2.4 Diffraction and pulse-echo

Name: _____ Class: _____ Date: _____ **Total: 22 marks**

KEY WORDS Diffraction • Huygens' construction • diffraction grating • order • de Broglie wavelength • transmitted • pulse-echo

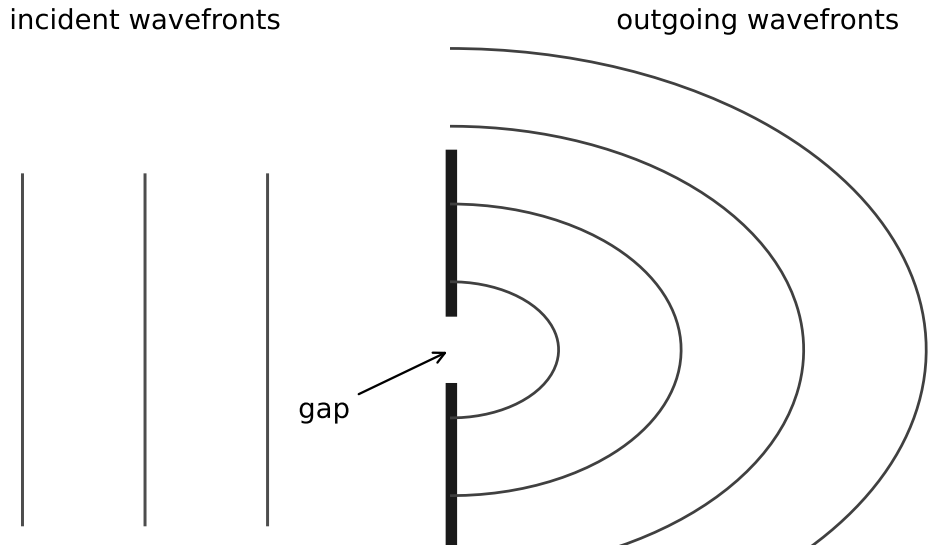
Objective

Build the methods for WPH12 statements 50–56: diffraction and pulse-echo. These are original teaching questions, not copied past-paper items.

1 Key knowledge and worked examples

Diffraction is the spreading of waves at a gap or edge. Spreading is greater when the gap width is comparable to the wavelength. A wide gap still diffracts at its edges, but the central wave spreads less.

In **Huygens' construction**, each point on a wavefront acts as a source of secondary wavelets. Draw wavelets of equal radius after the same time. Their forward common tangent gives the new wavefront. At a narrow gap only a small part of the original front supplies wavelets, so the emerging fronts spread widely. This explains spreading without inventing a change of frequency at the slit.



The gap limits which points supply the outgoing wavelets.

Gratings and core practical 6

A **diffraction grating** contains many equally spaced slits. Bright maxima occur when contributions from neighbouring slits arrive in phase:

$$k\lambda = d\sin\theta$$

Here k is the integer **order**, d is slit spacing, and θ is measured from the straight-through direction. The equation assumes normal incidence. If the grating has N lines per metre, $d = 1/N$. Do not confuse grating order with refractive index; printed papers may use n for either.

Worked example. A grating has 600 lines per millimetre. First-order light appears at 18.0°. Find its wavelength.

- Known: line density and first-order angle. Convert line density before taking its reciprocal.

$$d = \frac{1}{N} = \frac{1}{600 \times 10^3\ \text{m}^{-1}} = 1.67 \times 10^{-6}\ \text{m}$$

$$\lambda = \frac{d\sin\theta}{k} = \frac{1.67 \times 10^{-6}\ \text{m} \times \sin 18.0^\circ}{1} = 5.15 \times 10^{-7}\ \text{m}$$

- This is 515 nm. Check each proposed higher order using $k\lambda/d \leq 1$.

For CP6, aim a low-power laser normally at a grating and place a screen perpendicular to the central beam. Measure screen distance D and displacement x from the central spot to an order. Use $\tan\theta = x/D$, then the grating equation. Average corresponding left/right displacements, repeat distances, and use higher visible orders where measurement is clear. Measure from the grating to the screen, not from the laser casing. Do not substitute $\sin\theta = x/D$ unless a justified small-angle approximation is acceptable. Never look into the beam; keep it below eye level and stop stray beams.

