Physics Notes
Topic 14: Waves

14.6 Production and Use of Ultrasound in Diagnosis

Students should be able to:

☐ Explain the principles of the generation and detection of ultrasonic waves using piezo-electric transducers.
☐ Explain the main principles behind the use of ultrasound to obtain diagnostic information about internal structures.
☐ Understand the meaning of specific acoustic impedance and its importance to the intensity reflection coefficient at a boundary.
☐ Recall and solve problems by using the equation $I = I_0 e^{-\mu x}$ for the attenuation of ultrasound in matter.

The Generation and Detection of Ultrasound

Ultrasound waves is generated by a varying electrical voltage in a transducer, such as piezo-electric crystals or quartz (See Figure 14.1). A transducer is a device that converts energy from one form to another. In this case, electrical energy is converted into ultrasonic energy and vice versa.

Figure 14.1

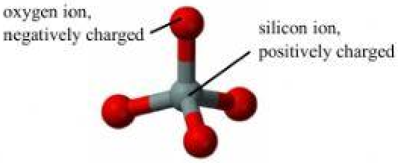


Figure 14.2

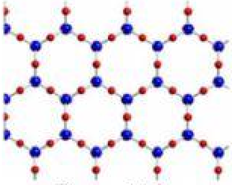


Figure 14.3

The structure of quartz is made up of tetrahedral silicate units, as shown in Figure 14.2. These units build up to form a crystal of quartz. It can be represented in 2-dimensions as shown in Figure 14.3.

The two opposite sides of the crystal are coated with silver to act as electrodes. When the crystal is unstressed, the centres of positive and negative charge coincide, as shown in Figure 14.4.

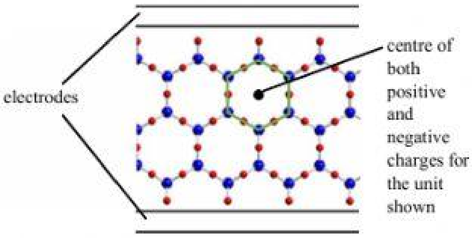


Figure 14.4

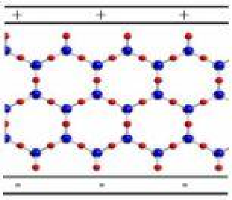


Figure 14.5

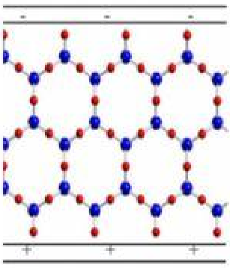


Figure 14.6

When a potential difference is applied across the crystal, between the electrodes, electric field is set up in the crystal, causing forces to act on the ions. The negatively-charged oxygen ions will be attracted to the positive electrode while the positively-charged silicon ions will be attracted to the negative electrode.

Because the ions are not held rigidly in position, they will be displaced slightly, changing the shape of the crystal to become slightly thinner (compressed) or slightly thicker (extended) depending on the direction of the electric field as shown in Figure 14.5 and 14.6 respectively. The centres of positive and negative charge move and therefore are not coincident anymore. (to know more, go to: https://onscale.com/blog/how-piezoelectricity-works/)

An alternating voltage in ultrasound frequency range applied across the electrodes causes the crystal to vibrate with a frequency equal to the applied voltage. If the frequency of the applied voltage is equal to the natural frequency of vibration of the crystal, resonance will occur, i.e. crystal vibrates at resonant frequency and the amplitude of vibration will be maximum.

Ultrasound frequencies as high as 10 MHz are used in medical diagnosis because there is better resolution at shorter wavelength and therefore smaller structures can be detected and distinguished.

When the crystal is made to vibrate by ultrasound wave, the forces applied to an uncharged quartz crystal will change the positions of the positive and negative charges. Alternating potential difference is produced across the crystal. The pressure variations in the ultrasound wave will give rise to voltage variations across the crystal. An ultrasound transducer may therefore also be used as a detector or receiver. Figure 14.7 shows the simplified diagram of a piezo-electric transducer/receiver.

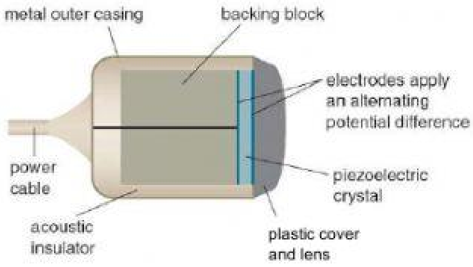


Figure 14.7

The Use of Ultrasound to Obtain Diagnostic Information

Ultrasound is often used to obtain diagnostic information about internal body structures. When short pulses of ultrasound directed into the body are incident on boundaries between two media (eg. fat-muscle and muscle-bone), some of the wave power are reflected at boundaries and some are transmitted, as shown in Figure 14.8.

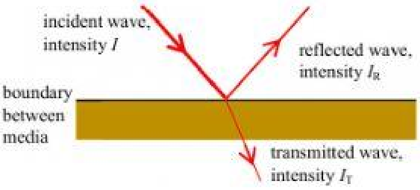
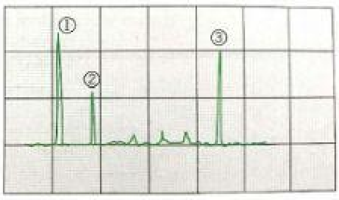


Figure 14.8`



1: transmitted pulse
2: reflected pulse at fat-muscle boundary
3: reflected pulse at muscle-bone boundary

Figure 14.9`

The reflected pulses return and are detected by transducer and converted into signal (voltage pulses) that can be amplified and processed by electronic circuits such that the output of the circuits may be displayed on a screen (eg. cathode-ray oscilloscope, as shown in Figure 14.9).

