OCR A Level Physics

Your notes

Ultrasound

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- The Piezoelectric Effect & the Ultrasound Transducer
- Acoustic Impedance
- Reflection of Ultrasound
- Doppler Effect in Ultrasound

Your notes

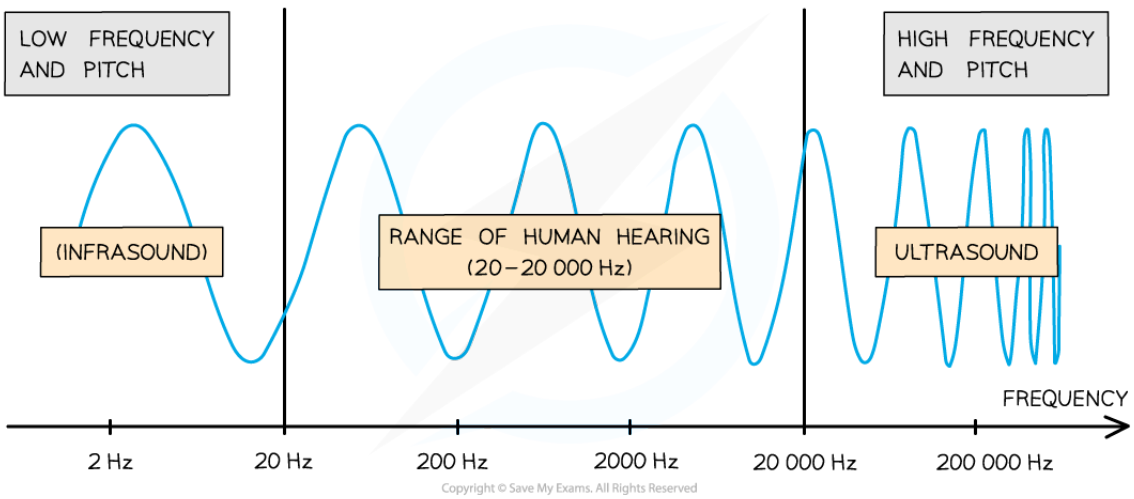
Ultrasound

Ultrasound

- Ultrasound is defined as:

  Sound waves with a frequency above the human hearing range of 20 000 Hz

- Ultrasound is, therefore, a longitudinal wave



Ultrasound is above 20 kHz, although in medical applications the frequencies can be up to the MHz range

A-Scan & B-Scan

- There are two types of ultrasound techniques that are used to obtain diagnostic information:
  - **A-Scan**, or amplitude scan
  - **B-Scan**, or brightness scan

A-Scan

- An A-scan, or amplitude scan, uses a single transducer to emit a signal and then later receive the reflected signal back
- It is defined as:

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A one-dimensional ultrasound scan used to determine the distance or depth of an internal structure

- This is achieved by:
  - Measuring the time delay between generating and receiving the signal
  - Using the speed of sound in the media to calculate the distance travelled by the signal
- This type of scan is used for:
  - Determining **distances** from the ultrasound device to the point of reflection (usually the boundary between two media)
  - For example, the length of an eye needs to be determined in planning surgeries or assessing the presence of abnormalities, such as tumours
- This type of scan gives **measurements only** and does **not** produce an image

B-Scan

- A B-scan, or brightness scan, is a more complex scan that produces a 2D or 3D image of internal structures in the body
- It is defined as:

An ultrasound scan used to build up a two or three-dimensional image of an internal structure using a number of sensors or one sensor in different positions

- This is achieved by:
  - Using pulsed ultrasound waves in **different positions** to produce **several** measurements of time intervals between generating and receiving pulses
  - Moving the transducer over the patient's skin, or using several transducers, to produce a series of A-scans that are combined to form an image
- This type of scan is used for:
  - Creating **images** of internal structures for diagnostic purposes
  - For example, bones, muscles and organs or checking on the progress of an unborn child
- To achieve the clearest images:
  - Pulsed ultrasound waves are used to allow time for the reflected waves to be received and not interfere with transmitted waves
  - Smaller wavelengths are used to give more detailed images as they will allow the sound waves to diffract around finer points of detail on the internal structure being studied

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Examiner Tips and Tricks

Make sure you can summarise the key differences between A-scans and B-scans:

Direction:

- A-scan = one direction
- B-scan = many directions / angles

End result:

