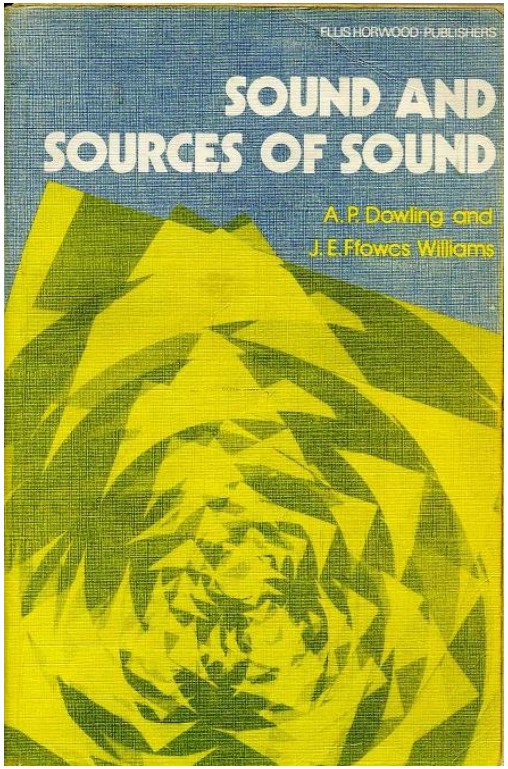
NOISE ENGINEERING

(Year 2014)

- Prof. Soogab Lee
  http://aancl.snu.ac.kr
- Time: Mon./Wed. 11:00-12:15
- Room: Blg. 301- Rm.304
- Office hour: Mon./Wed. 14:00-17:00
- T.A.: TBA



PART I. Introduction of Acoustics

- History
- Characteristics of Sound
- Three-dimensional Sound Waves
- Waves in Pipes
- Sound Waves Incident on a Flat Surface of Discontinuity
- Ray Theory
- Resonators-from Bubbles to Reverberant Chambers
- Acoustics of Moving Media

PART II. Basic Theory of Aero-acoustics

- Sources of Sound
- Effects of Solid Boundaries
- The Reciprocal Theorem and Sound Generated near Surfaces of Discontinuity
- Effects of Uniform Flow
- Theories Based on Solution of Linearized Vorticity-Acoustic Field Equations
- Effects of Non-uniform Mean Flow on Generation of Sound

PART III. Computational Aero-acoustics

- Introduction to Computational Aeroacoustics
- Hybrid Technique
  - Aeroacoustics of Rotating Machinery: Panel Method + Time-Domain Acoustic Analogy
  - Aeolian Tone: CFD + Acoustic Analogy
  - Aeroacoustics of High-speed Train: CFD + Kirchhoff Method
- Direct Flow-Acoustics Simulation
  - Trailing-Edge Noise: Acoustic-Viscous Splitting Methods
  - Twin-Cylinders : Immersed Surface Dipole Model
  - Turbo-Fan Engine Noise
  - Aeolian Tone: CAA

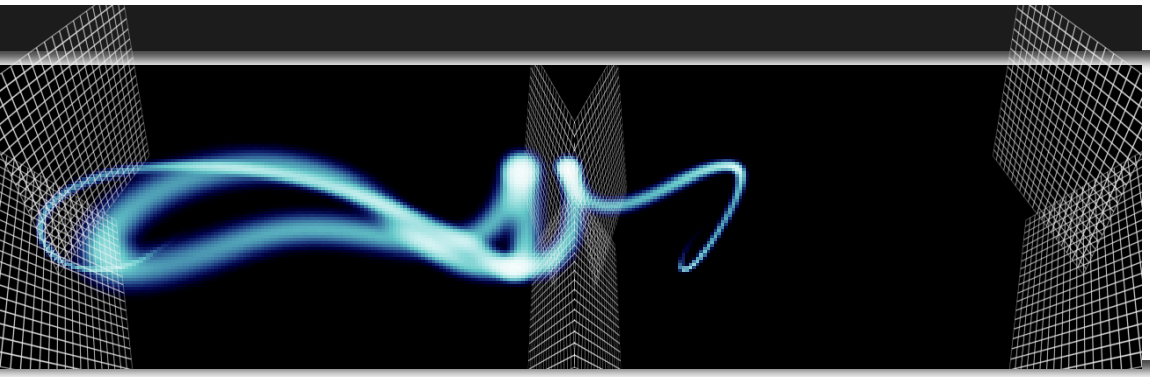
PART IV. Noise Assessment & Control

- Noise Metrics & Measurement
- Sound Absorbing Material and Its Application
- Active Noise Control
- Sound Quality
- Environmental Noise Assessment
- Human Response to Noise

