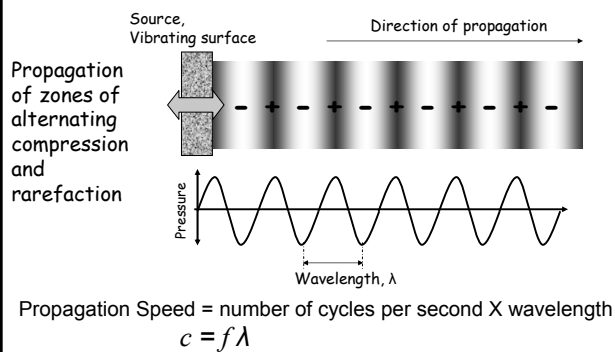


# Sound Waves

## In this lecture

- Sound waves
- Speed of sound
- Acoustic Pressure
- Acoustic Impedance
- Decibel Scale
- Reflection of sound waves
- Doppler effect

## Sound Waves (Longitudinal Waves)



## Sound

Range	Frequency
Audible Range	15 - 20,000Hz
Child's hearing	15 - 40,000Hz
Male voice	100 - 1500Hz
Female voice	150 - 2500Hz
Middle C	262Hz
Concert A	440Hz
Bat sounds	50,000 - 200,000Hz
Medical US	2.5 - 40 MHz
Max sound freq.	600 MHz

## Speed of Sound

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

- Speed at which longitudinal displacement of particles propagates through medium
- Speed governed by mechanical properties of medium
- Stiffer materials have a greater Bulk modulus and therefore a higher speed of sound

## Sound Particle Velocity

- Velocity,  $v$ , of the particles in the material as they oscillate to and fro



- Typically several tens of  $\text{mms}^{-1}$

## Acoustic Pressure

- Pressure,  $p$ , caused by the pressure changes induced in the material by the sound energy



- $p = P - P_0$ , (where  $P_0$  is normal pressure)
- Typically several tens of kPa

## Acoustic Impedance

- Pressure,  $p$ , is applied to a molecule it will exert pressure the adjacent molecule, which exerts pressure on its adjacent molecule.
- It is this sequence that causes pressure to propagate through medium.



## Acoustic Impedance

- Acoustic pressure increases with particle velocity,  $v$ , but also depends upon properties of the medium
- Relationship between acoustic pressure and particle velocity is characterised by the **acoustic impedance** of the medium

$$Z = \frac{p}{v} \quad \bullet \text{ Units: kg m}^{-2} \text{ s}^{-1} \text{ or a rayl}$$

## Acoustic Impedance

- Acoustic pressure is analogous to electrical resistance:

$$V = I R$$

$$p = v Z$$

- $Z$  is a constant for a material (resistance,  $R$ ) that inhibits velocity (current,  $I$ ) for a given pressure (voltage,  $V$ )

## Acoustic Impedance

- Acoustic impedance is also related to the elasticity of the medium
- Stiffer bonds between molecules increases the pressure exerted by a molecule moving with velocity  $v$ .
- A springy material will have high molecular motion and absorb sound energy in the bonds
  - less energy will be transferred between molecules

$$Z = \frac{B}{v}$$

## Acoustic Impedance

- Wave propagation speed depends upon elasticity of medium and density:

$$Z = \rho c = \sqrt{B \rho}$$

## Acoustic Power

- Sound energy is measured in Joules (J)
- Sound Power in  $\text{Js}^{-1}$  or Watts (W)
- Again analogous to electricity

$$P = p v = v^2 Z$$

## Acoustic Intensity

- Acoustic Intensity is measured in  $\text{W cm}^{-2}$
- Instantaneous power passing through a unit area of material
- Typical intensities used for ultrasound imaging are between  $0.01 - 1 \text{ mW mm}^{-2}$

## Recap Logarithms

- If  $\log_a(b) = c$
- Then  $c$  is the power to which you have to raise  $a$ , in order to get  $b$ .
- Put more simply,  $a^c = b$

## Decibel Scale

- Comparative sound intensity is measured using decibels
- Logarithmic unit used to describe a ratio

$$dB = 10 \log \left( \frac{I_2}{I_1} \right)$$

- Describe very big ratios using modest numbers

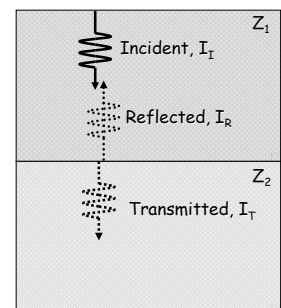
## Example

- For an incident ultrasound beam of intensity of  $1 \text{ Wcm}^{-2}$  is reflected with an intensity of  $0.1 \text{ mW cm}^{-2}$ . Express this power loss in dB.