- A-scan = measurement of distance
- B-scan = 2D or 3D image

The Piezoelectric Effect & the Ultrasound Transducer

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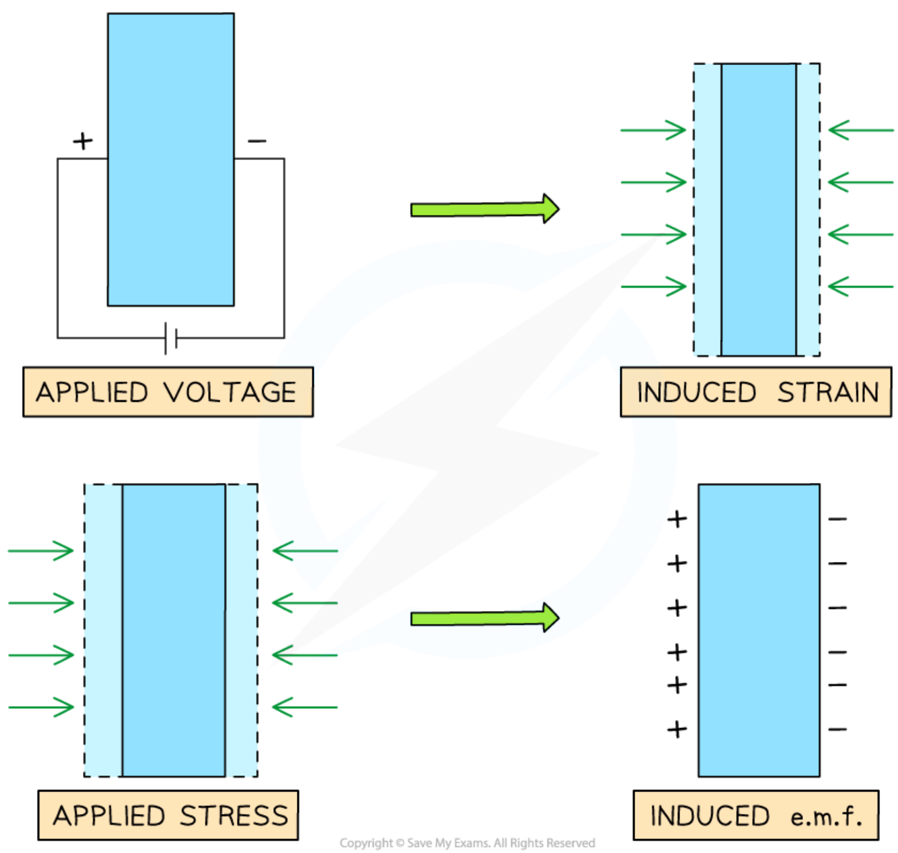
The Piezoelectric Effect & Generating Ultrasound

- The piezoelectric effect is defined as:

  The ability of particular materials to generate a potential difference (p.d.) by transferring mechanical energy to electrical energy

- This effect enables ultrasound generation and detection technology to exist in medicine



In the piezoelectric effect, an applied voltage causes a piezo-crystal to contract or expand, and vice versa

Piezoelectric Crystals

- At the heart of a piezoelectric transducer is a **piezoelectric crystal**

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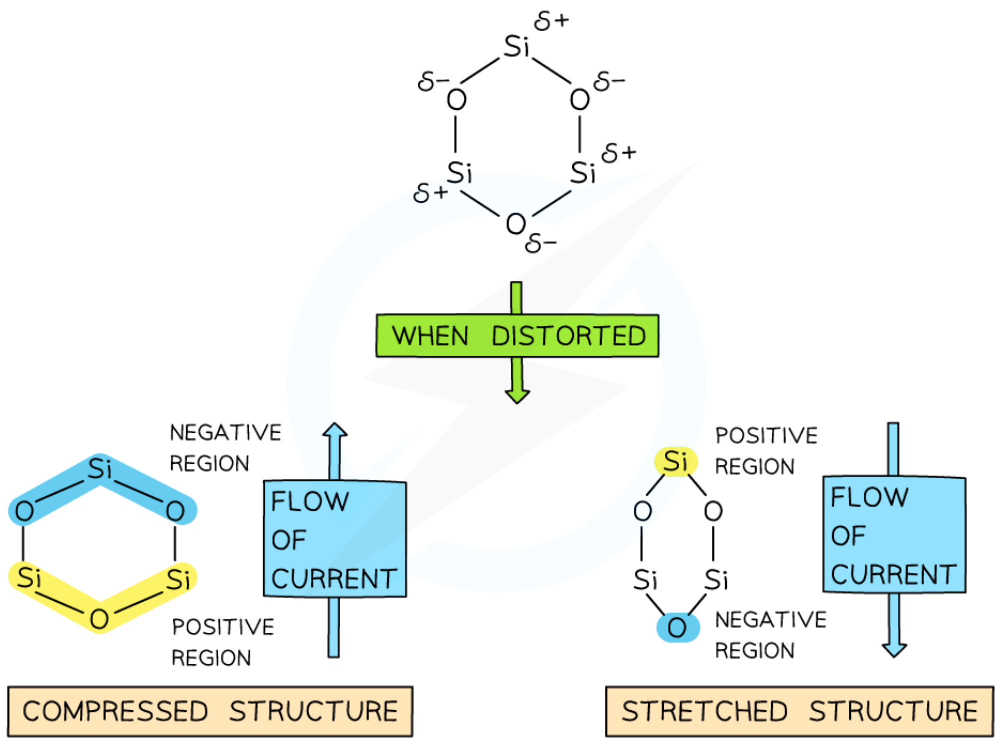
- A **transducer** is any device that converts energy from one form to another
- Piezoelectric crystals are materials which produce a p.d. when they are deformed
    - This deformation can be by compression or stretching
- If a p.d. is applied to a piezoelectric crystal, then it deforms, and if the p.d. is reversed, then it expands
    - If this is an alternating p.d. then the crystal will vibrate at the same frequency as the alternating voltage
    - Crystals must be cut to a certain size in order to induce resonance
- One of the most common piezoelectric crystals is **quartz**, which is made from a lattice of silicon dioxide atoms
    - When the lattice is distorted, the structure becomes charged creating an electric field and, as a result, an electric current
    - If an electric current is applied to the crystal, then this causes the shape of the lattice to alternate which produces a sound wave
    - Due to the conventional direction of electric current, it will flow from the positive to the negative region of the crystal