The time between the transmission of a pulse and its receipt back (echo) at the transducer gives information about the depth of the boundary (the distance of the boundary from the transducer). Meanwhile, the reflected intensity gives information as to the nature of the boundary.

When the signal from the pulse is processed, any signal received later at the detector is usually amplified more than that received at an earlier time because the later signal has passed through greater thickness of medium and therefore has greater attenuation, greater absorption and smaller intensity.

Specific Acoustic Impedance, Z

For a wave of incident intensity I, reflected intensity I_R and transmitted intensity I_T, by conservation of energy:

$$I = I_R + I_T$$

For a beam of constant intensity, the sum of the reflected and transmitted intensities is constant. Their relative magnitudes depend on the angle of incidence of the beam on the boundary. Other than that, the relative magnitudes of I_R and I_T are also quantified by reference to specific acoustic impedance Z of each of the media.

Specific acoustic impedance Z is defined as the product of density ρ of the medium and the speed c of sound wave in the medium. In equation:

$$Z = \rho c$$

From the equation above, we can see that the SI unit for specific acoustic impedance is kg m^{-2} s^{-1}.

Acoustic impedance is important when considering reflection of ultrasound at the boundary between two media because difference in acoustic impedances of the two media determines fraction of incident intensity that is reflected (as shown in the formula below).

Intensity Reflection Coefficient, α

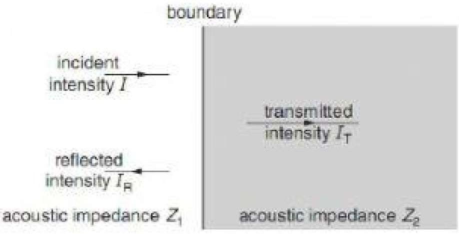


Figure 14.10

For a wave incident normally (at 90°) on a boundary between 2 media having specific acoustic impedances of Z_1 and Z_2 (as shown in Figure 14.10), the ratio of the reflected intensity I_R to the incident intensity I is given by:

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

The ratio $\frac{I_R}{I}$ is known as the intensity reflection coefficient for the boundary and is given the symbol α. Value of α depends on the difference between the specific acoustic impedances of the two media, as stated in the section above.

The difference between Z_1 and Z_2 is important for the transmission of ultrasound across the boundary because if $(Z_2 - Z_1)$ is small, then there is mostly transmission of ultrasound waves. Meanwhile if $(Z_2 - Z_1)$ is large, there is mostly reflection of ultrasound waves. Reflection or transmission also depends on $(Z_2 + Z_1)$.

Table 14.1 shows some typical values of specific acoustic impedance, together with the approximate speed of ultrasound in the medium.

Medium	speed of ultrasound / m s^{-1}	acoustic impedance / kg m^{-2} s^{-1}
Air	330	4.3×10^2
Blood	1600	1.6×10^6
bone	4100	5.6×10^6 - 7.8×10^6
fat	1500	1.4×10^6
Gel	1500	1.5×10^6
muscle	1600	1.7×10^6
soft tissue	1600	1.6×10^6
water	1500	1.5×10^6

Table 14.1

Where there is a large difference between the acoustic impedances of the two media, the value of α would be nearly equal to 1, i.e. the reflected intensity would be nearly equal to incident intensity. Therefore, coefficient for transmitted intensity = (1 – α) and hence the transmitted intensity would be small.

Gel is used on the surface of skin during ultrasound diagnosis because when ultrasound wave travels in or out of the body, majority of the incident ultrasound waves get reflected and there is very little transmission at an air-skin boundary (α ≈ 1), as shown below:

$$\alpha = \frac{I_R}{I} = \frac{(1.6 \times 10^6 - 4.3 \times 10^2)^2}{(1.6 \times 10^6 + 4.3 \times 10^2)^2} = 9.989 \times 10^{-1} \approx 1$$

Meanwhile, with gel, there is little reflection and almost complete transmission at a gel-skin boundary, as shown below:

$$\alpha = \frac{I_R}{I} = \frac{(1.6 \times 10^6 - 1.5 \times 10^6)^2}{(1.6 \times 10^6 + 1.5 \times 10^6)^2} = 0.001$$

Attenuation of Ultrasound in Matter

Once the ultrasound wave is within the medium, the intensity of the wave will be reduced by absorption of energy as it passes through the medium, causing the medium to be heated. The heating effect produced by ultrasound of appropriate frequencies is also used in physiotherapy to assist recovery from sprains and similar injuries.

For a parallel beam of ultrasound incident normally on a medium of thickness x, this absorption is approximately exponential and the transmitted intensity I is related to the incident intensity I_0 by the expression:

$$I = I_0 e^{-kx} \quad \text{or} \quad I = I_0 \exp(-kx)$$

Where k is a constant for the medium known as the linear absorption coefficient and it depends on the medium and on the frequency of the ultrasound. Table 14.2 shows some values of linear absorption coefficient.

medium	linear absorption coefficient / cm^{-1}
air	1.2
bone	0.13
muscle	0.23
water	0.0002

Table 14.2