Physics of Ultrasound

TI Precision Labs – Ultrasonic Sensing

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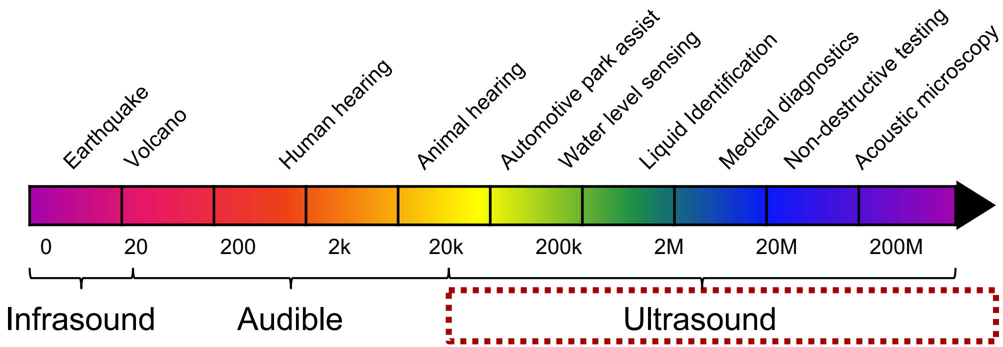
Definition of Ultrasound

Ultrasound is defined as:

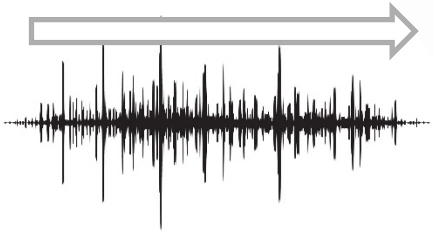
- sound waves with a frequency above the upper limit of human hearing at 20kHz.
- having physical properties that are identical to audible sound.
- a frequency some animals use for navigation and echo location.

This content will focus on ultrasonic systems that use transducers operating between 20kHz up to several GHz.

Sound Frequency Spectrum



Acoustics of Ultrasound



When ultrasound is a **stimulus:**
Generates and Emits Ultrasound Wave

When ultrasound is a **sensation:**
Detects and Responds to Ultrasound Wave

Sound Propagation

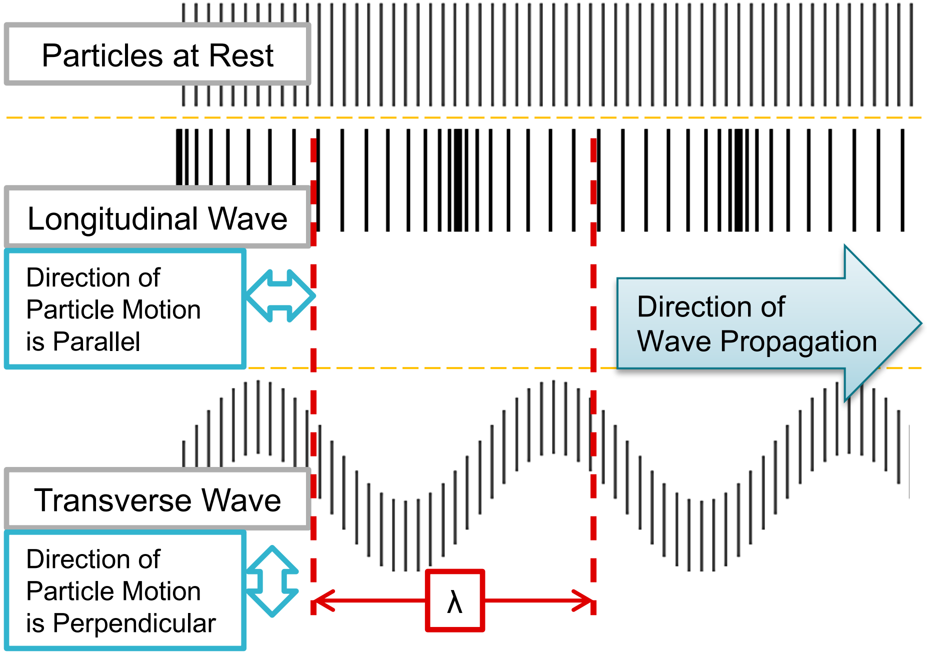
Ultrasound propagates as:

- longitudinal waves in air, water, plasma
- transverse waves in solids

The transducer's vibrating diaphragm is the source of the ultrasonic wave. As the source vibrates, the vibrations propagate away at the speed of sound to form a measureable ultrasonic wave.