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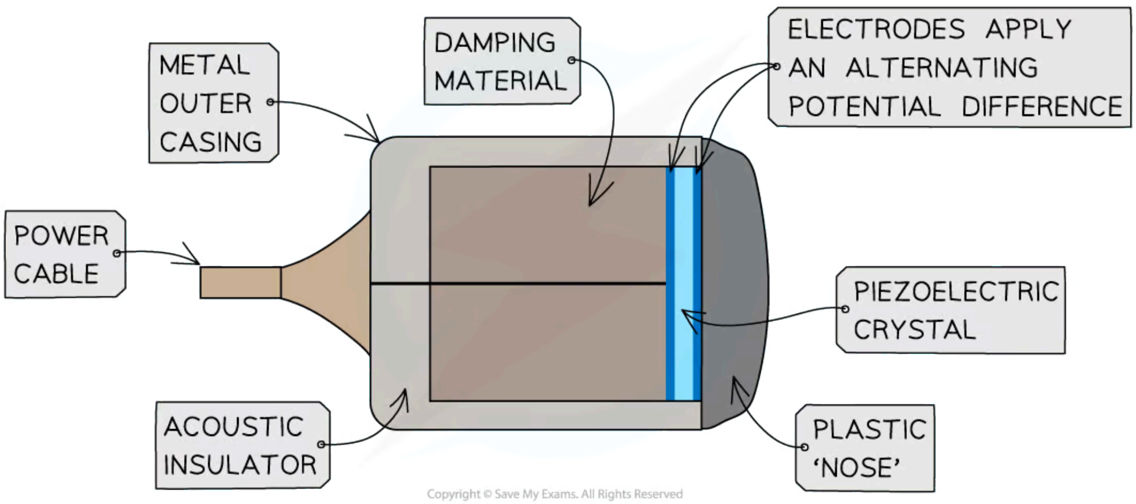
A molecule in a quartz crystal. When the compression and stretching alternates, an alternating e.m.f. is induced

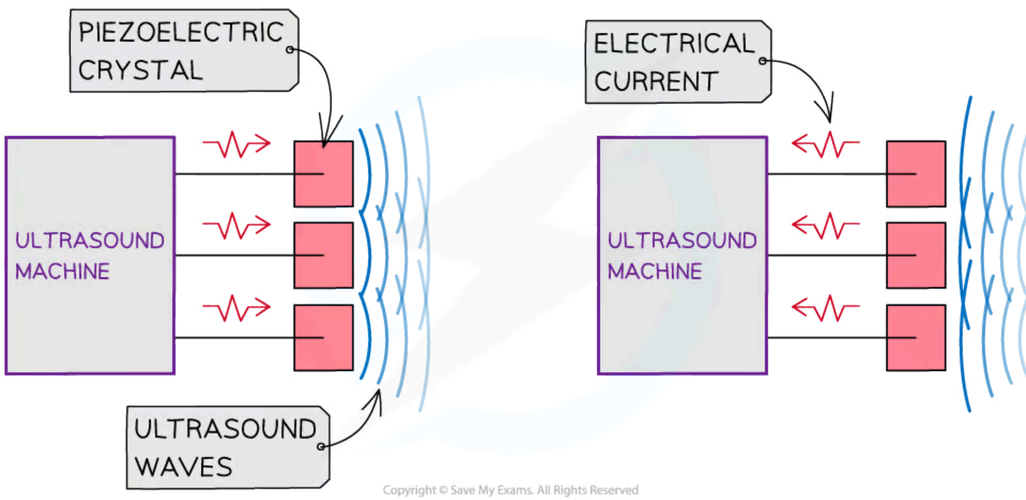
Generating & Detecting Ultrasound

- An ultrasound transducer is made up of a piezoelectric crystal and electrodes which produce an alternating p.d.
- The crystal is heavily damped, usually with epoxy resin, to stop the crystal from vibrating too much
  - This produces short pulses and increases the resolution of the ultrasound device



The structure of an ultrasound transducer

- A piezoelectric crystal can act as both a receiver or transmitter of ultrasound
  - When it is **receiving** ultrasound, it converts the sound waves into an alternating p.d.
  - When it is **transmitting** ultrasound, it converts an alternating p.d. into sound waves



A piezoelectric crystal can act as both a receiver or transmitter of ultrasound

Your notes

Worked Example

Explain the principles of the generation and detection of ultrasound waves.

