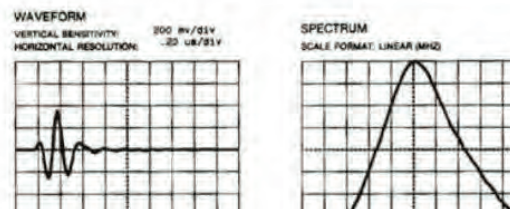
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where v_{metal} is the speed of sound in the metal, w_x and w_y are the lateral beam widths at the flaw depth, Δt is the pulse duration, $A_{\text{flow}}(f_0)$ is the flaw scattering amplitude at center frequency, and $\text{FOM}(f_0)$ is the noise Figure of Merit at center frequency.

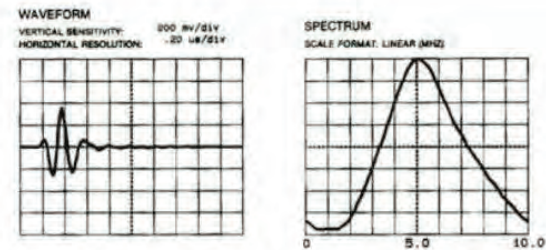
Rather than go into the details of this formulation, a few fundamental relationships can be pointed out. The signal-to-noise ratio (S/N), and therefore, the detectability of a defect:

- 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 (Δt). 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. See the figure below showing the waveform of a transducer and its corresponding frequency spectrum.
- Decreases in materials with high density and/or a high ultrasonic velocity. The signal-to-noise ratio (S/N) is inversely proportional to material density and acoustic velocity.
- Generally increases with frequency. However, in some materials, such as titanium alloys, both the " A_{flaw} " and the "Figure of Merit (FOM)" terms in the equation change at about the same rate with changing frequency. So, in some cases, the signal-to-noise ratio (S/N) can be somewhat independent of frequency.



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Review:

1. The signal-to-noise ratio is a measure of how the signal from the defect compares to other background reflections (categorized as "noise").
2. A signal-to-noise ratio of 3 to 1 is often required as a minimum to detect a flaw.

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NDT is the use of special equipment and methods to learn something about an object without harming the object. The term nondestructive testing usually implies that a nonliving object, such as a piece of metal, is being evaluated. NDT methods are used to make sure that important parts on airplanes and automobiles and in nuclear power plants are free of defects that could lead to an accident. NDT is also used in many other industries to make sure that parts do not have defects that would make the customer unhappy. The inspection and measurement methods used in the field of NDT are largely based on the scientific principles of physics and chemistry.

Where is NDT used?



Many of the parts that are used in complex systems like aircraft or the Space Shuttle must be inspected to make sure they do not contain defects that may lead to problems or accidents. In the picture at the right an NDT inspector examines a Space Shuttle component to make sure that it has been manufactured properly and that there are no defects present. Even very small defects that can not be seen



without magnification (like the one shown in the picture below) can sometimes cause problems and must be found. NDT inspectors use specialized equipment that can find these small defects even if they are buried inside the material.



Some of the equipment and procedures used by NDT personnel are similar to those used in the medical industry. NDT personnel use X-rays to make inspections just like a doctor or a dentist uses X-rays to produce an image of the internal features of your body or teeth. The image in the center below is an X-ray of a person's teeth showing fillings and other dental work. The image below on the right is an X-ray of what is

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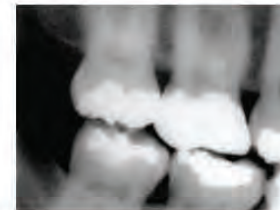
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fillings and other dental work. The image below on the right, is an X-ray or what is also called a radiograph of several welds. Flaws can be seen in one of the welds.



Another NDT method that is also used in the medical industry is ultrasound (high frequency sound waves). In a hospital, ultrasound might be used to produce an image of a baby still in the womb or to look at the heart as it pumps away. In the field of NDT, technicians use ultrasound to locate cracks and other flaws inside materials and also to measure the thickness of materials. The man in the picture to the right is using ultrasound to inspect the wall of the ship for areas that may be thinning due to corrosion damage.



