Oxford Cambridge and RSA

Thursday 14 October 2021 – Morning

A Level Physics B (Advancing Physics)

H557/02 Scientific literacy in physics

Advance Notice Article

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Seeing with sound

In the 1790s, the Italian scientist Lazarro Spallanzani performed a rather surprising experiment. He observed the flights of owls and bats in a room lit only by dim candlelight. The birds and mammals both successfully navigated the room without bumping into anything. However, when the candle was blown out the owls could no longer confidently fly around the room whilst the behaviour of the bats was unchanged – the bats could ‘see’ in the dark. Rather gruesomely, Spallanzani went on to blind his experimental animals only to find that the bats could still ‘see’ in the dark. It was only when he blocked the bats’ ears that the creatures lost their navigational ability. The conclusion – bats ‘see’ with their ears, but how could this be?

This problem went unanswered for 140 years until the discovery of ultrasound echolocation in the 1930s. Simply put, the bat produces an ultrasonic ‘click’ and listens for the returning echo. The time delay between click and echo allows the bat to judge the distance to objects. But the reality is much more complicated and impressive than this simple picture. Some species of bat change the frequency of the note they emit for more efficient range finding. Many species have adapted mouth, nose and ears to increase the range and resolution of the echolocation system. When hunting, a bat needs to know more than just the distance of its target (often a moth). The relative speed of the target is required, as is the target’s horizontal and vertical position. The methods used for this data capture are given in the table.

measurement	**method**
distance to prey	echolocation: distance = $\frac{1}{2}$ × speed of sound in air × time interval between bat emitting pulse and detecting echo
vertical position of prey	interference patterns of echo signal produced by ridges in the bat’s ears (see **Fig. 1**)
horizontal position of prey	comparison of intensity of echo signal in right and left ears
movement of prey	Doppler effect detection
size of prey	intensity of echo signal

Fig. 1 The long-eared bat shows clear ridges on its ears. These act in a similar fashion to a diffraction grating and help the bat determine the vertical position of its prey.

Detecting distance

Waves will reflect from objects which are at least as long as the wavelength. For this reason, the bat must emit short wavelength, high frequency sound. Typically, they use pulses of sounds of around 80 kHz in echolocation – way beyond the upper limit of human hearing. The pulses have to be short in duration so that the spatial length of the pulse (how long it is in metres) is as small as possible to establish the distance to the prey with precision. When searching for prey a bat might produce a pulse every 200 ms; this rises to about one pulse every 5 ms when the bat comes close to the prey.

The problem of power

The power of sound is measured in decibels (dB). Strictly, it measures **differences** in sound power. Sound power difference in decibels is given by the equation

$$\text{difference in sound power (dB)} = 10\log_{10}\left(\frac{P_1}{P_0}\right)$$

where, often, P_0 is the power of a sound that can just be heard and P_1 is the power of the sound produced by the source under consideration. Therefore, a sound that can just be heard will have a power difference of 0 dB. A sound of 3 dB will have approximately twice the power of the smallest audible signal.

The echolocating signal of a bat can be 110 dB at a few centimetres distance from the bat. However, the power diminishes very quickly. Two effects produce this loss of power; the spreading of the sound from the source and absorption and scattering of the sound by the atmosphere. Without absorption and scattering, the power of sound waves from a point source shows inverse square variation. Bats reduce the effects of signal loss through spreading by using high frequency sounds which diffract less on leaving the sound source. Some species project the echolocation signals through their nostrils. This means that there are two sources of waves which superpose constructively in the zeroth-order direction. This concentrates the power of the beam so that it travels greater distances through air.

Sound absorption in air is highly frequency-dependent. The power of the signal decreases exponentially with distance. With no spreading, a 100 kHz signal halves its power over a distance of about one metre, a change of 3 dB. The power approximately follows the relationship

$$P_x = P_0 e^{-\alpha R}$$

where P_x is the power at distance R from the source, P_0 is the power at the source and α is the atmospheric attenuation constant.

The Doppler effect

One of the most remarkable adaptations bats have evolved is that of Doppler effect detection. As the figure shows, some species of bats can use the Doppler effect to judge the relative velocity of the object it is locating. A moth flying away from the bat produces an increase in the wavelength of the reflected waves (**Fig. 2 a**). An approaching moth produces reflections of decreased wavelength (**Fig. 2 b**).