Answer:

Generation:

- An alternating p.d. is applied across a piezoelectric crystal, causing it to change shape
- The alternating p.d. causes the crystal to vibrate and produce pulses of ultrasound waves
- The crystal vibrates at the frequency of the alternating p.d., so, the crystal must be cut to a specific size in order to produce resonance

Detection:

- The ultrasound pulse is reflected at the boundary of the tissue and returns to the transducer
- When the ultrasound wave returns, the crystal vibrates which produces an alternating p.d. across the crystal
- This received signal can then be processed and used for medical diagnosis

Acoustic Impedance

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Acoustic Impedance

- The **acoustic impedance**, Z, of a medium is defined as:

  The product of the speed of the ultrasound in the medium and the density of the medium

- This quantity describes how much resistance an ultrasound beam encounters as it passes through a tissue
- Acoustic impedance can be calculated using the equation:

$$Z = \rho c$$

- Where:
  - Z = acoustic impedance ($kg\ m^{-2}\ s^{-1}$)
  - ρ = the density of the material ($kg\ m^{-3}$)
  - c = the speed of sound in the material ($m\ s^{-1}$)
- This equation shows:
  - The **higher** the **density** of a tissue, the greater the **acoustic impedance**
  - The **faster** the ultrasound travels through the material, the greater the **acoustic impedance** also
- This is because sound travels faster in **denser** materials
  - Sound is **fastest** in solids and **slowest** in gases
  - The closer the particles in the material, the faster the **vibrations** can move through the material
- At the boundary between media of different acoustic impedances, some of the wave energy is **reflected** and some is **transmitted**
- The greater the **difference** in acoustic impedance between the two media, the greater the reflection and the smaller the transmission
  - Two materials with the same acoustic impedance would give no reflection
  - Two materials with a large difference in values would give much larger reflections
- Air has an acoustic impedance of Z_{air} = 400 $kg\ m^{-2}\ s^{-1}$
- Skin has an acoustic impedance of $Z_{skin} = 1.7 \times 10^6\ kg\ m^{-2}\ s^{-1}$

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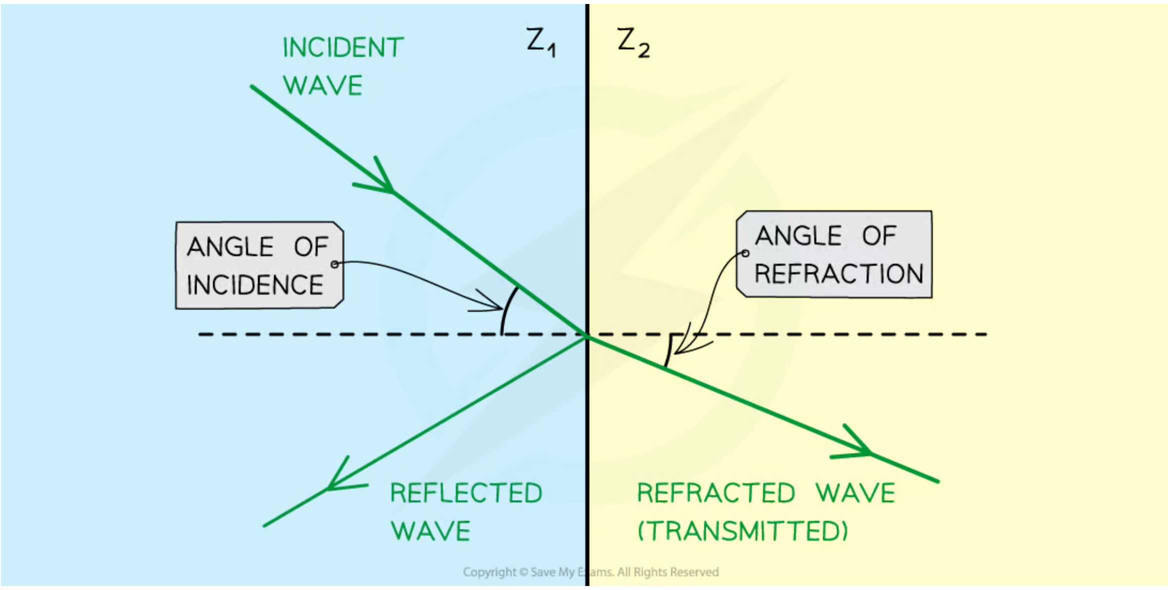
- The large difference means ultrasound would be significantly reflected, hence a coupling gel is necessary
- The coupling gel used has a similar Z value to skin, meaning that very little ultrasound is reflected



Refraction and reflection of ultrasound waves at a boundary between two materials with different acoustic impedances (in this case, $Z_1 < Z_2$)

Worked Example

The table shows the speed of sound acoustic impedance in four different materials.

medium	speed of ultrasound / m s^{-1}	acoustic impedance / kg m^{-2} s^{-1}
air	330	4.3×10^2
gel	1500	1.5×10^6
soft tissue	1600	1.6×10^6
bone	4100	7.0×10^6

Your notes

Use the table to calculate the value for the density of bone.

