Unit 1 – Physics in Action – Section C

Imaging

X-rays

X-rays are invisible, highly penetrating electromagnetic radiation of much shorter wavelength (higher frequency) than visible light. The wavelength range for X-rays is from about **10^{-8} m to about 10^{-11} m**, the corresponding frequency range is from about **3×10^{16} Hz to about 3×10^{19} Hz.** X-rays are part of the electromagnetic spectrum and hence travel through a vacuum at **3×10^{8} ms**$^{-1}$. X-rays with a wavelength approximately longer than **0.1 nm** are called **soft** X-rays. At wavelengths shorter than this, they are called **hard** X-rays.

X-rays are made by an electrode pair (cathode and anode) which sit inside a glass vacuum tube. An X-ray machine passes a current through the cathode filament, heating it up. The positively charged anode (a flat disc made of tungsten) draws the electrons across the tube.

The voltage difference between the cathode and anode is extremely high, so the electrons fly through the tube with lots of energy. When a speeding electron collides with a tungsten atom, it knocks loose an electron in one of the atom's lower orbitals. An electron in a higher orbital immediately falls to the lower energy level, releasing its extra energy in the form of a photon. The photon has a high energy level - it is an X-ray photon.

The detection of X-rays is based on various methods. The most commonly known method is the photographic plate, frequently used in hospitals. The X-rays blacken the photographic plate (negative), it is black where the X-rays go through ("soft" parts of the body like organs and skin) and white where the X-rays are stopped.

Normally parts of the body such as the brain and kidneys are transparent to X-rays, but injecting an iodine compound into the bloody results in it being carried vary rapidly to all the cells. A computer scan enables doctors to see the detailed structure of the organs to help their diagnosis.

X-rays are especially useful in the detection of pathology of the skeletal system, and are also useful for detecting some disease processes in soft tissue. Some notable examples are the very common chest X-rays, which can be used to identify lung diseases such as pneumonia or lung cancer. X-rays are also useful in x-ray spectroscopy, x-ray crystallography and x-ray astronomy.

This image can be displayed on a computer too. The numerical data is stored, usually, as a 24-bit display per pixel. This is produced by scanning the image in and each pixel colour is digitally coded as a binary number – with 16 million combinations.

Ultrasound

What is it?

Ultrasound is sound with a frequency too high for the human ear to hear. Sound is a longitudinal wave (a wave where the particles move in the same direction as it is going) which travels through materials. Therefore, sound and ultrasound cannot exist in a vacuum.

An average person can hear sounds with a frequency of up to about 20 **kHz**, hence an Ultrasound wave is any sound wave with a frequency higher than that. The frequency of ultrasound in actual use is usually between **2MHz and 10MHz**. Since Ultrasound is still sound, it still travels at about 330ms^{-1} in the air. Since Wave Speed = Frequency x Wave Length, the wavelength of an ultrasound will be between 16.5mm (for a frequency of 20kHz) and 0.033mm (for a frequency of 10MHz).

How is it produced?

The device that produces the ultrasound wave is called a **transducer**. It does this by taking advantage of the **Piezoelectric Effect**. This is when a material – generally Quartz – is given an electric current. Piezoelectric materials slightly change shape when a current is passed through them, so a AC current will make it deform, and so change shape, slightly and rapidly. This causes vibrations, which is the source of sound. Because it is very high frequency, it is ultrasound. The transducer may also have facilities for focusing the sound (e.g. an acoustic lens).

How is it used to take pictures?

Ultrasound is often used for taking pictures. The pictures it generates, however, are different to the sorts of photo's you may take using a camera. For example, there is no colour (as that is a consequence of light).

The method works because sound reflects against objects. The Ultrasound waves are produced and directed at the target. **Between materials (changes of density)**, some of the sound will reflect back. The receiver can then detect this, and a computer can calculate, from the amount of time it took for the reflections to get back, the distance between the two objects. This is then displayed in a picture. If the transmitter and receiver are in the centre of the thing which is to be scanned and are rotated, or if there are multiple of them, then from many images a 3D model of the object being scanned can be produced.