PART V. Some Illustrative Applications

- Aerospace Science
- Mechanical Science
- Naval & Ocean Engineering
- Human Perception & Response
- Environmental Engineering
- Medical Application

Future Technology
- What & How -



Prof. Soogab Lee

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Next-G Wind Energy Research Center

CENVR
Center for Enviromental Noise & Vibration Research

Watch –Paradigm Shift

1510

1728

1969

2000

Camera –Paradigm Shift









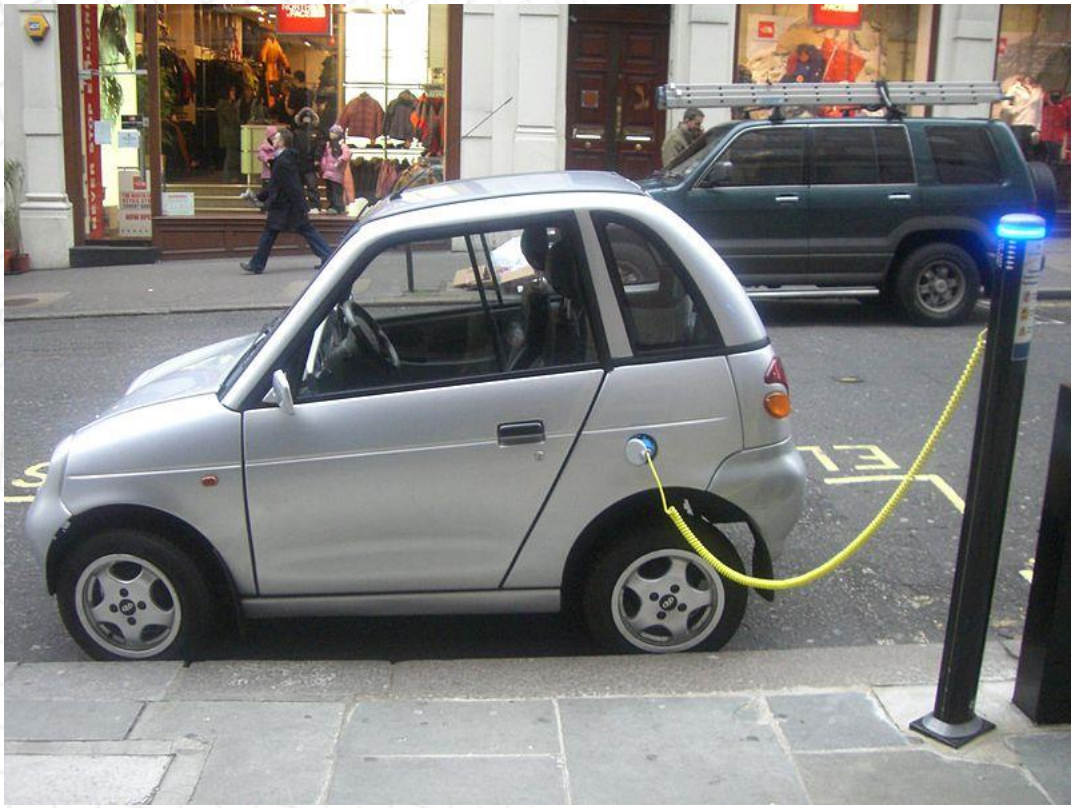

Paradigm Shift: Audio amplifier

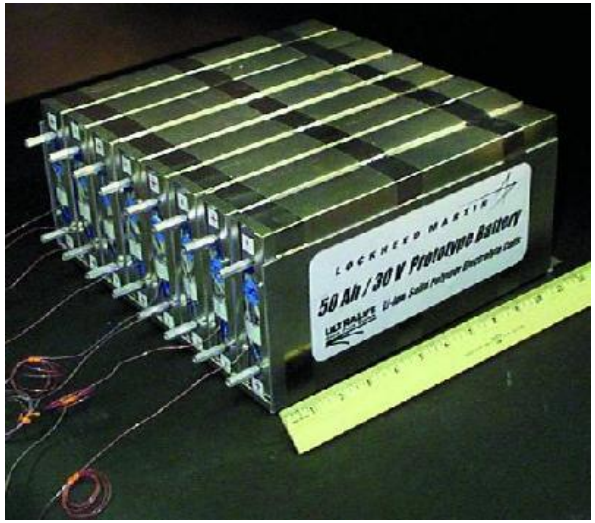
Vacuum Tube (RCA, David Sarnoff)

Transistor (Analog)

Digital Amp (Neo-fidelity Inc.)