Answer:

Step 1: Write down known quantities

- Acoustic impedance of bone, $Z = 7.0 \times 10^6$ kg m^{-2} s^{-1}
- Speed of ultrasound in bone, c = 4100 m s^{-1}

Step 2: Write out the equation for acoustic impedance

$$Z = \rho c$$

Step 3: Rearrange for density and calculate

$$\rho = \frac{Z}{c} = \frac{7.0 \times 10^6}{4100} = \mathbf{1700\ kg\ m^{-3}}$$

Examiner Tips and Tricks

A common mistake is to confuse the c in the acoustic impedance equation for the speed of light - don't do this!

Impedance Matching in Ultrasound Scans

- The intensity reflection coefficient α is defined as:

The ratio of the intensity of the reflected wave relative to the incident (transmitted) wave

Your notes

- This can be calculated using the fraction:

$$\alpha = \frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

- Where:
  - α = intensity reflection coefficient
  - I_R = intensity of the reflected wave (W m^{-2})
  - I_0 = intensity of the incident wave (W m^{-2})
  - Z_1 = acoustic impedance of one material (kg m^{-2} s^{-1})
  - Z_2 = acoustic impedance of a second material (kg m^{-2} s^{-1})
- This ratio shows:
  - If there is a large difference between the impedance of the two materials, then most of the **energy** will be reflected
  - If the impedance is the same, then there will be **no reflection**

Coupling Medium

- When ultrasound is used in medical imaging, a **coupler** is needed between the transducer and the body
  - This is because the soft tissues of the body are **much denser** than air
- If air is present between the transducer and the body, then almost all the ultrasound energy will be **reflected**
- To counter this, a coupling gel is placed between the transducer and the body
  - This is because skin and coupling gel have a **similar density**, so little ultrasound is reflected
- This is an example of impedance matching, which is defined as when:

  Two media have a similar acoustic impedance, resulting in little to no reflection of the ultrasound wave

- In terms of intensity reflection coefficient, α, between the two media:
  - At **lower** values of α, the media are impedance matched, so **less** reflection occurs
  - At **higher** values of α, the media are not impedance matched, so **more** reflection occurs

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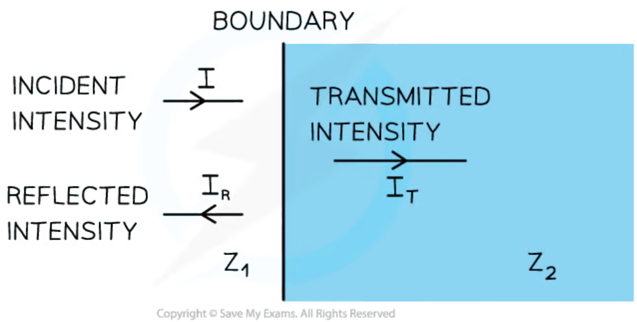
Worked Example

A beam of ultrasound is incident at right-angles to a boundary between two materials, as shown in the diagram.



The materials have acoustic impedances of Z_1 and Z_2. The intensity of the transmitted ultrasound beam is I_T, and the reflected intensity is I_R.

medium	speed of ultrasound / m s^{-1}	acoustic impedance / kg m^{-2} s^{-1}
air	330	4.3×10^2
gel	1500	1.5×10^6
soft tissue	1600	1.6×10^6
bone	4100	7.0×10^6

a) State the relationship between I, I_T and I_R.

b) Use the data from the table to determine the reflection coefficient, α, for a boundary between

(i) Gel and soft tissue

(ii) Air and soft tissue

c) Explain why gel is usually put on the skin during medical diagnosis using ultrasound.

Your notes

Answer:

Part (a)

Step 1: List the known quantities

- Intensity of incident wave = I
- Intensity of the transmitted wave = I_T
- Intensity of the reflected wave = I_R

Step 2: Relate the quantities:

- The incident intensity is equal to the sum of the transmitted and reflected intensities:

Incident intensity = Transmitted intensity + Reflected intensity

$$I = I_T + I_R$$

Part (b)(i)

Step 1: List the known quantities

- Acoustic impedance of gel, $Z_1 = 1.5 \times 10^6$ kg m^{-2} s^{-1}
- Acoustic impedance of soft tissue, $Z_2 = 1.6 \times 10^6$ kg m^{-2} s^{-1}

Step 2: Write down the equation for intensity reflection coefficient α

$$\alpha = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

Step 3: Calculate the intensity reflection coefficient

$$\alpha = \frac{(1.6\times10^6 - 1.5\times10^6)^2}{(1.6\times10^6 + 1.5\times10^6)^2} = \frac{(0.1)^2}{(3.1)^2} = 0.001$$

- This result means that only **0.1%** of the incident intensity will be reflected, with the remaining being transmitted

Part (b)(ii)

Step 1: List the known quantities

- Air, $Z_1 = 4.3 \times 10^2$ kg m^{-2} s^{-1}
- Soft tissue, $Z_2 = 1.6 \times 10^6$ kg m^{-2} s^{-1}