The resolution of Ultrasound

The resolution of an image is the smallest possible detail that can be picked out from it. For example, if the resolution of an image is 1m (for example, from a detailed satellite) then each 'dot' (pixel) of the imagine will represent 1m. The resolution of Ultrasound is around **1mm**, which is enough to see the shape of the baby in an ultrasound scan, or enough to find out where a submarine is in a boat. A higher resolution might still be desirable, however the benefits of ultrasound make it a good choice (see advantages). The shape of the transmitter can affect the resolution of the image.

Uses

The biggest use of Ultrasound is in Ultrasound Scans. This is where ultrasound is used to create an image of an unborn foetus inside the pregnant mother. It can be used to observe the sex and any problems with the baby.

It can also be used in fishing boats to detect where fish are, or used by mariners to work out the shape of the floor of the ocean. Navy ships may use it to detect where a submarine might be, too (SONAR).

Ultrasound can detect the speed that things are travelling at using the Doppler effect. This is when the frequency of waves is modified depending on how something is moving. When an object moves away from the transmitter, when the waves echo, they will have increased in wavelength (to imagine this, bare in mind that the whole time the object is moving). This effect will be exaggerated if the object is moving faster. This can be utilised to calculate the speed of blood flowing around the body.

Some animals make use of Ultrasound (e.g. bats, dogs and dolphins), often for navigational reasons, where there might not be light (e.g. in a cave)

Receivers

Receivers are made from the same material (or could even physically be the same device) as the emitters. As well as deforming when given an electric current, they can produce an electric current when deformed (e.g. by the ultrasound waves hitting them again). This is because there are both positively and negatively charges in the crystal, but they are distributed in such a way that they cancel each other out. When the distribution is modified (for example, by being compressed) the charges no longer balance each other out, and a charge is produced. The charge is higher when the compression is more severe.

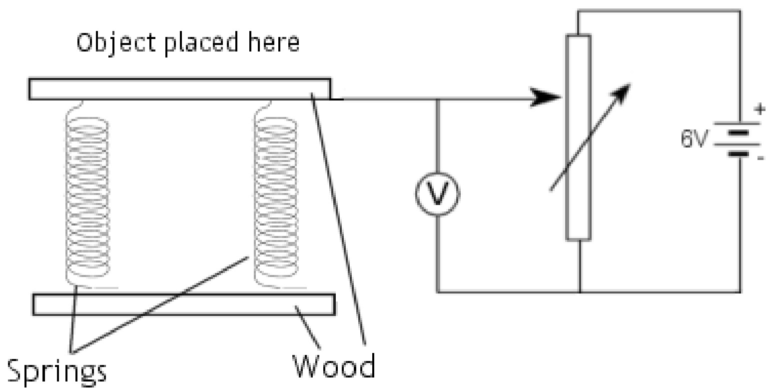
Advantages and Disadvantages

The biggest advantage of Ultrasound is that it allows diagnosis without the need for radiation, which could be harmful for someone's health if done too regularly. Ultrasound is also quick and requires less precaution. Ultrasound cannot cause cuts, bleeding, infections or side effects such as reactions to chemicals.

However, the quality of images taken with Ultrasound can vary (it depends upon the skill of the user) and generally isn't as good as other methods, which means that in some cases it should only be used as the 'first check'. It can also heat up tissues and water inside the body, or cause bubble to form. This could possibly have a harmful side effect. In boats, Ultrasound is quick and does the job. For animals, Ultrasound has the advantage of working where there is no light (Which is helpful for dark places. The disadvantage of sound not working in a vacuum will of course not affect an animal).

Sensing

Mass Detector



The purpose of this sensor (electronic scales) is to weigh masses for transport by lorries.

Explanation of the circuit

As a load is applied to the scales, the springs compress a certain amount (depending on the mass). This moves the contact of the linear potentiometer down, changing the voltage output across it. Because springs follow Hooke's law, and the potentiometer is linear, the resultant potential difference will be proportional to the mass of the load applied. The voltmeter will be calibrated so that a particular value will correspond to a particular mass, and hence the mass of the load can be determined.

