

Exercise walk-through

24.1

Production and use of ultrasound

A-Level Physics

Piezo-electric – two linked effects

A **piezo-electric** crystal (quartz, PZT) changes shape when a p.d. is put across it, and makes an e.m.f. when its shape is changed.



apply a p.d.

the crystal vibrates –
used to **make** ultrasound

squeeze it

an e.m.f. appears – used
to **detect** ultrasound

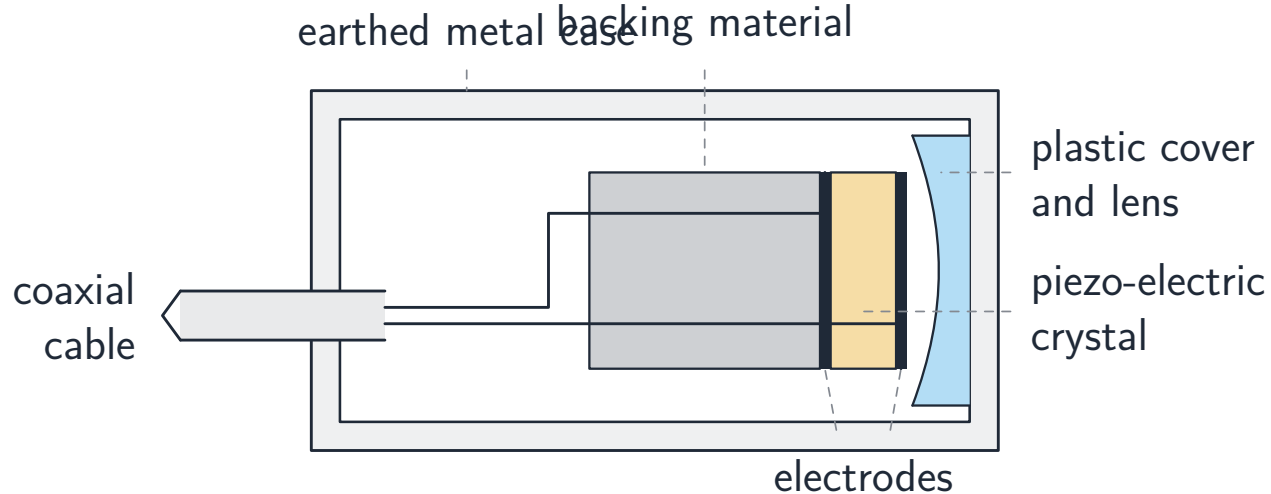
One transducer both sends and listens

An alternating p.d. (a few MHz) makes the crystal vibrate, sending **longitudinal** waves above 20 kHz (1–10 MHz for imaging). Returning ultrasound makes it vibrate and produce an e.m.f.

One transducer switches between sending and listening. **Coupling gel** pushes out the air – without it almost all the ultrasound would reflect at the skin.

Inside the transducer

The crystal sits between a **damping block** (to kill ringing so pulses stay short) and a **matching layer** (to cut the reflection at the skin).



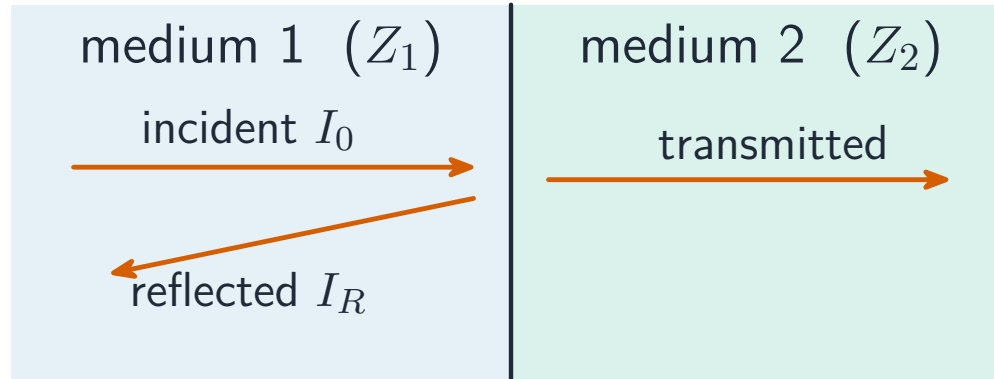
Pulse-echo: depth from the time delay

- 1 send a short pulse
- 2 at each tissue boundary, part reflects and part goes on
- 3 detect each echo
- 4 depth $d = ct/2$ (there and back); amplitude $\Rightarrow$ strength of the reflection

Echo after $60\ \mu\text{s}$; $c = 1500\ \text{m s}^{-1}$

$$d = \frac{ct}{2} = \frac{1500 \times 60 \times 10^{-6}}{2} = 0.045\ \text{m} \ (4.5\ \text{cm})$$

Pulse-echo: depth from the time delay, in detail



$$\frac{I_R}{I_0} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2 \text{ — a bigger impedance difference gives a bigger echo}$$

At a boundary, part of the pulse reflects and part transmits – a bigger impedance difference gives

Exercises 2.1·2.3

2.1 Describe the **piezo-electric effect**.

[2]

2.2 Define the **specific acoustic impedance** of a medium.

[1]

2.3 Explain how **one** transducer can both send and detect ultrasound.

[2]

Exercises 2.1-2.3

2.1 Describe the **piezo-electric effect**.

[2]

2.1

- applying a p.d. across the crystal makes it **change shape**
- changing its shape makes it produce an **e.m.f.**

2.2 Define the **specific acoustic impedance** of a medium.

[1]