Step 2: Calculate the intensity reflection coefficient

Your notes

$$\alpha = \frac{(1.6\times10^{6} - 4.3\times10^{2})^{2}}{(1.6\times10^{6} + 4.3\times10^{2})^{2}} \approx \frac{(1.6\times10^{6})^{2}}{(1.6\times10^{6})^{2}} \approx 1$$

- This result means that **100%** of the incident intensity will be reflected, with none being transmitted

Part (c)

Why gel is usually put on the skin during medical diagnosis using ultrasound

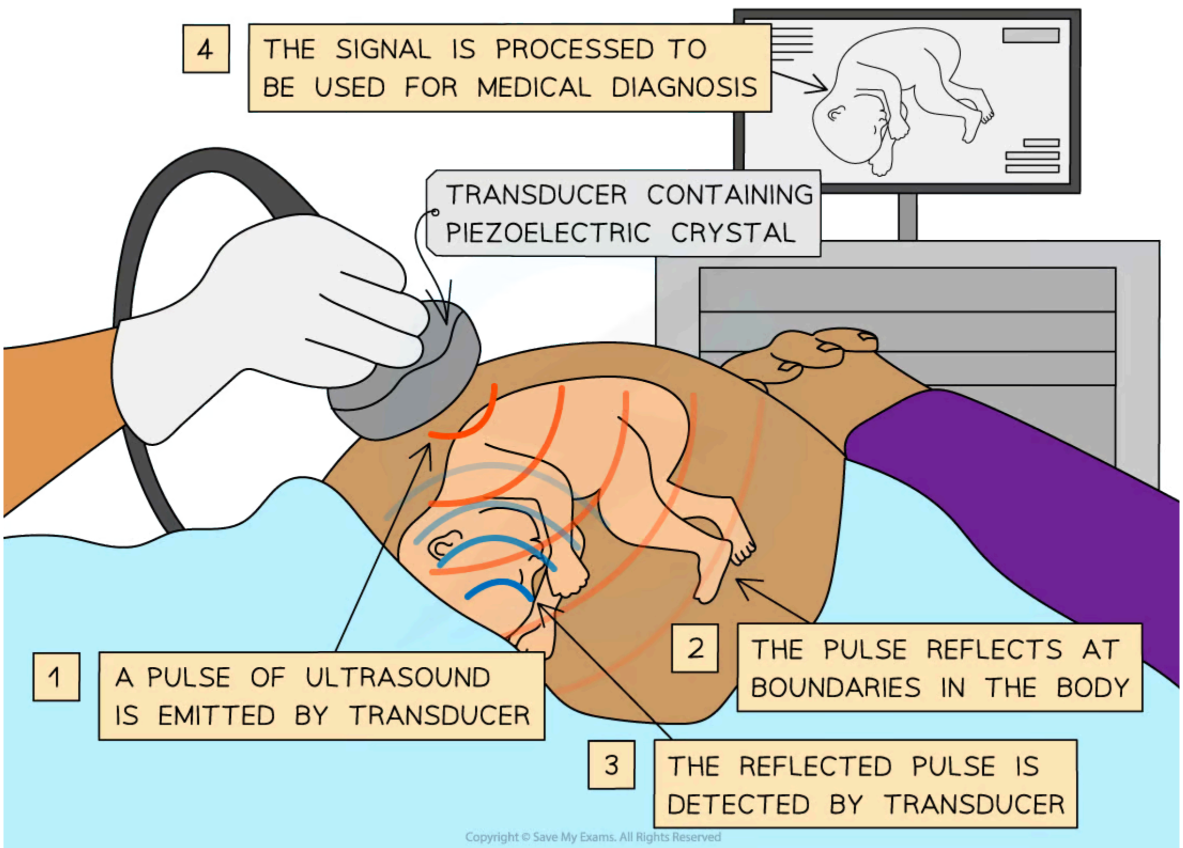
- At the air-soft tissue boundary, the intensity reflection coefficient is $\alpha \approx 1$
  - Therefore, without gel, there is almost complete reflection - no ultrasound is transmitted through the skin
- At the gel-soft tissue boundary, the intensity reflection coefficient is $\alpha = 0.001$
  - Therefore, the gel enables almost complete transmission of the ultrasound through the skin, with very little reflection

Your notes

Reflection of Ultrasound

Reflection of Ultrasound

- In an ultrasound scanner, the transducer sends out a beam of **high-frequency** sound waves into the body
- The sound waves are reflected back to the transducer by **boundaries** between tissues in the path of the beam
  - For example, the boundary between fluid and soft tissue or tissue and bone
- When these echoes hit the transducer, they generate electrical signals that are sent to the ultrasound scanner
  - Using the speed of sound and the time of each echo's return, the scanner calculates the distance from the transducer to the tissue boundary
- These distances can be used to generate two-dimensional **images** of tissues and organs



Using ultrasound to obtain information about an unborn child

- The frequency of the ultrasound is important because:
  - The **higher** the **frequency** (or the **shorter** the **wavelength**) of the ultrasound, the **higher** the **resolution** of the image
  - This is desirable so that the finer detail and smaller structures can be distinguished
- The ultrasound gives two main pieces of information about the boundary:
  - **Depth**: the time between transmission and receipt of the pulse (the time delay)
  - **Nature**: amount of transmitted intensity received (will vary depending on the type of tissue)

Your notes

Worked Example

Explain the main principles behind the use of ultrasound to obtain diagnostic information about internal body structures.

