Chapter 13 Physics of the Ear and Hearing

- Hearing
  - 100 times greater dynamic range than vision
  - Wide frequency range (20 ~ 20,000 Hz)
- Sense of hearing
  - Mechanical system that stimulates the hair cells in the cochlea
  - Sensors that produce action potentials in the auditory nerves
  - Auditory cortex in the brain
- Ear (Fig. 13.1): conversion of weak mechanical waves in air into electrical pulses in the auditory nerve
  - Outer ear: ear canal and eardrum (tympanic membrane)
  - Middle ear: three small bones (ossicles) and Eustachian tube
  - Inner ear: cochlea (hair cells in the origin of Corti in the cochlea)
- Medical specialists
  - Otologist, MD: disease of the ear and ear surgery
  - Otorhinolaryngologist or ENT specialist, MD: disease of the ear, nose, and throat
  - Audiologist, non-MD: measuring hearing response, diagnosing hearing disorders, hearing aids

1. The Outer Ear

- External auricle or pinna: not a part of the outer ear
  - Negligible effect on hearing
  - Cupping hand behind the ear ⇒ 6 ~ 8 dB gain
- External auditory canal
  - Storage of ear wax
  - 2.5 cm long with the diameter of a pencil ($\lambda/4 = 10$ cm)
  - Increase the sensitivity in the region of 3000 ~ 4000 Hz
  - Resonance frequency of 3300 Hz ($\lambda = 10$ cm): Fig. 13.2
- Eardrum or tympanic membrane
  - 0.1 mm thick (paper thin) and 65 mm$^2$
• Couples the vibrations in the air to ossicles
• Non-symmetric vibration (Fig. 13.3)
• At 3000 Hz, \(10^{-9}\) cm movement for the sound intensity of the threshold of hearing
• At lower frequency, longer movement
• Sound pressure over 160 dB rupture the eardrum
• Ruptured eardrum normally heals like other living tissues

2. The Middle Ear

- Three small bones or ossicles (Fig. 13.3): full adult size before birth, fetus can hear in the womb
- Ossicles
  - Impedance matching between the eardrum and the liquid-filled chamber of the inner ear
  - Malleus (hammer), incus (anvil), stapes (stirrup)
  - Force amplification by a factor of about 20 (Fig. 13.4)
    - Lever action amplifies the force by a factor of about 1.3 between M and S
    - Piston action amplifies the force by a factor of about 15 between the eardrum and S
- Ossicles and their sensory ligaments
  - Protection against loud sounds: loud sound ⇒ muscles in the middle ear pull sideways on the ossicles in 15 ms or longer ⇒ reduce sound intensity by 15 dB
  - Noise pollution ⇒ may result in hearing loss
- Eustachian tube
  - Normally closed
  - Muscle movement during swallowing, yawing, or chewing causes a momentary opening
  - Equilibrate air pressure on both sides of the eardrum
  - Rapid pressure change ⇒ pressure difference across the eardrum ⇒ decreased sensitivity of the ear
  - 60 dB across the eardrum ⇒ pain
  - Viscous fluid from a head cold and the swelling of the tissue around the entrance of the tube ⇒ blockage of the Eustachian tube
3. The Inner Ear

- Best-protected sense organ (hidden deep within the hard bone of the skull)
- Oval window
  - Flexible membrane
  - Interface between the ossicles and the cochlea
  - Stapes transmits pressure vibrations to the cochlea through the oval window
- Cochlea
  - Small, spiral-shaped, fluid-filled structure
  - About the size of the tip of the little finger
  - About 3 cm long when straightened out
  - Produce coded electric pulses
  - The organ of Corti and three small fluid-filled chambers (Fig. 13.5): vestibular chamber, cochlear duct, tympanic chamber
  - Vestibular chamber and tympanic chamber are interconnected at the end of the spiral
  - Pressure transmission: stapes ⇒ oval windows ⇒ vestibular chamber ⇒ end of the spiral ⇒ tympanic chamber ⇒ flexible round window at the end of tympanic chamber
  - Action potential generation: oval window ⇒ wave-like ripple in the basilar membrane ⇒ small shear force on hair cells in the organ of Corti ⇒ action potentials
  - Encoding
    - Cochlear duct near the oval window ⇒ high-frequency sound
    - Cochlear duct near the tip of the spiral ⇒ low-frequency sound
    - < 10,000 Hz: frequency of nerve pulses is the same as sound frequency
    - > 10,000 Hz: frequency of nerve pulses < 10,000 Hz, location is encoded
- Auditory nerve
  - Interface between the cochlea and the brain
  - Bundle of about 8000 conductors
  - Carries electric pulses from the cochlea containing frequency and intensity information of the sound

4. Sensitivity of the Ear
Not uniform over 20 ~ 20,000 Hz
Most sensitive range: 2 ~ 5 kHz (Fig. 13.2)
Sensitivity is decreased for old people
  • 45 years old: no perception for over 12 kHz, need 10 dB more at 4 kHz than 20 years old
  • 65 years old: 25 dB loss for > 2 kHz
Loudness
  • Proportional to the logarithm of intensity
  • Unit: phone, one phone = 1 dB sound at 1000 Hz, 10 phones = 10 dB sound at 1000 Hz
  • Frequency dependent (Fig. 13.7)

5. Testing Your Hearing

Soundproof room
Test sound: 250 ~ 8000 Hz
Hearing threshold plot (Fig. 13.8)

6. Deafness and Hearing Aids

Deaf or hard of hearing: problem in hearing 300 ~ 3000 Hz, hearing threshold of 90 dB
Sound level: average 60 dB, 45 dB in a quiet room, 90 dB in a noisy party
Conduction hearing loss
  • May be temporary
  • May be due to solidification of the small bones in the middle ear
  • Surgery: replace the stapes with a piece of plastic
  • Use a hearing aids
Nerve hearing loss
  • May affect only a limited frequency range
  • Use a cochlear implant (artificial ear)
Hearing aids
  • Ear trumpet (Fig. 13.9, 10)
- Electronic hearing aids (Fig. 13.11, 12, 13): microphone, amplifier, loudspeaker