Is a Paradigm shift? or Just a High Tech?

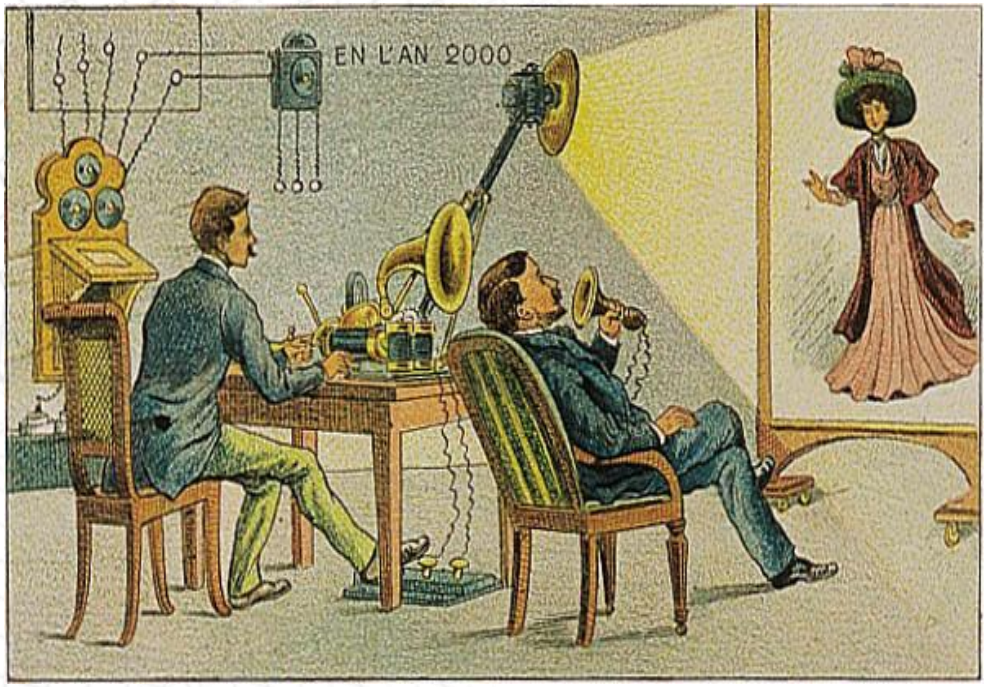




Is a Paradigm shift? or Just a High Tech?

Is High-Tech always winner?

❖ Video-Phone

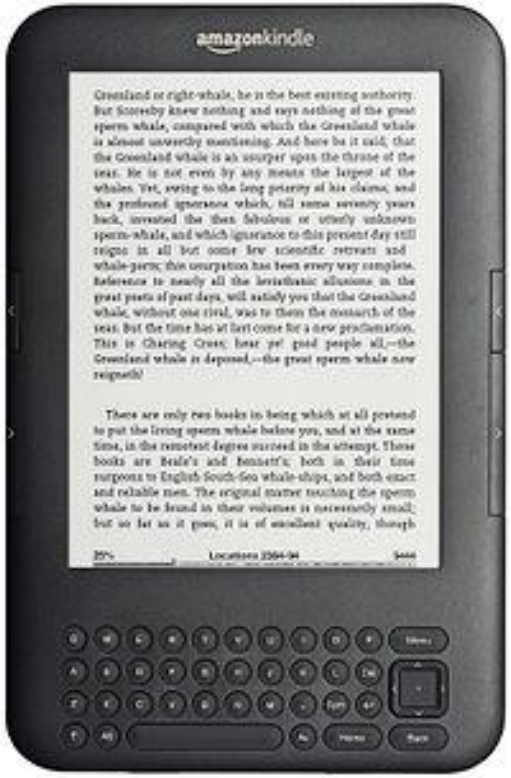


Artist's conception: Video-telephony in the 21st century, as imagined in 1910

AT&T (1970)

Avaya Nortel (2008)

❖ Electronic Book (E- book)



Amazon Kindle 3

Is High-Tech always winner?