$$\begin{aligned} dB &= 10 \log \left( \frac{I_2}{I_1} \right) \\ &= 10 \log \left( \frac{0.0001}{1} \right) \\ &= 10 \times -4 \\ &= -40 \text{ dB} \end{aligned}$$

## Reflection & Transmission of Sound Waves

- A pulse of sound incident on an interface between media with different mechanical properties can undergo two processes

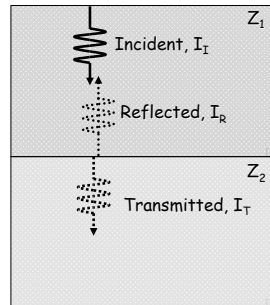


- Transmission or Reflection

## Reflection & Transmission of Sound Waves

- Amount of reflected and transmitted light depends upon impedance difference

$$I_I = I_T + I_R$$

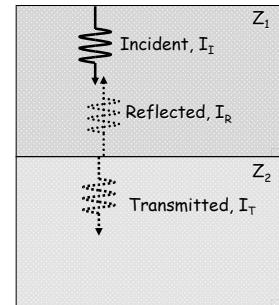


## Reflection & Transmission of Sound Waves

- Reflected Intensity

$$I_R = R \times I_I$$

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

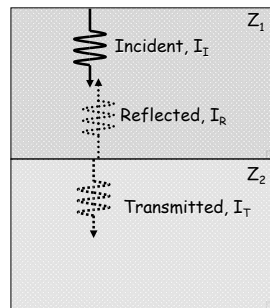


## Reflection & Transmission of Sound Waves

- Transmitted Intensity

$$I_T = T \times I_I$$

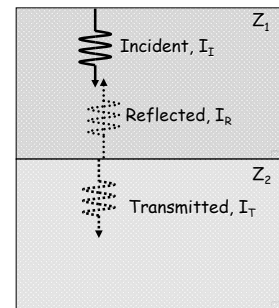
$$T = \frac{I_T}{I_I} = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2}$$



## Reflection & Transmission of Sound Waves

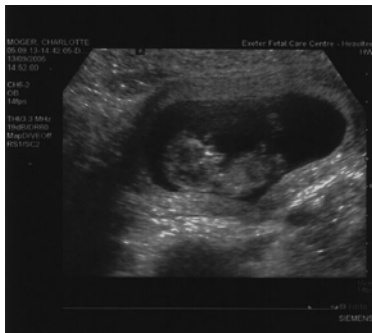
- If no energy is lost to medium

$$T + R = 1$$



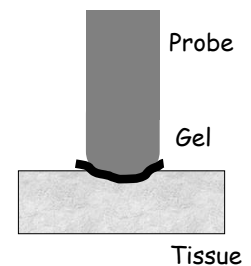
## Reflection & Transmission of Sound Waves

- Reflection and transmission of sound waves forms the basis of ultrasound imaging



## Impedance Matching

- To optimise Transmission of US into patient from probe an impedance matching medium is used



$$Z_M = \sqrt{Z_T \times Z_p}$$

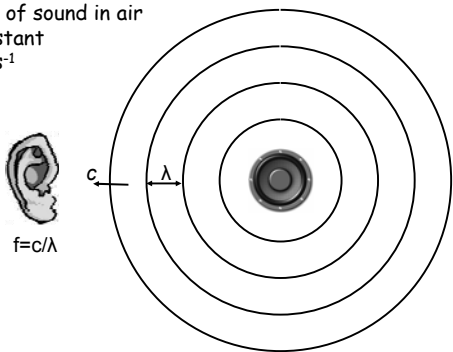
## Example

- If a transducer and tissue have acoustic impedances of  $30 \times 10^6$  &  $1.5 \times 10^6 \text{ kgm}^{-2}\text{s}^{-1}$  respectively, what acoustic impedance should a matching medium have to minimise reflection?

