Chapter 16

Summary of Waves II - Sound and Hearing (Ch. 16)

Introduction to Sound Waves

Sound waves are longitudinal waves, meaning the oscillations of the medium's particles are parallel to the direction of the wave's travel. This contrasts with transverse waves where oscillations are perpendicular. We can visualize sound waves as a series of compressions and expansions of the medium. The human ear is sensitive to a frequency range of approximately 20 to 20,000 Hz, known as the audible range. Frequencies above this range are ultrasonic, while those below are infrasonic.

Speed of Sound

The speed of any mechanical wave depends on the inertial and elastic properties of the medium.
- For a fluid, the speed of sound (v) is given by

$$v = \sqrt{\frac{B}{\rho}}$$

where B is the bulk modulus and ρ is the density of the medium.
• For a solid rod, the speed is:

$$v = \sqrt{\frac{Y}{\rho}}$$

where Y is the Young's modulus.

• In an ideal gas, the speed of sound is dependent on temperature and is given by:

$$v = \sqrt{\frac{\gamma RT}{M}}$$

where γ is the ratio of heat capacities, R is the gas constant, T is the temperature (in Kelvin), and M is the molar mass.

Sound Intensity and Level

Sound intensity (I) is the average rate of energy transfer per unit area. It is defined as:

$$I = \frac{P}{A}$$

where P is the power and A is the area. For an isotropic point source, intensity follows the inverse-square law:

$$I = \frac{P_s}{4\pi r^2}$$

where r is the distance from the source. The intensity can also be expressed in terms of the maximum pressure variation (p_{max}):

$$I = \frac{p_{max}^2}{2\rho v}$$

Sound level (β) is measured in decibels (dB) and is a logarithmic scale relative to a reference intensity$(I_0 = 10^{-12} W/m^2)$:

$$\beta = (10 \text{ dB}) \log_{10}\left(\frac{I}{I_0}\right)$$

Standing Waves and Resonance

Standing sound waves can be created in pipes, leading to resonance. The boundary conditions (open or closed ends) determine the possible harmonics.

• **Pipe open at both ends:** Both ends are displacement antinodes. Wavelengths are$\lambda = \frac{2L}{n}$ and frequencies are $f = n\frac{v}{2L}$ for $n = 1, 2, 3, ...$All integer harmonics are possible.

• **Pipe open at one end:** The open end is a displacement antinode, and the closed end is a displacement node. Wavelengths are $\lambda = \frac{4L}{n}$ and frequencies are $f = n\frac{v}{4L}$ for $n = 1, 3, 5, ...$ Only odd harmonics are possible.

Wave Interference and Beats

Interference occurs when waves from two or more sources overlap. The outcome depends on the path length difference, $\triangle L = |L_2 - L_1|$

• **Constructive Interference**: Occurs when waves are in phase. $\triangle L = m\lambda$ for $m = 0, 1, 2...$

- **Destructive Interference**: Occurs when waves are out of phase. $\triangle L = (m + 0.5)\lambda$ for

$m = 0, 1, 2...$

Beats

are produced when two sound waves with slightly different frequencies$(f_1$ and $f_2)$ interfere. The intensity of the resulting sound varies periodically with a beat frequency given by

$$f_{beat} = |f_1 - f_2|$$

Doppler Effect and Shock Waves

The **Doppler effect** is the apparent change in frequency of a wave due to the relative motion between the source and the detector. The detected frequency (f') is given by:

$$f' = f\left(\frac{v \pm v_D}{v \pm v_S}\right)$$

where f is the emitted frequency, v is the speed of sound, vD is the detector's speed, and vS is the source's speed. The signs are chosen to increase the frequency for motion towards the other and decrease it for motion away.
When a source's speed (vS) exceeds the speed of sound (v), the equations for the Doppler effect no longer apply. Instead, a **shock wave** forms a Mach cone. The angle (θ) of this cone is given by:

$$\sin\theta = \frac{v}{v_S}$$

The Mach number (M) is defined as $M = \frac{v_S}{v}$

Other

- The max displacement is presented by :

$$A = \frac{P_{max}}{BK}$$

- The relationship for sound waves is the one that connects the **pressure amplitude** $(\triangle p_{max})$ **and the displacement amplitude** (s_{max})**. It looks like this:**

$$\triangle p_{max} = (pvw)s_{max}$$

Remember $w = 2\pi f$

- Young's modulus : measure of a material's **stiffness**
- Density ρ : a measure of how much **mass** is packed into a given volume.

▼ Quiz:

1. What is the primary physical characteristic that distinguishes musical sound from noise?

A. The shape of the pressure fluctuation versus time graph.

✓ **Bonne réponse !**
Musical sound has a regular, repeating waveform, while noise has an irregular and chaotic waveform, which is visible on a pressure fluctuation graph.