Concord – Last flight

‘요즘 떠드는 미래의 Life style은 바로 지옥 (Hell) 이다’

- German Futurist, Matthias Horx (2010)

- **Future Technology Should Be <u>Friendly to:</u>**

Human (Comfortable)

Environment (Sustainable)

Earth Resources (Renewable)

❖ General overview

- Wheel of Acoustics (Lindsay, 1964)

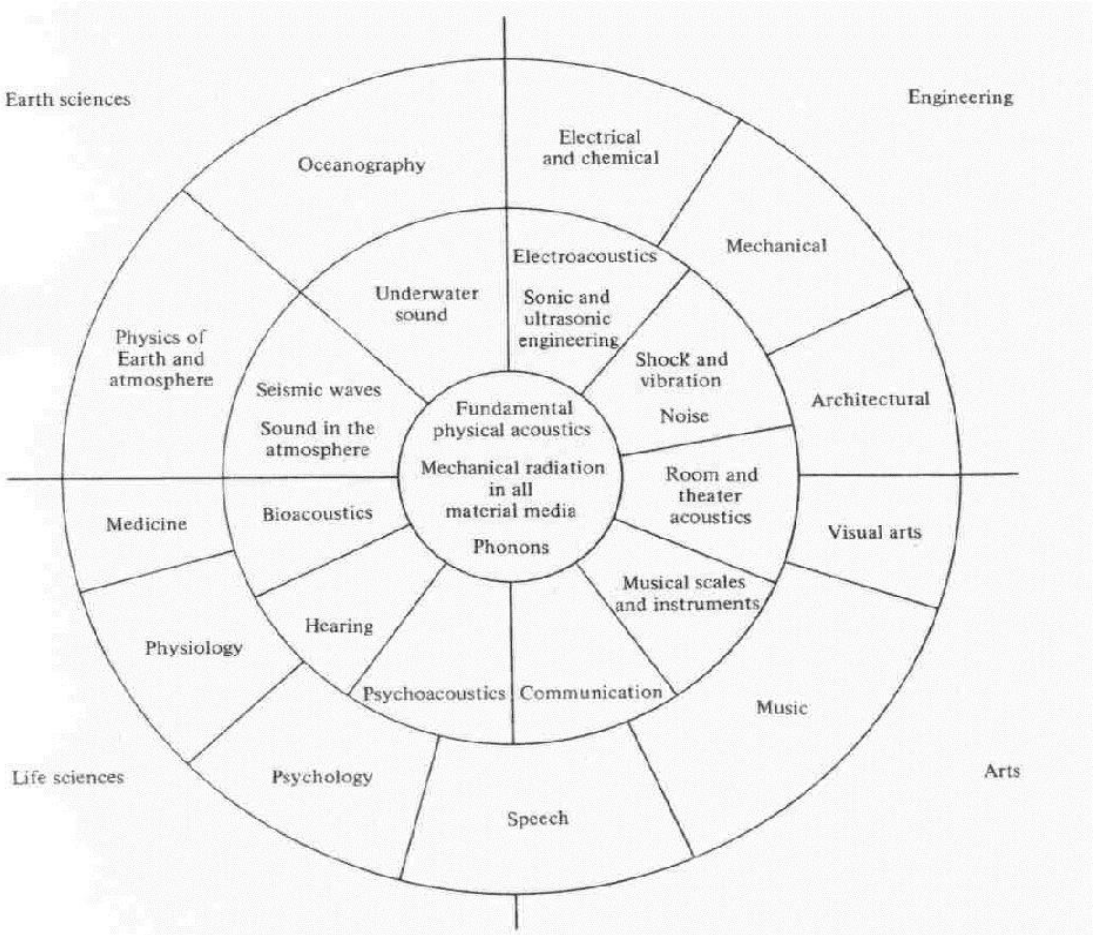
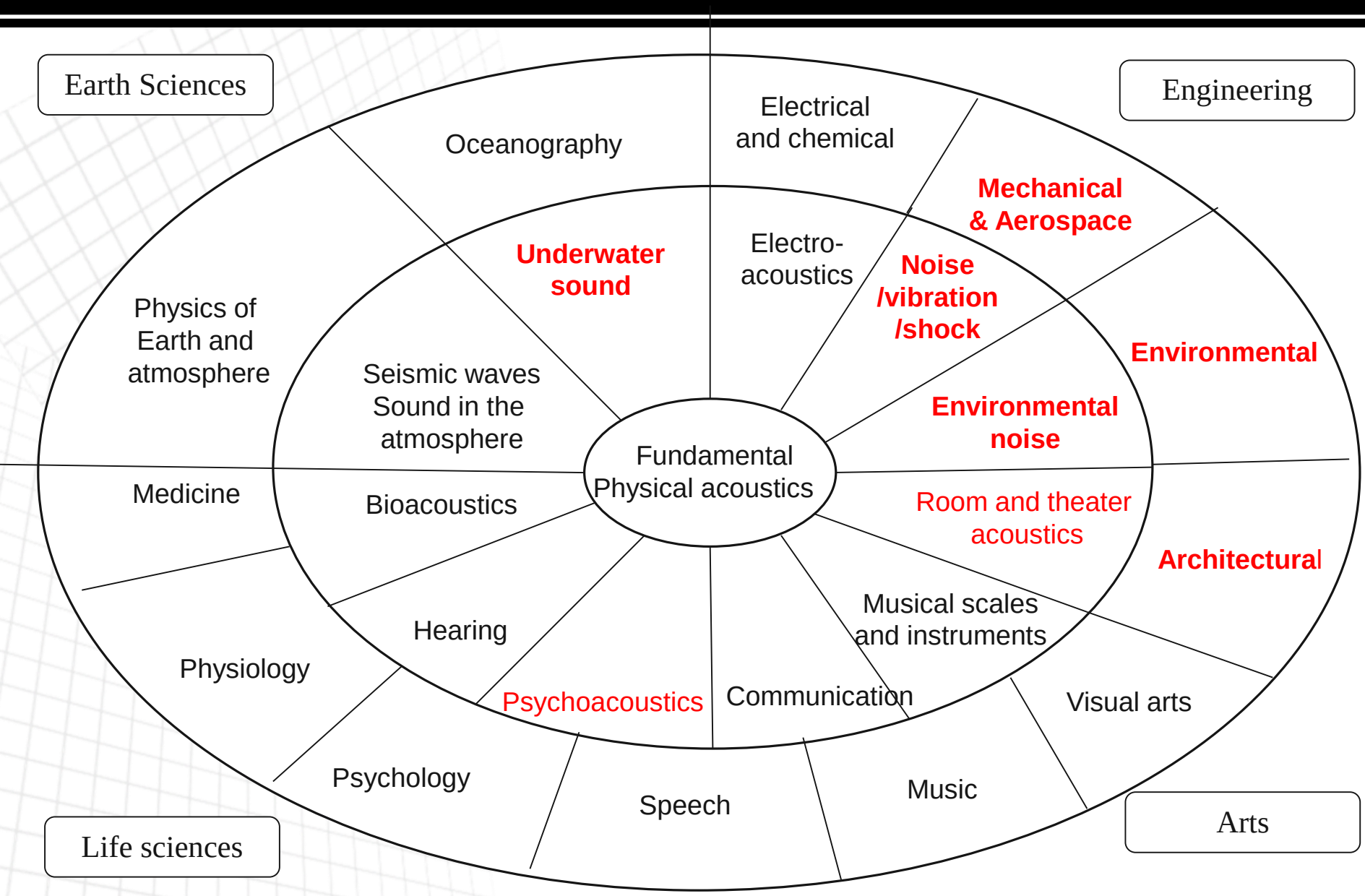