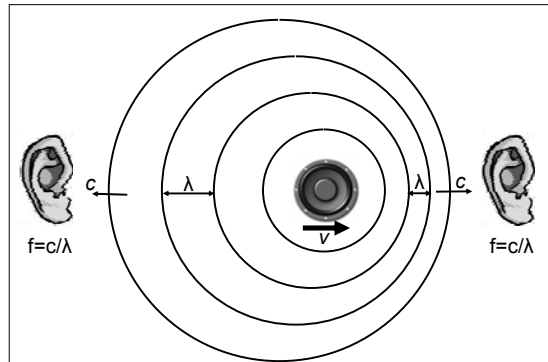
# Doppler Effect

## Stationary Sound Source

Speed of sound in air is constant  
 $340\text{ms}^{-1}$



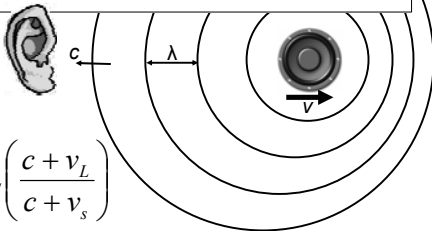
## Moving Sound Source



## Moving Sound Source

### Definitions

$V_s$  : Velocity of Source  
(+ve when source is travelling away from listener)  
 $V_L$  : Velocity of Listener  
(+ve when listener is travelling away from source)

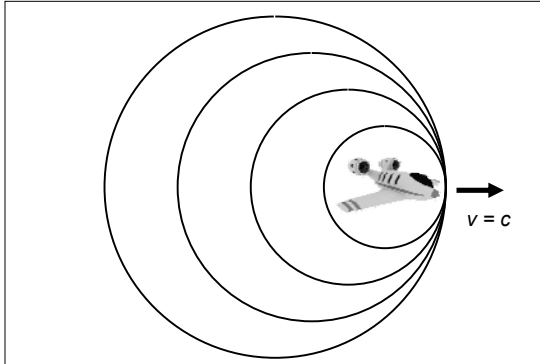


$$f_L = f_s \left( \frac{c + v_L}{c + v_s} \right)$$

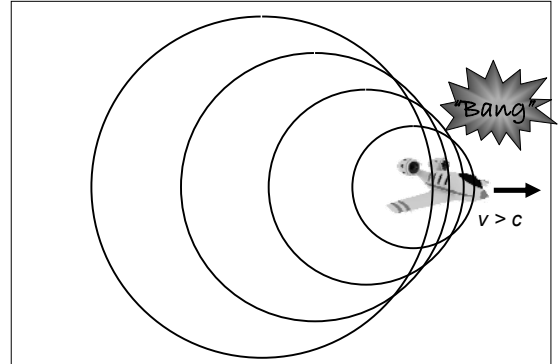
## Example

- A police car travelling at 60mph has a siren emitting sound with frequency ( $f_s$ ) 300Hz. What frequency would a stationary observer measure if the police car was travelling away from her?

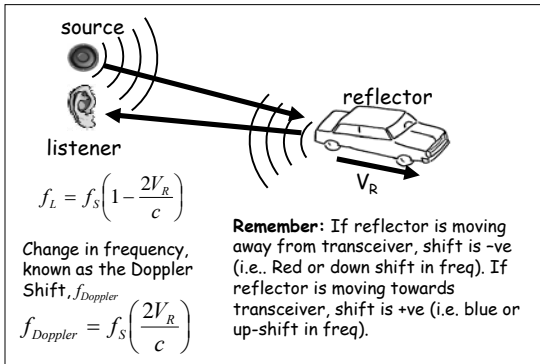
## Super-sonic



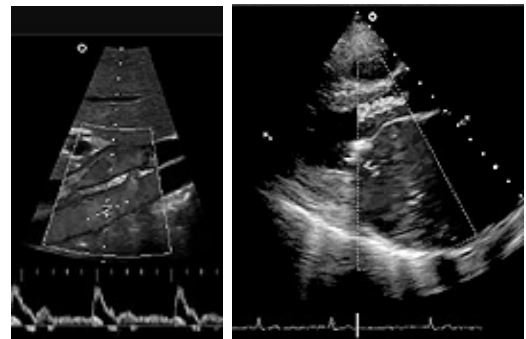
## Super-sonic



## Reflected Sound



## Doppler Ultrasound



## Summary

- Sound waves
- Speed of sound
- Acoustic Pressure
- Acoustic Impedance
- Reflection of sound waves
- Decibel Scale
- Doppler effect

## Practice Questions

1. A sound wave propagates at  $300\text{ms}^{-1}$  through a medium with an acoustic pressure of  $10\text{ pa}$ . Calculate the acoustic impedance of the medium
2. A sound wave propagates at  $4080\text{ms}^{-1}$  through a medium with a density of  $1700\text{ kgm}^{-3}$ . Calculate the acoustic impedance of the medium