The particles of the medium only transport the vibration of the ultrasonic wave, but do not travel with the wave. The medium can cause waves to be reflected, refracted, or attenuated over time.

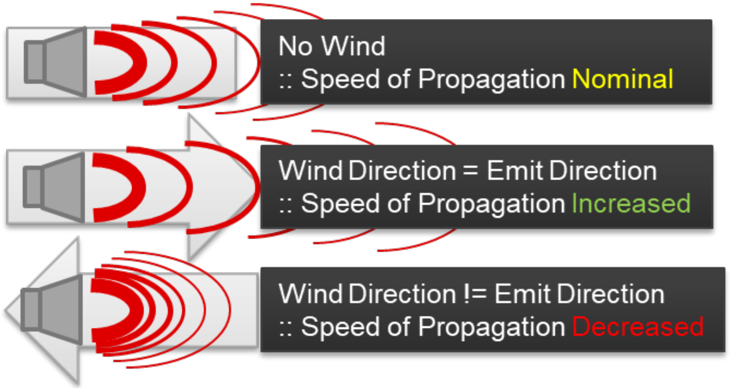
An ultrasonic wave cannot travel through a vacuum.

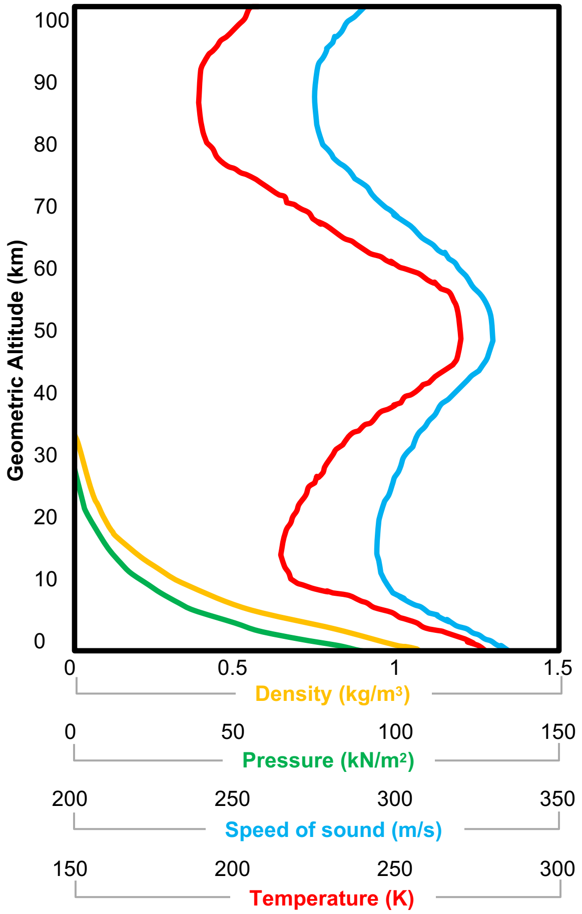


Acoustic Properties

Ultrasonic propagation is affected by:

1. Relationship between density, pressure, and temperature to determine the speed of sound.
2. Motion of the transmission medium itself can increase or decrease the speed of sound.
3. Medium viscosity determines the rate at which sound attenuates.





Sound Wave Properties

Ultrasound is interpreted as pressure and time with the following properties:

- Frequency, Period, or Wavelength
- Amplitude, Sound Pressure, or Intensity
- Speed of Sound
- Direction

Speed & Direction → Velocity Vector

Wave Number & Direction → Wave Vector

Speed of Sound

- The speed of sound depends on the medium the waves pass through, and is a fundamental property of the material. Use the Newton–Laplace equation to solve for speed of sound:

$$c = \sqrt{\frac{K_s}{\rho}}$$

  - where K_s is the elastic bulk modulus, c is the velocity of sound, and ρ is the density.

- The physical properties and the speed of sound change with ambient conditions, such as temperature and humidity.
  - In 20 °C air, at sea level, the speed of sound is approximately 343 m/s, and be calculated using the formula:

$$v = 331 + (0.6 \times T)$$

  - where v is velocity and T is temperature in Celsius

Effects of Temperature On Air

Temperature T (°C)	Speed of sound c (m/s)	Density of air ρ (kg/m³)	Acoustic Impedance z_0 (Pa·s/m)
35	351.88	1.1455	403.2
30	349.02	1.1644	406.5
25	346.13	1.1839	409.4
20	343.21	1.2041	413.3
15	340.27	1.2250	416.9
10	337.31	1.2466	420.5
5	334.32	1.2690	424.3
0	331.30	1.2922	428.0
−5	328.25	1.3163	432.1
−10	325.18	1.3413	436.1
−15	322.07	1.3673	440.3
−20	318.94	1.3943	444.6
−25	315.77	1.4224	449.1