Figure 1-1 Circular chart illustrating the scope and ramifications of acoustics. [*Adapted from R. B. Lindsay, J. Acoust. Soc. Am.*, **36**:2242 (1964).]

Modified Wheel of Acoustics



❖ Acoustics in 19th Century

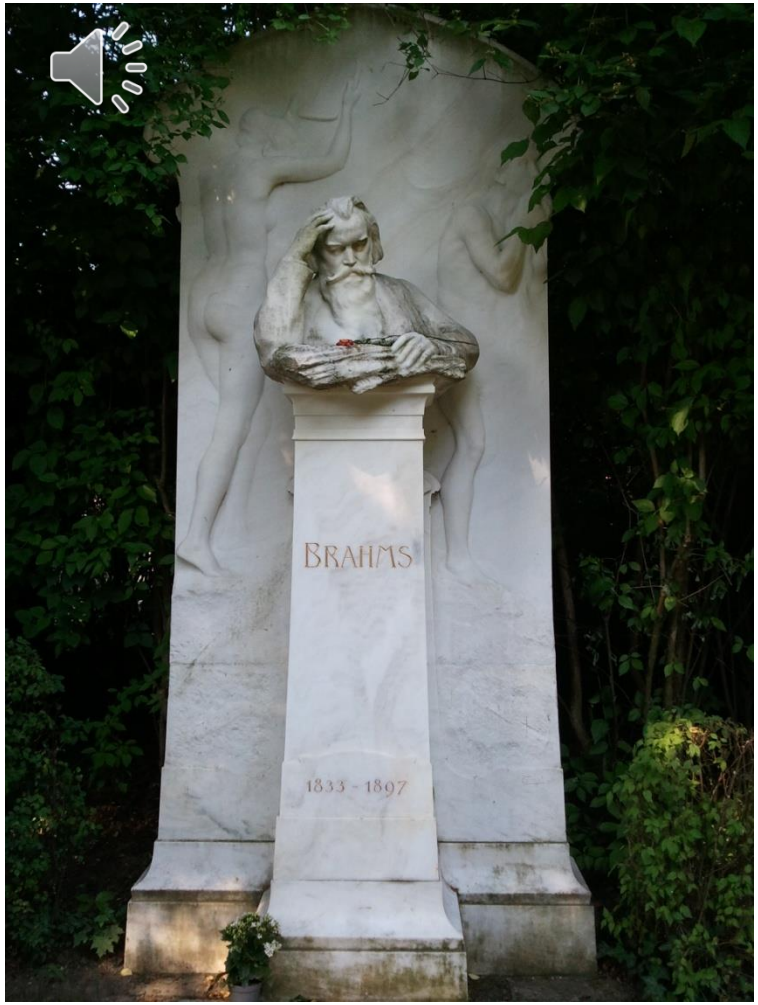
- Stokes and Rayleigh was the subject's greatest figures
  - Vibration string
  - Organ pipe
- The sounds they were interested in were generally pleasant.
- Nowadays most of the sounds of engineering interest are unpleasant, there being a large research effort concerned with the sound generated by Transportation vehicle and Machinery, etc.

❖ Modern-day Acoustics (Scopes of Acoustics)

- Architectural Acoustics

- Musical Acoustics

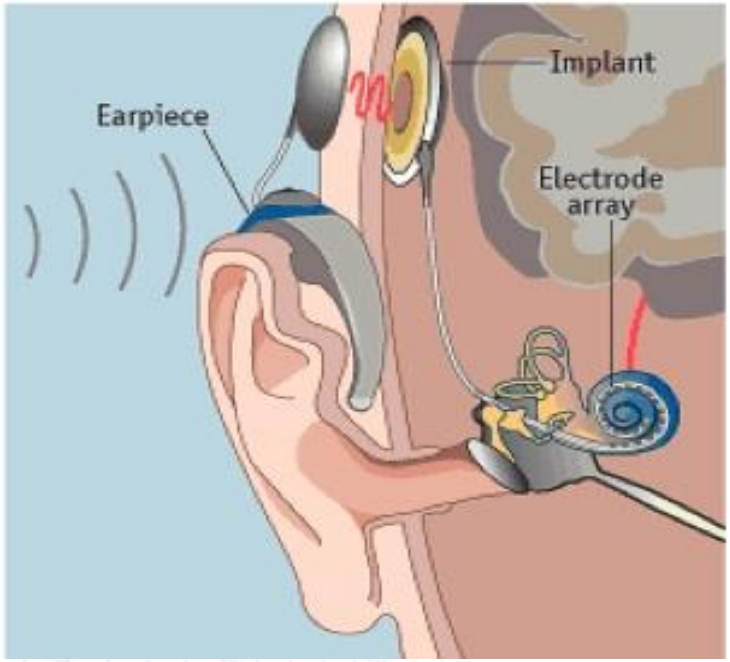
Vs.