Calibration

Known masses from 50kg to 1000kg at 10kg intervals could be applied to the scales. Each mass will correspond to a potential difference which will be recorded. A calibration curve will be plotted from these data so that the output voltage from the subsequent unknown loads can be described as known masses.

The sensitivity of the sensor could be determined by applying unknown masses to the scales, recording their measured mass (according to the calibrated sensor), then a comparison could be made between this and the real mass of the object.

Typical Response Time

The response time is almost immediate as the the voltmeter reading appears almost instantaneously, but it may take a few seconds for the springs to stop oscillating. This has no particular implications as the system as we do not need to be particularly fast when weighing masses for lorries.

Estimated Sensitivity: 5 grammes.

To improve the sensitivity:

- The springs could be replaced with springs which compress more easily (*soft* springs).
- The wire in the linear potentiometer could be made thinner in diameter, and made from nichrome which has a high resistivity ($100 \times 10^{8}\ \Omega$m).
- The contact (arm of the potentiometer) could be made of a metal with a high conductivity e.g. copper.
- Smaller intervals could be taken when calibrating.

This sensor is a good choice in this application because the circuit is simple and you can easily change the linear potentiometer so that different resistances can be used. This is useful when weighing a wide variety of masses, which is needed for weighing the many different objects which are transported by lorries.

Signalling

Radio

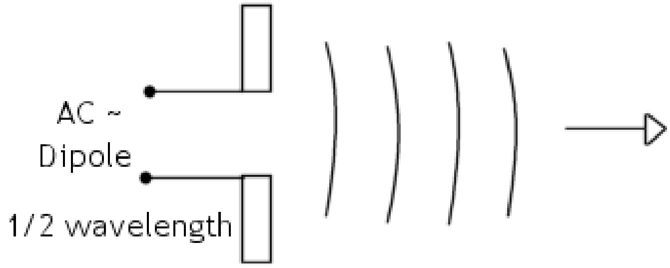
- Radio waves cover a frequency band from about 30kHz to about 30GHz.
- Long wave = 30-300kHz
- Medium wave = 300-3000kHz
- Short wave = 3-30 MHz
- Very high frequency = 30-300 MHz
- Ultra high frequency = 300-3000 MHz
- Microwave = 3-30 GHz

Transmitting radio signals

Radio waves are transmitted from an aerial as a result of high frequency **alternating voltage** which accelerates electrons up and down the aerial. Most broadcasting transmitters use an aerial which is **half the length** of the transmitted radio waves, known as a **dipole** aerial.

The accelerating electrons become excited and transmit radio waves to release their surplus energy. The **faster** the current alternates, the **higher** the frequency of radio waves the electrons emit.

The dipole can also be used as a receiving aerial. As the alternating radio signal reaches the aerial it induces an alternating voltage in the dipole.



Transmitting

Between the transmitter and receiver, the signal may go via a range of media. The signal may travel through: air, space, coaxial cable, optical fibre or wire. In some cases the signal may need to be changed to another form like light, electrical or microwave.

Waves may travel as:
- **Ground waves:** low frequency waves in the LW/MW bands, used for long distance broadcasts.
- **Sky waves:** these reflect from the ionosphere back to the ground. The ionosphere will reflect frequencies up to 30MHz.
- **Space waves:** frequencies greater than 30MHz. Used for satellite links. Cover VHF, UHF and microwave frequencies. Transmitter sends to satellite, which **re-transmits** signal to receiver.

The Transmitted Signal

There are 2 parts to a transmitter signal:
- Carrier waves
- Information Signal

The carrier wave is a radio frequency wave which has constant amplitude and constant frequency. Added to this, using a **modulator**, is the information signal which constantly fluctuates. The information signal changes or **modulates** the carrier wave.

Amplitude Modulation (AM)

This is when the amplitude of the carrier wave is altered, but the frequency remains constant. This is prone to being affected by noise and interference.

Frequency Modulation (FM)

Here, the frequency of the carrier wave is altered, but the amplitude remains constant. This method has much less problems with noise and interference.

Both FM and AM are analogue, not digital, signals.

- **Speed of signal:** The signals travel at approximately $3 \times 10^8 ms^{-1}$.