Sound Pressure

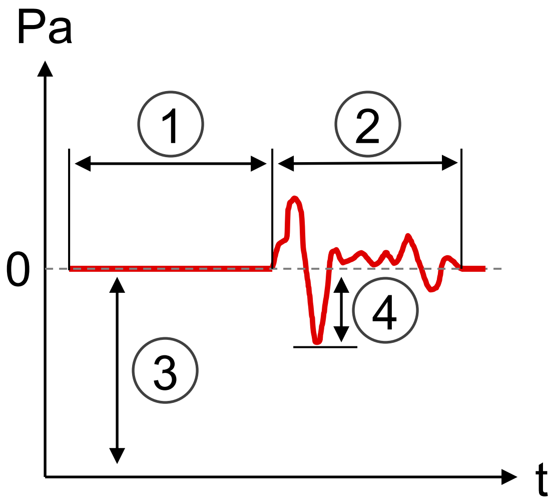
Sound pressure or acoustic pressure is the local pressure deviation from the ambient atmospheric pressure, caused by a sound wave.

The SI unit of sound pressure is the pascal (Pa). Sound pressure level (SPL) or acoustic pressure level is a logarithmic measure of the effective pressure of a sound relative to a reference value. Sound pressure level, denoted Lp and measured in dB, and is solved by the equation:

$$L_p = 20 \log_{10}\left(\frac{p}{p_0}\right) dB$$

where

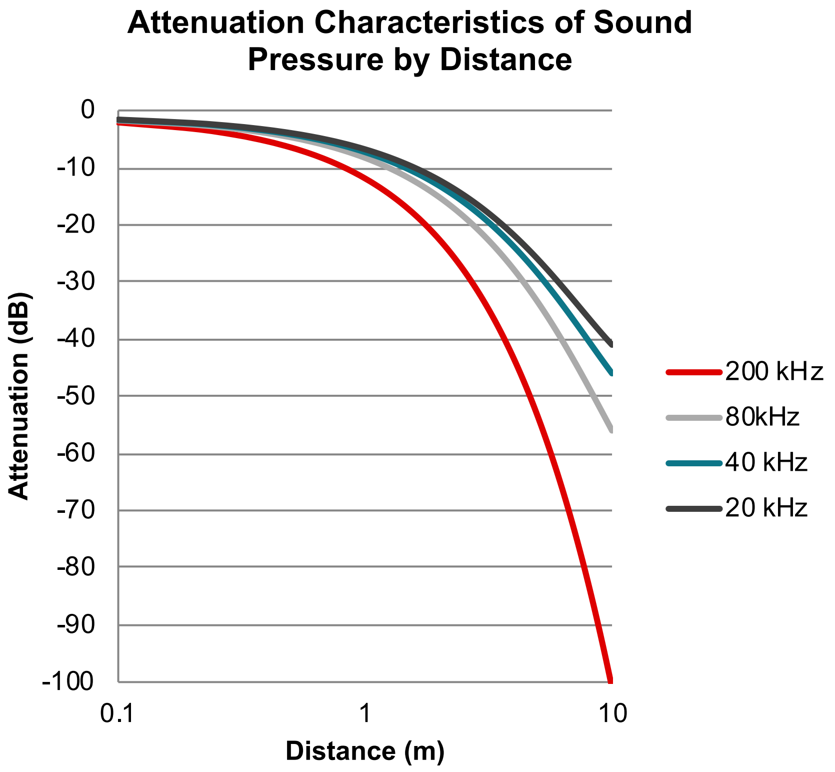
- p is the root mean square sound pressure
- p_0 is the *reference sound pressure*



Sound pressure diagram:
1. silence
2. sound
3. atmospheric pressure
4. sound pressure

Acoustic Attenuation

- When sound travels through a medium, its sound pressure diminishes with distance.
- Scattering and absorption of the sound wave are real-world attenuation factors.
  - Scattering is the reflection of the sound in directions other than its original direction of propagation
  - Absorption is the conversion of the sound energy to other forms of energy.



Acoustic Impedance

Acoustic impedance is a measure of the opposition that a system presents to the acoustic flow resulting of an acoustic pressure applied to the system. The acoustic impedance (Z) of a material is defined as the product of its density (p) and acoustic velocity (V): **Z = pV**

Acoustic impedance is important in:

- the determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedances.
- the design of ultrasonic transducers.
- assessing absorption of sound in a medium.