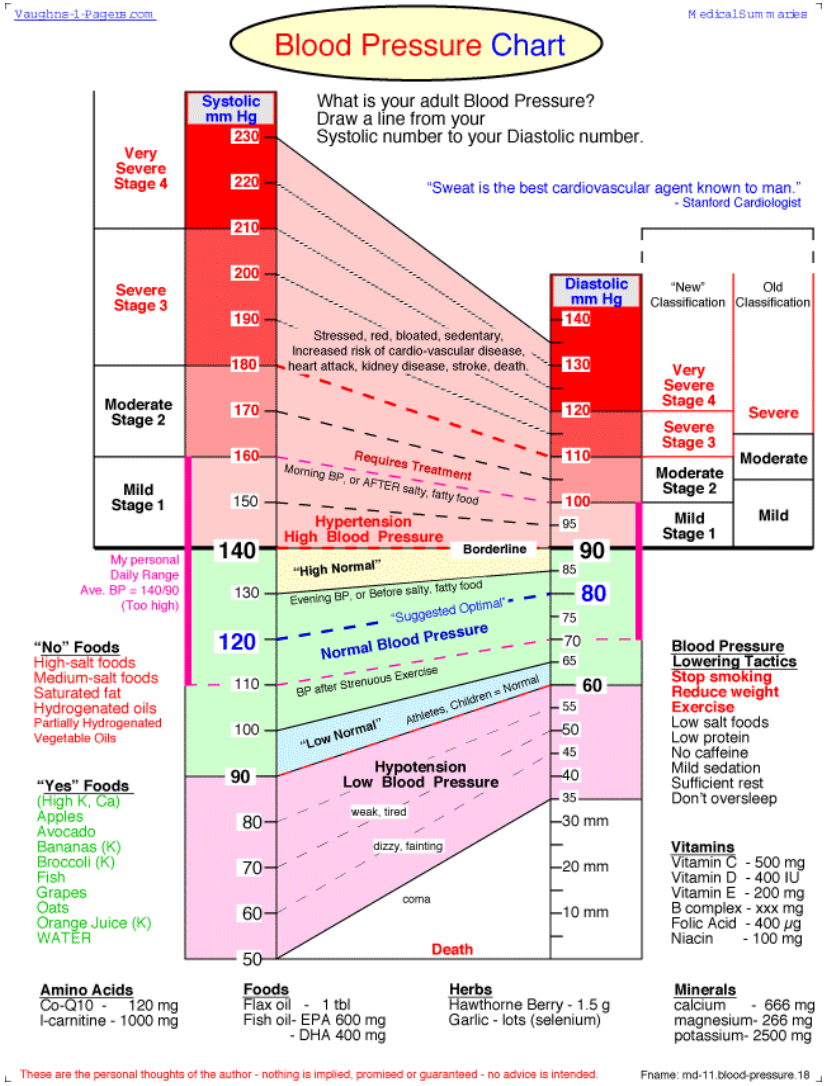


Musical Acoustics

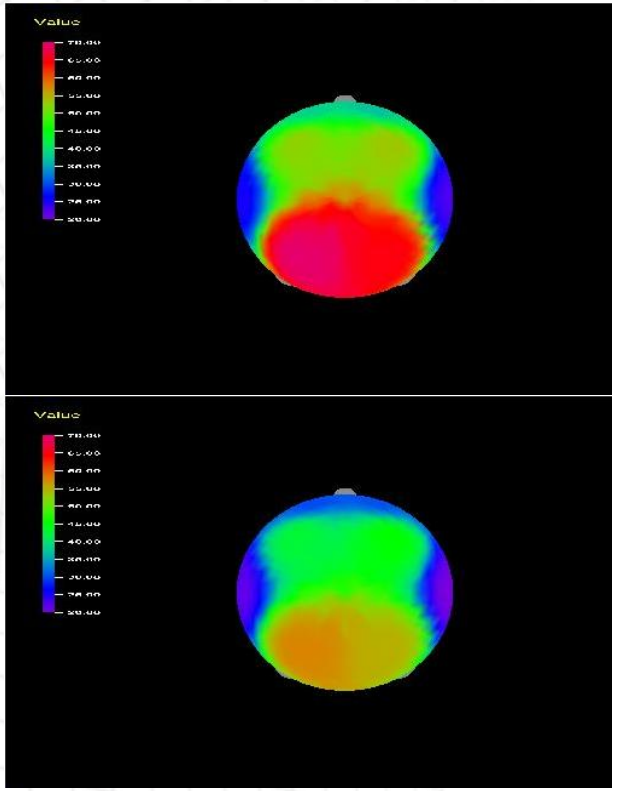
Introduction

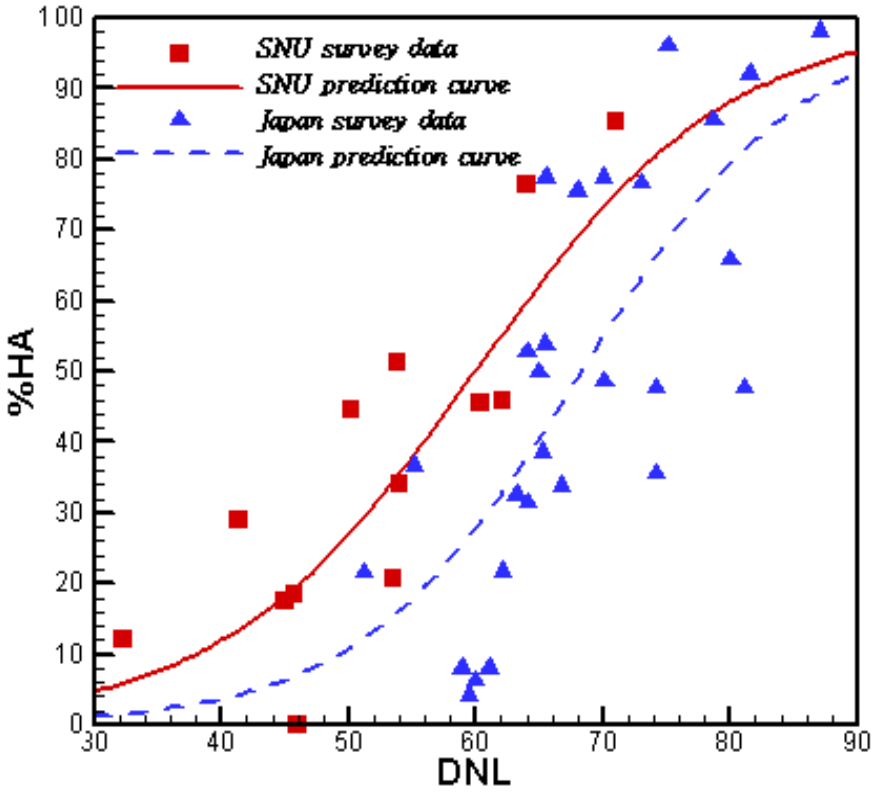
- Physiological acoustics :
  - Hearing disorder (Artificial Cochlea)
  - Effect of noise on human