Electrons also show wave behaviour

An electron beam passing through a thin crystal produces a diffraction pattern. Regular atom spacing provides the diffracting structure. Changing electron momentum changes the pattern spacing. This is evidence of wave behaviour; particles travelling along simple straight paths alone cannot explain the diffraction maxima.

The **de Broglie wavelength** is:

$$\lambda = \frac{h}{p}$$

For a non-relativistic electron, $p = mv$. If it gains kinetic energy by crossing a potential difference, $E_k = eV$ and $p = \sqrt{2mE_k}$. Use these links only when the question gives or requires that energy relation.

Worked example. An electron has momentum 2.0×10^{-24} kg m s^{-1}. With $h = 6.63 \times 10^{-34}$ J s:

$$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{2.0 \times 10^{-24}}\ \text{m} = 3.3 \times 10^{-10}\ \text{m}$$

Increasing momentum reduces wavelength. Electrons have both particle and wave properties; diffraction does not mean that an electron becomes a sound wave.

■ Reflection, transmission and echoes

At an interface, part of a wave's energy may be **transmitted** and part reflected. A reflected pulse can locate a boundary. In **pulse-echo** , measured delay includes the outward and return journeys:

$$2s = vt \quad \Rightarrow \quad s = \frac{vt}{2}$$

Worked example. Ultrasound travels in metal at 5900 m s^{-1}. An echo returns after 12 μs.

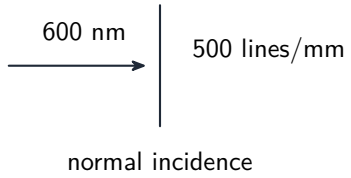
$$s = \frac{vt}{2} = \frac{5900\ \text{m s}^{-1} \times 12 \times 10^{-6}\ \text{s}}{2} = 0.0354\ \text{m}$$

The boundary is 35 mm away, not 71 mm. A nearby echo may overlap the transmitted pulse. Shorter pulse duration reduces this blind region and separates close echoes. Shorter wavelength helps detect or distinguish smaller features. These are related limits, but pulse duration and wavelength are not the same quantity. Use the speed in the actual material, not automatically the speed in air.

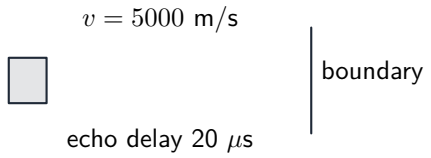
2 Practice

2.1 Explain using Huygens' construction why waves spread after passing through a narrow gap. [2]

2.2 A grating has 500 lines per millimetre. Light of wavelength 600 nm arrives normally. Calculate the first-order angle. [3]

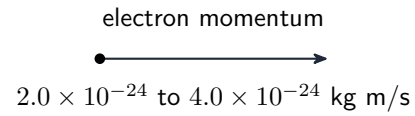


2.3 An ultrasound echo returns 20 μs after transmission in metal. Wave speed is 5000 m s^{-1}. Calculate boundary depth and explain the factor two. [3]

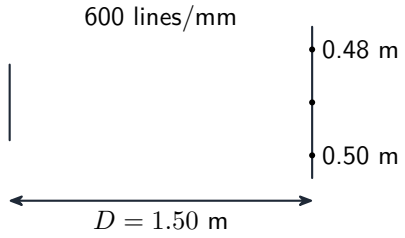
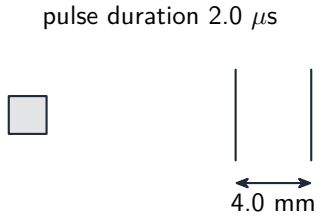


3 Exam-style questions

3.1 An electron momentum changes from 2.0×10^{-24} to 4.0×10^{-24} kg m s^{-1}. Calculate both de Broglie wavelengths using $h = 6.63 \times 10^{-34}$ J s. Explain why electron diffraction supports wave behaviour. [4]



3.2 A laser/grating screen is 1.50 m from the grating. First-order spots are 0.48 m left and 0.50 m right of centre. The grating has 600 lines per millimetre. Find wavelength using the mean displacement. State two improvements or precautions. Explain why $\sin\theta = x/D$ is not exact. [6]



3.3 Two reflectors in a material are 4.0 mm apart along the beam. Sound speed is 5000 m s^{-1}. Calculate the separation of their echo arrival times. Explain why a 2.0 μs pulse makes them difficult to distinguish, and give a change that improves timing resolution. [4]