B. The speed at which the sound travels through the medium.

C. The amplitude of the sound wave.

D. The frequency of the sound wave.

2. The speed of sound in a fluid is determined by what two properties of the medium?

A. Young's modulus and bulk modulus.

B. Bulk modulus and density.

✓ **Bonne réponse !**
The bulk modulus is the elastic property related to the fluid's compressibility, and density is the inertial property that resists changes in motion.

C. Frequency and wavelength.

D. Density and temperature.

3. If a point source emits sound uniformly in all directions, how does the sound intensity change if you double your distance from the source?

A. The intensity is halved.

✕ **Pas tout à fait**

This would be true if intensity were linearly related to distance, but it is related to the square of the distance.

B. The intensity is quartered.

✓ **Réponse correcte**

According to the inverse-square law, the intensity is inversely proportional to the square of the distance from the source. Doubling the distance, therefore, quarters the intensity.

C. The intensity is four times greater.

D. The intensity remains the same.

4. What is the sound intensity level in decibels for a sound wave with an intensity of 10^{-6} W/m^2?

A. 100 dB

B. 40 dB

C. 60 dB

✓ **Bonne réponse !**

The sound level is calculated using the formula $\beta = (10 \text{ dB}) \log(I/I_0)$, which gives $\beta = 10 \log(10^{-6}/10^{-12}) = 10 \log(10^6) = 10(6) = 60 \text{ dB}.$

D. 20 dB

5. For a pipe open at both ends, which of the following harmonics are possible?

A. Only harmonics with a wavelength of $4L/n$.

B. Only odd harmonics (1st, 3rd, 5th, etc.).

C. All integer harmonics (1st, 2nd, 3rd, etc.).

✓ **Bonne réponse !**

A pipe with two open ends allows for all integer multiples of the fundamental frequency because both ends can be displacement antinodes.

D. Only even harmonics (2nd, 4th, 6th, etc.).

6. Two sound waves of slightly different frequencies are played simultaneously. What phenomenon will be observed?

A. A constant, uniform sound.

B. The Doppler effect.

✕ **Pas tout à fait**

The Doppler effect involves a change in frequency due to relative motion between a source and an observer, not the superposition of two sources with different frequencies.

C. A standing wave.

D. Beats.

✓ **Réponse correcte**

The superposition of two waves with slightly different frequencies results in periodic constructive and destructive interference, which is heard as a wavering of intensity called beats.

7. A sound source is moving away from a stationary listener. How will the detected frequency change?

A. The detected frequency will be higher than the emitted frequency.

B. The detected frequency will be lower than the emitted frequency.

✓ **Bonne réponse !**

When the source moves away from the listener, the waves are stretched out, resulting in a lower detected frequency.

C. The detected frequency will vary based on the listener's position.

D. The detected frequency will be the same as the emitted frequency.

8. What is the general formula for the detected frequency, f', in the Doppler effect?

A. $f' = f(v_S/v)$

B. $f' = f(v \pm v_D/v \pm v_S)$

✓ **Bonne réponse !**

This is the general equation for the Doppler effect, where the signs depend on the direction of motion relative to the other object.

C. $f' = f(v/v_S)$

D. $f' = f(v_D/v_S)$

9. A sound wave is propagating in the $+x$-direction, and its pressure fluctuation is given by $p(x,t) = BkA\sin(kx - \omega t)$. What is the equation for the particle displacement, $y(x,t)$?

A. $y(x,t) = -A\sin(kx - \omega t)$

B. $y(x,t) = A\sin(kx - \omega t)$

C. $y(x,t) = -A\cos(kx - \omega t)$

D. $y(x,t) = A\cos(kx - \omega t)$

✓ **Bonne réponse !**

The pressure fluctuation is proportional to the negative partial derivative of the displacement with respect to position, which means the waves are 90 degrees out of phase and the displacement is a cosine function.

10. What is the name for the conical wave front that is created when a sound source travels faster than the speed of sound?

A. A shock wave.

✓ **Bonne réponse !**

A shock wave is the high-pressure wave front that forms in the shape of a cone when a source moves at a supersonic speed.

B. The Doppler wave.

C. An infrasonic wave.

D. A standing wave.

3. Sound waves are longitudinal waves. What does this mean for the motion of particles in the medium as the wave propagates?

A. The particles move perpendicular to the direction of wave propagation.

✕ **Pas tout à fait**

This describes a transverse wave, not a longitudinal wave.

B. The particles move in circles.

C. The particles do not move at all.

D. The particles move parallel to the direction of wave propagation.

✓ **Réponse correcte**

In a longitudinal wave, particles oscillate back and forth in the same direction that the wave energy is traveling.

4. Based on the properties of a medium, in which of the following would sound generally travel the fastest?

A. The speed is the same in all three.

B. A solid (like a metal rod)

✓ **Bonne réponse !**

Particles in a solid are tightly packed with strong bonds, allowing them to transfer vibrations (sound) very efficiently and quickly.

C. A liquid (like water)

D. A gas (like air)