Answer:

- A pulse of ultrasound is emitted by the piezo-electric crystal
- This is reflected from the boundaries between media
- The reflected pulse is detected by the ultrasound transmitter
- The signal is then processed and displayed on the screen for the healthcare worker to analyse and use for medical diagnosis
- The **intensity of the reflection** gives information about the nature of the boundary
- The time between transmission and receipt of the pulse (**the time delay**) gives information about the depth of the boundary

Examiner Tips and Tricks

6 mark exam questions about this topic are very common, make sure you practice writing about using and detecting ultrasounds in full, coherent sentences with correct spelling and grammar. Writing short or vague answers could lose you marks, as well as misspelling words!

Doppler Effect in Ultrasound

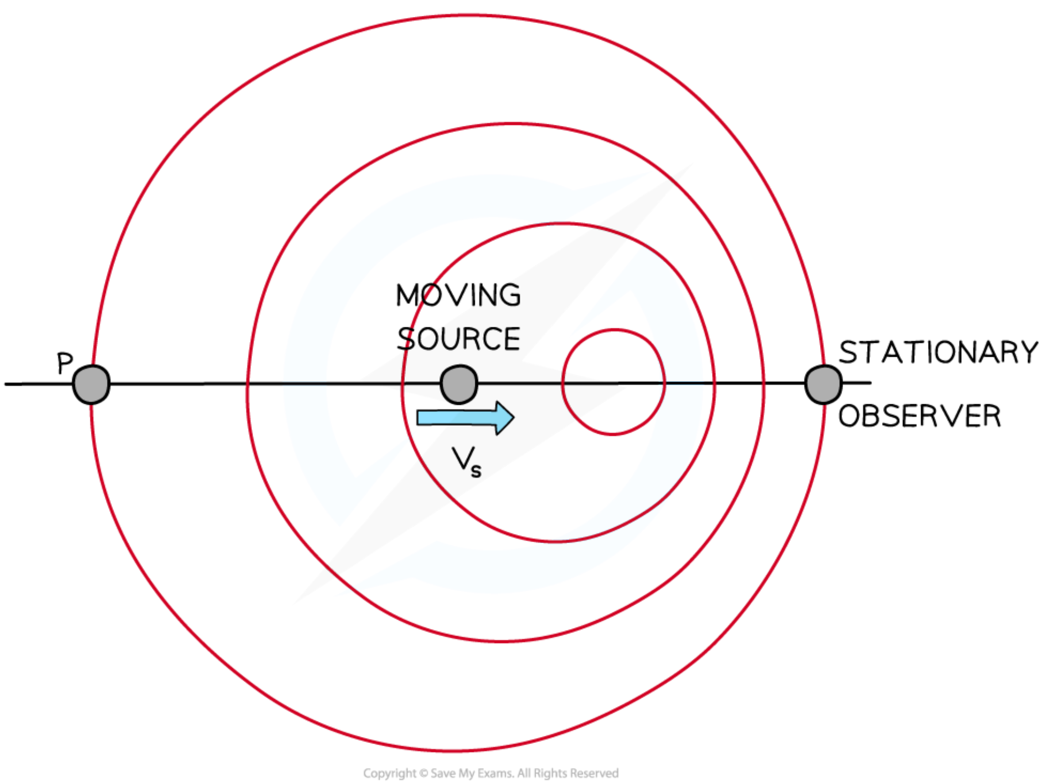
Your notes

Doppler Effect in Ultrasound

- The Doppler effect is defined as:

  The frequency change of a wave due to the relative motion between a source and an observer

- When the source starts to move **towards** the observer, the wavelength of the waves is **shortened**
  - The sound therefore appears at a **higher** frequency to the observer
- The frequency is **increased** when the source is moving **towards** the observer
- The frequency is **decreased** when the source is moving **away** from the observer
  - This applies to ultrasound in the exact same way as it does to sound waves



Doppler effect of a moving source and stationary observer

Your notes

- For a wave of frequency, f_0, that reflects at a moving boundary, the new frequency, f_r, of the reflected pulse is given by:

$$f_r = f_0\left(\frac{c}{c-2v}\right)$$

- Where:
  - f_0 = frequency of original wave (Hz)
  - f_r = frequency of reflected wave (Hz)
  - v = velocity of the moving boundary (m s^{-1})
  - c = velocity of the wave (m s^{-1})
- The factor of 2 appears due to the wave travelling to the boundary and back again
- In medicine, **Doppler imaging** can be used as a **non-invasive** technique to measure the speed of blood flow in the heart or in an artery
  - This is effective because blood contains **iron** which is very reflective
- The journey of the ultrasound is as follows:
  - Pulses of ultrasound are emitted from a transducer into a blood vessel
  - The ultrasound pulses are reflected by moving blood cells
  - The moving blood causes a shift in the frequency of the ultrasound
  - The transducer detects an **increase** in frequency if the blood is moving **towards** the transducer and a **decrease** if it is moving **away**