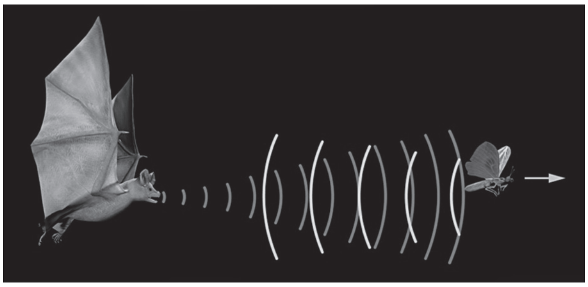

Fig. 2 a

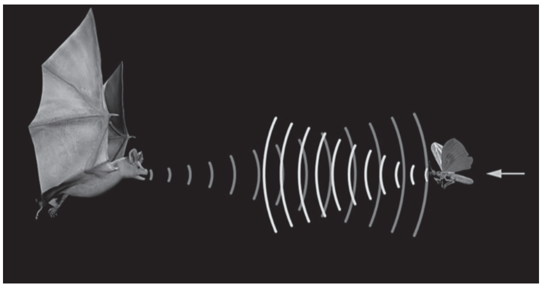

Fig. 2 b

The new frequency f produced by the relative motion of the source and the receiver is given by the Doppler shift equation

$$f = \left(\frac{c - v_r}{c - v_s}\right) f_0$$

where c is the velocity of sound in air (about $340\,\mathrm{m\,s^{-1}}$), v_r is the velocity of the receiver (the moth) and v_s the velocity of the source (the bat). Even in this one-dimensional case, c, v_r and v_s are vectors, so v_r and v_s are positive if they are in the same direction as c and negative if they are in the opposite direction. This means that in **Fig. 2 a**, a moth flying at $5\,\mathrm{m\,s^{-1}}$ pursued by a bat flying at $40\,\mathrm{m\,s^{-1}}$ emitting ultrasound at $f_0 = 100\,\mathrm{kHz}$ receives a frequency $f = \left(\frac{340 - 5}{340 - 40}\right) \times 100\,\mathrm{kHz} = 112\,\mathrm{kHz}$ whereas a moth flying at the same speed towards the bat in **Fig. 2 b** receives a frequency of $f = \left(\frac{340 - [-5]}{340 - 40}\right) \times 100\,\mathrm{kHz} = 115\,\mathrm{kHz}$.

To calculate the frequency heard by the bat it is necessary to treat it in two stages: the frequency the moth receives is calculated using the bat as the source and then the reflection the bat receives from the moth is calculated using the moth as the source, emitting sound at the frequency it received.

Some species of bat have developed this form of echolocation to the extent that they can identify the species of moth by the Doppler shift produced by the manner in which the moths flutter their wings.

Medical ultrasound

Many babies in the world are scanned before birth using ultrasound echolocation, another example of seeing with sound.

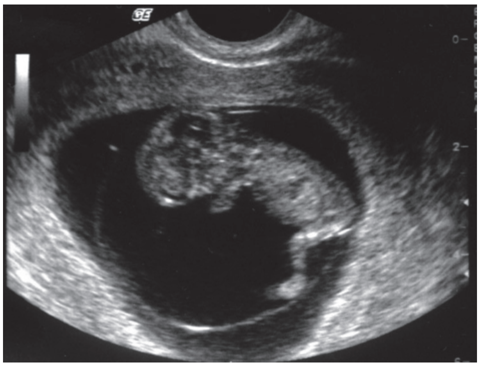

Fig. 3 Ultrasound scan of a healthy 10 week-old foetus

Ultrasonic waves used in medical imaging are produced using a **piezoelectric transducer**. When a direct potential difference is applied to the transducer plate it either compresses or expands, reverse the process and the opposite happens. When the crystal expands it produces a compression (region of high pressure) followed by a rarefaction (region of low pressure) which moves through the air. This is the ultrasound wave. A single, sudden change of p.d. across the plate will set the transducer oscillating in the same manner as striking the edge of a wine glass. Like the wine glass, the transducer will oscillate at its resonant frequency. This frequency depends on the width of the transducer crystal: a standing wave will be formed in the crystal of wavelength equal to twice the width of the crystal. The crystal will oscillate at the frequency of the standing wave, producing a pulse of sound at the same frequency.

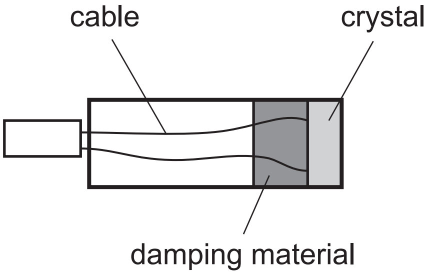

Fig. 4 Simplified diagram of single-element piezoelectric transducer (not to scale)

Sound waves travel in tissue at about $1540\,\mathrm{m\,s^{-1}}$, but this depends on the type of tissue. For example, the velocity of sound in body fat is about $1450\,\mathrm{m\,s^{-1}}$ and in muscle it is around $1585\,\mathrm{m\,s^{-1}}$.