Acoustic Impedance by Material

Material	Density (kgm^{-3})	Speed of Sound (kgm^{-1})	Acoustic Impedance ($kgm^{-2}s^{-1} \times 10^6$)
Air	1.3	330	0.000429
Sponge	100	750	0.075
Water	1000	1450	1.45
Soft Tissue	1050	1500	1.58
Aluminum	2700	6320	17.1
Steel	7800	5900	46.02
Iron	7700	5900	45.43
Gold	19320	3240	62.6

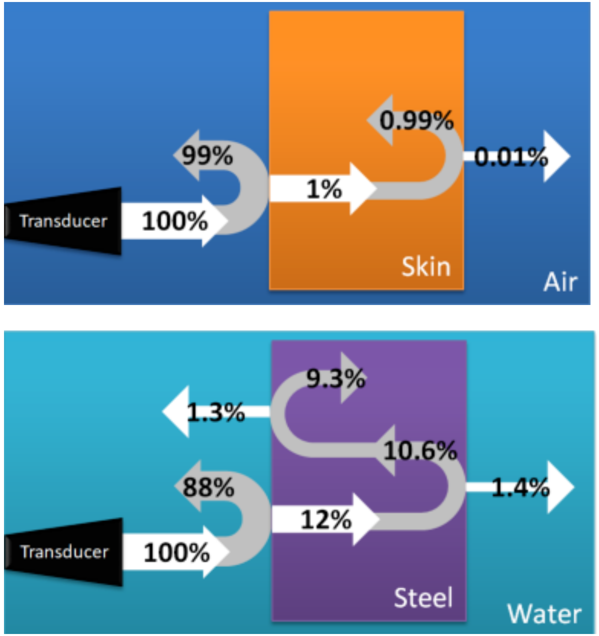
Impedance Mismatch

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.

When the acoustic 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 equation below. The value produced is known as the **reflection coefficient**.

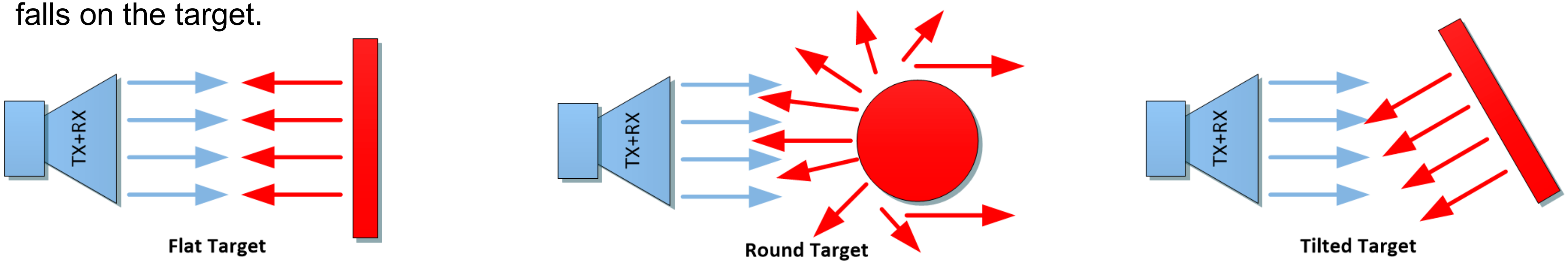
$$Reflection\ Coefficient = R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

Reflection Coefficient Examples



RADAR or SONAR Cross Section

RADAR or SONAR Cross Section (RCS or SCS) is the measure of a target's ability to reflect radar signals in the direction of the radar receiver. The conceptual definition of RCS includes the fact that not all of the radiated energy falls on the target.



Target	Maximum Sonar Cross Section	Advantage	Disadvantage
Sphere	$\sigma_{max} = \pi \times r^2$	Nonspecular	Lowest RCS for size; radiates isotopically
Cylinder	$\sigma_{max} = (2 \times \pi \times r \times h^2) / \lambda$	Nonspecular along radial axis	Low RCS for size; specular along axis
Flat rectangular plate	$\sigma_{max} = (4 \times \pi \times l^2 \times w^2) / \lambda^2$	Largest RCS for size	Specular along both axes; difficult to align

A target's RCS (σ) can be visualized as the product of three factors:

σ = **Projected cross section** x **Reflectivity** x **Directivity**

- Reflectivity: The percent of intercepted power reradiated (scattered) by the target
- Directivity: The ratio of the power scattered back in the radar's direction to the power that would have been backscattered had the scattering been uniform in all directions (i.e. isotropically)

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