An extreme example of how NDT is important to all of us can be seen in a video of an actual airline crash on the next page.

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Nondestructive Testing (NDT)

The field of Nondestructive Testing (NDT) is a very broad, interdisciplinary field that plays a critical role in assuring that structural components and systems perform their function in a reliable and cost effective fashion. NDT technicians and engineers define and implement tests that locate and characterize material conditions and flaws that might otherwise cause planes to crash, reactors to fail, trains to derail, pipelines to burst, and a variety of less visible, but equally troubling events. These tests are performed in a manner that does not affect the future usefulness of the object or material. In other words, NDT allows parts and materials to be inspected and measured without damaging them. Because it allows inspection without interfering with a product's final use, NDT provides an excellent balance between quality control and cost-effectiveness. Generally speaking, NDT applies to industrial inspections. While technologies are used in NDT that are similar to those used in the medical industry, typically nonliving objects are the subjects of the inspections.

Nondestructive Evaluation (NDE)

Nondestructive Evaluation (NDE) is a term that is often used interchangeably with NDT. However, technically, NDE is used to describe measurements that are more quantitative in nature. For example, a NDE method would not only locate a defect, but it would also be used to measure something about that defect such as its size, shape, and orientation. NDE may be used to determine material properties such as fracture toughness,

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formability, and other physical characteristics.

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Background on NDT and NDE

Nondestructive testing has been practiced for many decades. One of the earliest applications was the detection of surface cracks in railcar wheels and axles. The parts were dipped in oil, then cleaned and dusted with a powder. When a crack was present, the oil would seep from the defect and wet the powder providing visual indicating that the component was flawed. This eventually led to oils that were specifically formulated for performing these and other inspections and this inspection technique is now called penetrant testing.

X-rays were discovered in 1895 by Wilhelm Conrad Roentgen(1845-1923) who was a Professor at Wuerzburg University in Germany. Soon after his discovery, Roentgen produced the first industrial radiograph when he imaged a set of weights in a box to show his colleagues. Other electronic inspection techniques such as ultrasonic and eddy current testing started with the initial rapid developments in instrumentation spurred by technological advances, and subsequent defense and space efforts following World War II. In the early days, the primary purpose was the detection of defects. Critical parts were produced with a "safe life" design, and were intended to be defect free during their useful life. The detection of a defects was automatically a cause for

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removal of the component from service.

In the early 1970's, two events occurred which caused a major change in the way inspections were viewed. The continued improvement of inspection technology, in particular the ability to detect smaller and smaller flaws, led to more and more parts being rejected (even though the probability of part failure had not changed). At this time the discipline of fracture mechanics emerged, which enabled one to predict whether a crack of a given size would fail under a particular load if a particular material property or fracture toughness were known. Other laws were developed to predict the rate of growth of cracks under cyclic loading (fatigue). With the advent of these tools, it became possible to accept structures containing defects if the sizes of those defects were known. This formed the basis for a new design philosophy called "damage tolerant designs." Components having known defects could continue to be used as long as it could be established that those defects would not grow to a critical size that would result in catastrophic failure.

A new challenge was thus presented to the nondestructive testing community. Mere detection of flaws was not enough. One needed to also obtain quantitative information about flaw size to serve as an input to fracture mechanics calculations to predict the remaining life of a component. These needs, which were particularly strong in the defense and nuclear power industries, led to the creation of a number of research programs around the world and the emergence of nondestructive evaluation (NDE) as a new discipline.

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Sioux City Airline Crash

Before we get started on the fun stuff. Let's take a look at the serious side of NDT for a moment. The very unfortunate event that you are about to see in the video is used here to further introduce the field of NDT and to illustrate its importance to our everyday life. Traveling by plane is, statistically, a very safe mode of transportation. Thankfully, accidents such as what you're about to see don't happen very often. Because of all the effort that the aircraft manufactures, the material suppliers, the aircraft operators, and government regulators make to keep air travel safe, accidents like this are rare.