As the ultrasound pulse produced by the transducer travels through tissue it will reflect from interfaces where the velocity of sound changes. The reflections are detected by the transducer and produce a change in potential difference. The potential difference changes of the transducer are digitised and displayed as the ultrasound image.

The time interval between the outgoing and return pulses allows distance between the transducer and the reflecting surface to be found, this is **longitudinal imaging**. The image shown in **Fig. 3** is taken by scanning *across* the object and detecting return pulses from a constant depth. This is **latitudinal imaging**.

Resolution of medical ultrasound

It is important for an ultrasound imaging system to have good depth resolution (longitudinal) and good latitudinal resolution.

As with bats, obtaining good longitudinal resolution requires short spatial pulse lengths, where spatial pulse length = wavelength of pulse × number of cycles of pulse. A lightly damped crystal will vibrate for a number of cycles as shown in **Fig. 5 a**, which oscillates for seven and a half cycles.

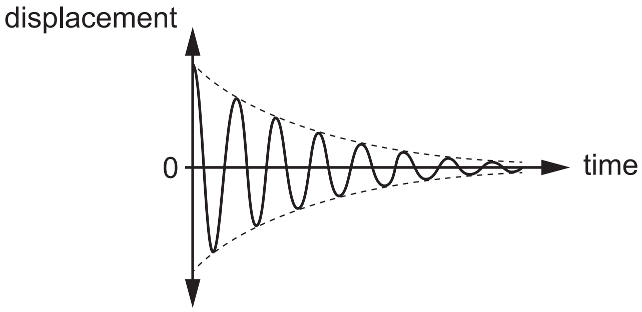

Fig. 5 a

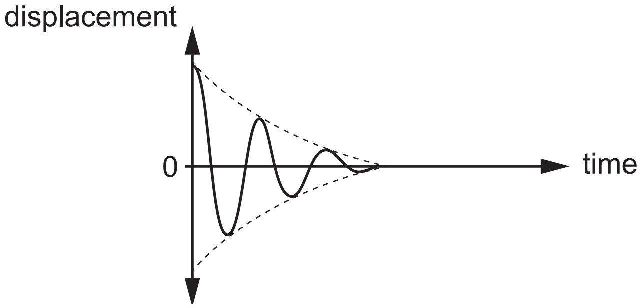

Fig. 5 b

Placing a damping block behind the crystal reduces the number of oscillations and reduces the pulse time. This is equivalent to placing a hand on a ringing wine glass. A heavily damped oscillation is shown in **Fig. 5 b**.

The longitudinal resolution of an ultrasound scan is equal to half the spatial pulse length of the pulse. An ultrasound pulse of 1 μs corresponds to about 3 cycles for a typical ultrasound frequency used in medical imaging. This produces a longitudinal resolution of less than 1 mm.

Latitudinal resolution depends on the width of the beam. The narrower the beam the better the resolution. One way of achieving a narrow beam where required is to electronically focus the beam at a given depth in the tissue. Consider the set of transducers labelled A to D in **Fig. 6**. When activated each transducer will emit an ultrasound pulse in the manner described above. Applying the principle of superposition, the ultrasound beam can be seen to have the greatest power at point X if the pulse from the pair of transducers labelled D is emitted slightly earlier than the pulse from pair C, which is emitted slightly earlier than pair B. The final pulse comes from transducer A. Changing the time delay between pulses from different transducers allows the beam to be focused at different depths.

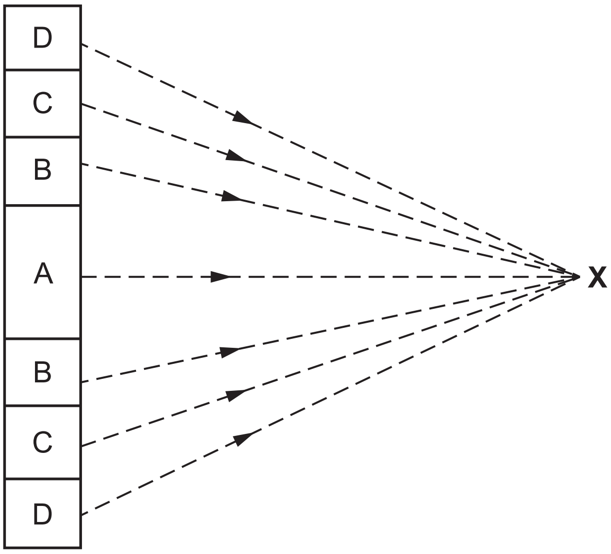

Fig. 6

This highly technical focusing system uses similar principles to those species of bats which strengthen the power of their pulses through using two sources of sound. Scientists and technologists are developing ways of seeing with sound similar to those which evolution produced in bats millions of years ago.