- **Distance the messages are sent:** The distance they will be sent will be approximately 30km (width of a large city – hence reflected off ionosphere).

- **Time for a message to be sent:** V = s/t, hence the time taken to send this is approximately $30{,}000 / 3 \times 10^{8} = 1 \times 10^{-4}$ s.

- **Approximate rate of transfer of information:** The approximate rate of information transfer is 2 × highest frequency = 2 × 30MHz = 60MHz.

Microwaves - Mobile phones

Letters are input by the keypad. The phone converts and stores the letters as digital ASCII code. The message data is this code with various bits of information such as the sending date attached to it. The code is superimposed onto a microwave signal and transmitted to base station and switching centre. This is then sent on to the mobile phone that should receive it. The signal is received and the phone converts the microwave signal back into text. Encryption is applied.

Noise could cause incorrect characters or incorrect pixels on graphics. Ensuring no nearby signals transmitting on the same frequency avoids this.

The speed of the transfer of information depends on the speed of the carrier wave and the number of other messages loading the system. An approximate rate of transfer of information is 50kbps.

The speed of the signal is $3 \times 10^{8} ms^{-1}$. The messages might be sent 50km. Hence approximate time is the larger of these divided by the smaller.

Estimated frequency: 10^{9} Hz – this is the number of waves per second.

The advantage of using high transmission frequency: High frequencies can travel through the ionosphere, and can therefore be send to satellites. This allows communication to take place across the world.

Advantage: World wide communication – we can communicate with each other no matter where we are in the world. This is critical for progress in the scientific community and for events like wars and natural disasters.

Disadvantage: Health risks – some scientists believe that mobile phones can cause cancer and tumours in the brain due to the possible danger of the microwaves being emitted.

Materials

Silicon

Purpose:

Used in transistors, which are used in many different devices and electronic circuits.

Properties for this purpose:

- Must be a semiconductor because the conductivity needs to be controlled, and this can only happen if the semiconductor has been doped with another element from group 5 or 3, depending on whether it's a p or n-type material that is needed.
- Must be 99.999999% pure because the presence of impurities in very small proportions can have

big effects on the electronic properties of the transistor.
- Abundance/Cost (see below).

Internal Structure:
Silicon has a tetrahedral covalent bonding structure, similar to diamond, but with more loosely held electron pairs. The atomic spacing is around **0.1nm**.

The structure of silicon makes it a semiconductor. Most of the electrons orbiting the nucleus of silicon are in its valence band at room temperature. It still has a sizeable current though, as some of the electrons are also in the conduction band. At a very low temperature, the electrons are all in the valence band, hence silicon is an insulator at a low temperature. This is the definition of a semiconductor.

When the temperature rises, this thermally excites the electrons into the conduction band, making them free to carry electric current.

Silicon is a tetravalent element. It can be doped with pentavalent elements (one more electron in the outer shell). These pentavalent elements can be placed in the silicon crystal lattice, the extra electrons are easily detached – increasing the number of free electrons and hence the conductivity (n-type doping).

A missing electron from a bond can also move through the crystal lattice, behaving like a positively charged hole (p-type doping).

The crystalline structure of silicon can be damaged quite easily. This interferes with the electronic properties of the material and is a cause of defective devices in production processes. In the production process, silicon is heated to just the right temperature to try to prevent this from happening, but sometimes it still happens and this is a major cause of faults in transistors.

Factors influencing the choice of the material:

- **Availability** – Silicon is the second most abundant element on Earth. It is found in rocks and sand in the form of oxides and silicates and is hence easy to acquire. Transistors are needed in many electronic circuits, thousands at a time so the choice of material needs to be one which is widely available.

- **Cost –** Again, thousands of transistors are needed in electronic circuits at a time, so it is crucial that the cost is low. Because transistors are produced in a large volume, they maintain a low cost. This low cost has meant that the transistor has become an almost universal tool for non-mechanical tasks.

Other properties:

A mechanical property of silicon is its resistance to hardness (resilience to scratching/denting). This is conferred by the three-dimensional nature of the covalent bonding, making a giant crystal structure, with all atoms quite strongly bonded to their four nearest neighbours and hence to the whole crystal.