In the airline crash of a DC 10 at Sioux City, Iowa, a very tiny defect in a piece of material used to build the plane started a fatigue crack that grew and ultimately led to the accident. To ensure that defects, like the one you are about to see, do not find their way into airplane parts, the material producers and part manufactures perform inspections using NDT techniques. Using NDT, airplanes are periodically inspected for cracks that may have started and other damage, so that any cracks or damage are located before it becomes dangerous. Almost without exception, the defects are found before they present a problem to the airplane. Unfortunately the accident in Sioux City was one of those exceptions. After this crash occurred, improvements were made in materials and NDT methods to prevent similar accidents from happening. To watch the video click on the link below.



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[Video of Crash](#) (webm, 3.3M)

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About This Site

This Internet site was originally created in the early 2000's by the Collaboration for Nondestructive Testing, a group of educational institutions including Iowa State University and five community colleges. The site was renovated and updated in 2021 by Iowa State University with support from the American Society of Nondestructive Testing and the National Science Foundation.

Contributions and suggestions for improvement are highly encouraged. It is hoped that the site will continue to grow and increase in value based on contributions and recommendations from academic and industry users. Partial support for the original site was provided by the National Science Foundation's



'Start to Finish' sculpture by George Greenamyre

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original site was provided by the National Science Foundation's Division of Undergraduate Education through grant DUE 0101709. The 2020 update was funded under NSF grant DUE #1801010. This site would also not be possible without the hard work and generous support of content contributors and industrial sponsors; ASNT, AWS, and Weld-Ed. We would also encourage you to visit another NSF-supported site on welding education at <https://www.weld-ed.org>.

Background Information

In 1996, four Midwest colleges (Cowley County, KS, Northeast Iowa, IA, Ridgewater, MN, and Southeast, NE) and Iowa State University joined to form the North Central Collaboration for Education in Nondestructive Testing. This collaboration was started as a National Science Foundation ATE program to enhance the quality of NDT technician education and strengthen the ties between these Midwest institutions. This program has successfully developed advanced teaching methods and new science-based materials at the junior/senior high school and community college levels.

A major part of the Collaboration's efforts was the development of new, science-based course materials for community college students. These materials supplement the materials already in use and help student learn important concepts with visual and interactive tools. Another project involved the development of science-based materials for both middle/high school and community college students. Since most of the materials are computer-based, the Internet became a very useful tool for distribution of the materials. These materials have been very well received and are being used by individuals and groups across the nation.

In 2001, the collaboration was expanded to become the Collaboration for NDT Education and, received additional funding from the NSF to create a national focal point for NDT education on the Internet. The establishment of this site is one of the main product of collaboration. While collaboration members have been

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major contributors to this site, a number of other individuals, companies, institutions have contributed as well. While the Collaboration is unfortunately no longer active, these materials remain widely used nationally and internationally. As of 2021, Iowa State University's Center for Nondestructive Evaluation performed a major NSF-funded renovation of the site in collaboration ISU's College of Engineering, ISU Library, and the American Society for Nondestructive Testing (ASNT). The goals of the renovation were to update and expand the technical content and make the site sustainably maintainable for twenty more years.

Members of the Collaboration of for NDT Education were:

- Cowley County Community College, Arkansas City, Kansas
- Iowa State University, Ames, IA
- Northeast Iowa Community College, Peosta, IA
- Ridgewater College, Hutchinson, MN
- Salt Lake Community College, Salt Lake City, UT
- Southeast Community College, Milford, NE

Contact Us

Your comments and suggestions for improvement are very important to us. This site is intended to serve as a resource to students of NDT, and the NDT community as a whole. This site is the product of the Collaboration for NDT Education and primarily maintained by the Center for NDE at Iowa State University. It is our goal to make this site as useful and technically accurate as possible. Any assistance that you can provide in helping to reach this goal will be greatly appreciated.

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Coordinator and Liaison: TBD

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