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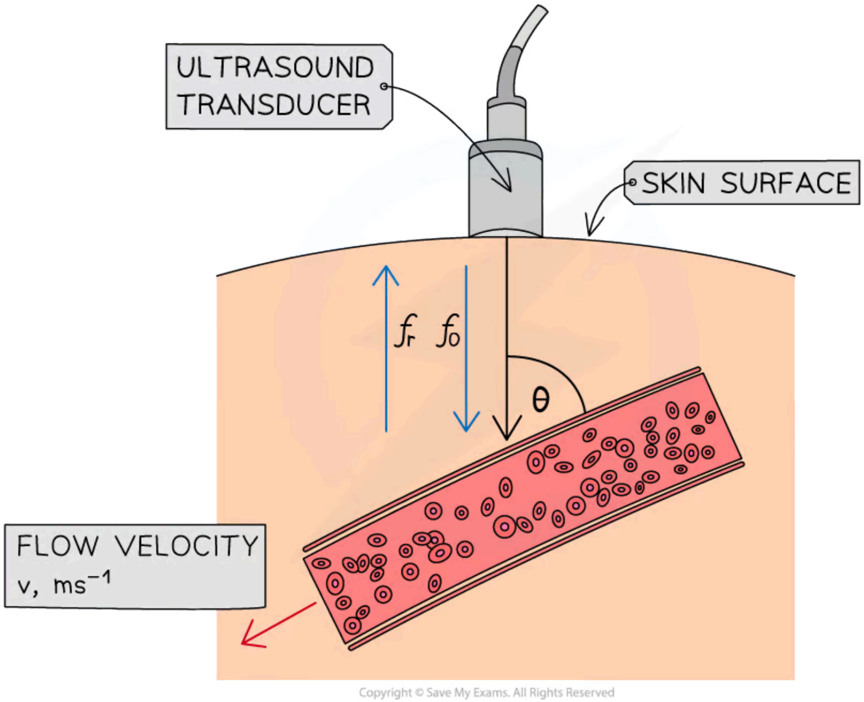

- This frequency shift, Δf, can be calculated using the equation:

$$\Delta f = f_0 - f_r = \frac{2 f_0 v \cos\theta}{c}$$

- Where:
  - f_0 = frequency of ultrasound emitted by the transducer (Hz)
  - f_r = frequency of ultrasound received by the transducer (Hz)
  - Δf = difference between emitted and received frequencies (Hz)
  - v = velocity of the blood (m s^{-1})
  - c = velocity of ultrasound in blood (m s^{-1})
  - θ = angle between the transducer and the blood vessel (°)
- This can be rearranged to give:

$$\frac{\Delta f}{f_0} = \frac{2 v \cos\theta}{c}$$

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Worked Example

A patient is undergoing diagnostic tests to determine the cause of an underlying heart condition. Blood flow tests are done on the patient's aorta using ultrasound imaging.

Ultrasound of frequency 8.5 MHz is transmitted from a transducer through the skin into the aorta. The reflected frequency is found to be 8.495 MHz. The angle the transducer makes with the skin is 15°.

The velocity of sound in blood is 1570 m s^{-1} and the aorta has an internal diameter of 30 mm.

Calculate:

a) The speed of the blood flow in the aorta.

b) The volume of blood, in cm^3, moving past any point in 1 s.

Answer:

Part (a)

Step 1: List the known quantities

- Transmitted frequency of the ultrasound, f_0 = 8.5 MHz
- Reflected frequency of the ultrasound, f_r = 8.495 MHz
- Change in frequency, Δf = 8.5 – 8.495 = 0.005 MHz
- Velocity of sound in blood, c = 1570 m s^{-1}
- Angle between the transducer and skin, θ = 15°

Step 2: Write out the equation for Doppler shift of ultrasound

$$\frac{\Delta f}{f_0} = \frac{2v\cos\theta}{c}$$

Step 3: Rearrange for the speed, *v*, and calculate

$$v = \frac{c}{2\cos\theta}\left(\frac{\Delta f}{f_0}\right) = \frac{c\Delta f}{2f_0\cos\theta}$$

$$v = \frac{1570 \times (0.005 \times 10^6)}{2(8.5 \times 10^6)\cos 15} = 0.478$$

$$v = 0.48 \text{ m s}^{-1}$$

Part (b)

Your notes

Step 1: List the known quantities

- Radius of the aorta, r = 15 mm = 1.5 cm
- Blood flow rate, v = 0.48 m s^{-1} = 48 cm s^{-1}

Step 2: Calculate the cross-sectional area of the aorta

- Cross-sectional area = $\pi r^2 = \pi(1.5)^2 = 7.1$ cm^2

Step 3: Determine the volume of blood passing through the aorta each second

- Volume flow rate = cross-sectional area (cm^2) × blood flow rate (cm s^{-1})
- Volume flow rate = 7.1 × 48 = 341 cm^3 s^{-1}

Step 4: State the volume of blood in 1 s

- The volume of blood that flows in 1 s = 341 cm^3