2.2

- $Z = \rho c$, the product of the medium's density and the speed of sound in it

2.3 Explain how **one** transducer can both send and detect ultrasound.

[2]

2.3

- an alternating p.d. makes the crystal **vibrate**, emitting ultrasound
- a returning pulse makes it vibrate and produce an **e.m.f.**, which is detected

Exercises 2.4·3.1

2.4 Write the equation for the **attenuation** of ultrasound.

[1]

3.1 For a **strong** reflection at a tissue boundary, the two acoustic impedances must be:[1]

☐

A equal

B very different

C both zero

D both very large

Exercises 2.4·3.1

2.4 Write the equation for the **attenuation** of ultrasound.

[1]

2.4

- $I = I_0 e^{-\mu x}$

3.1 For a **strong** reflection at a tissue boundary, the two acoustic impedances must be:[1]

☐

A equal

B very different

C both zero

D both very large

3.1 B

- a large reflection when the two impedances are **very different**

Exercises 3.2-3.3

3.2 Calculate the intensity reflection coefficient for a boundary where $Z_1 = 1.6 \times 10^6$ and $Z_2 = 1.7 \times 10^6$ (SI units). [3]

3.3 Explain why a **coupling gel** is used between the transducer and the skin. [2]

Exercises 3.2·3.3

3.2 Calculate the intensity reflection coefficient for a boundary where $Z_1 = 1.6 \times 10^6$ and $Z_2 = 1.7 \times 10^6$ (SI units). [3]

3.2

- $I_R/I_0 = (Z_2 - Z_1)^2/(Z_2 + Z_1)^2$

$$\frac{I_R}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2} = \frac{(1.6 - 1.7)^2}{(1.6 + 1.7)^2} = \mathbf{9.2 \times 10^{-4}}$$

3.3 Explain why a **coupling gel** is used between the transducer and the skin. [2]

3.3

- without gel there is an **air gap**, whose acoustic impedance is very different from skin
- so almost all the ultrasound would be reflected; the gel removes the air gap so the ultrasound enters the body

Exercise 3.4

3.4 Ultrasound of intensity I_0 passes through 5.0 cm of tissue with $\mu = 23 \text{ m}^{-1}$. Calculate I/I_0 . [2]

Exercise 3.4

3.4 Ultrasound of intensity I_0 passes through 5.0 cm of tissue with $\mu = 23 \text{ m}^{-1}$. Calculate I/I_0 . [2]

3.4

- $I/I_0 = e^{-\mu x}$

$$\frac{I}{I_0} = e^{-\mu x} = e^{-(23 \text{ m}^{-1})(0.050 \text{ m})} = e^{-1.15} = \mathbf{0.32}$$

Exercise 3.5 (a)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

(a) **Define specific acoustic impedance.**

[1]

Exercise 3.5 (a)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

- (a) **Define specific acoustic impedance.** [1]
- (a) the product of the **density** of the medium and the **speed of sound** in it, $Z = \rho c$

Exercise 3.5 (b)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

(b) **Explain** how a piezoelectric crystal **detects** the reflected ultrasound. [2]

Exercise 3.5 (b)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

(b) **Explain** how a piezoelectric crystal **detects** the reflected ultrasound. [2]

(b) the reflected wave's pressure variation makes the crystal **change shape**

- a piezoelectric crystal produces a **potential difference** across its faces when it is deformed, giving an electrical signal that varies with the received wave

Exercise 3.5 (c)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

(c) **Determine** the intensity reflection coefficient at a soft tissue-bone boundary. [3]

Exercise 3.5 (c)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

(c) **Determine** the intensity reflection coefficient at a soft tissue-bone boundary. [3]

(c) $I_{\text{R}}/I_0 = (Z_2 - Z_1)^2/(Z_2 + Z_1)^2$

$$\frac{I_{\text{R}}}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2} = \frac{(6.40 - 1.63)^2}{(6.40 + 1.63)^2} = \mathbf{0.35}$$

Exercise 3.5 (d)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

(d) **Determine** the intensity reflection coefficient at a soft tissue-air boundary, and **explain** why a gel is smeared on the skin before a scan. [3]

Exercise 3.5 (d)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

(d) **Determine** the intensity reflection coefficient at a soft tissue-air boundary, and **explain** why a gel is smeared on the skin before a scan. [3]

(d) with air

$$\frac{(1.63 \times 10^6 - 429)^2}{(1.63 \times 10^6 + 429)^2} \approx \mathbf{0.999}$$

- essentially **all** the ultrasound is reflected at a skin-air boundary; gel excludes the air layer and has an impedance close to that of skin, so the pulse actually enters the body

Exercise 3.5 (e)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

(e) The pulse returns from a boundary 9.6 cm deep after $1.2 \times 10^{-4} \text{ s}$. **Determine** the speed of ultrasound in the tissue. [2]

Exercise 3.5 (e)

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$, of bone $6.40 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$ and of air $4.29 \times 10^2 \text{ kg m}^{-2} \text{ s}^{-1}$.

(e) The pulse returns from a boundary 9.6 cm deep after $1.2 \times 10^{-4} \text{ s}$. **Determine** the speed of ultrasound in the tissue. [2]

(e) the pulse travels **there and back**, a distance of $2d = 2 \times 0.096 \text{ m} = 0.192 \text{ m}$

$$c = \frac{2d}{t} = \frac{0.192 \text{ m}}{1.2 \times 10^{-4} \text{ s}} = \mathbf{1.6 \times 10^3 \frac{m}{s}}$$