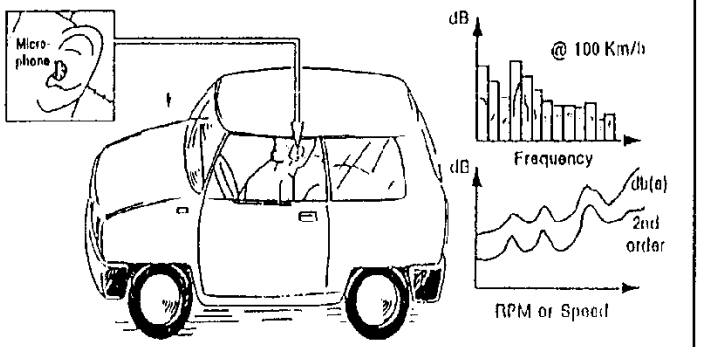


- Psychological acoustics :
  - Sound Quality (Zewicker's Loudness)
  - Mental stress (Annoyance & Sleep disturbance)



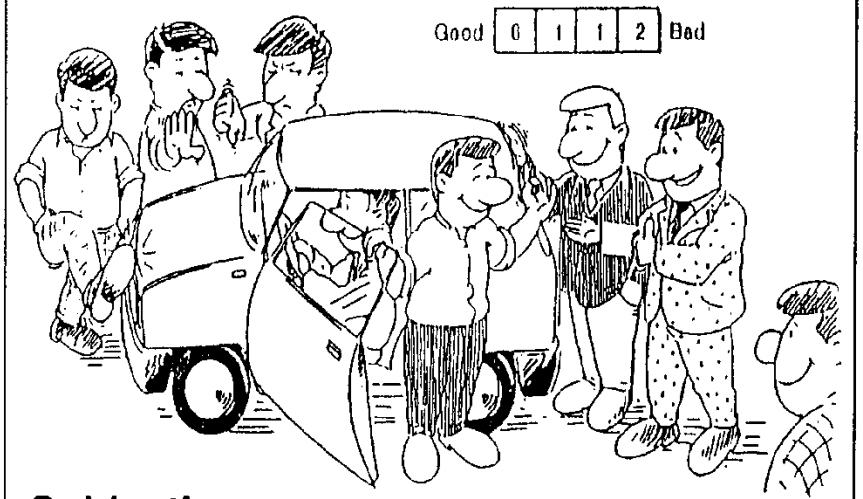


Objective / Subjective Feedback



Objective

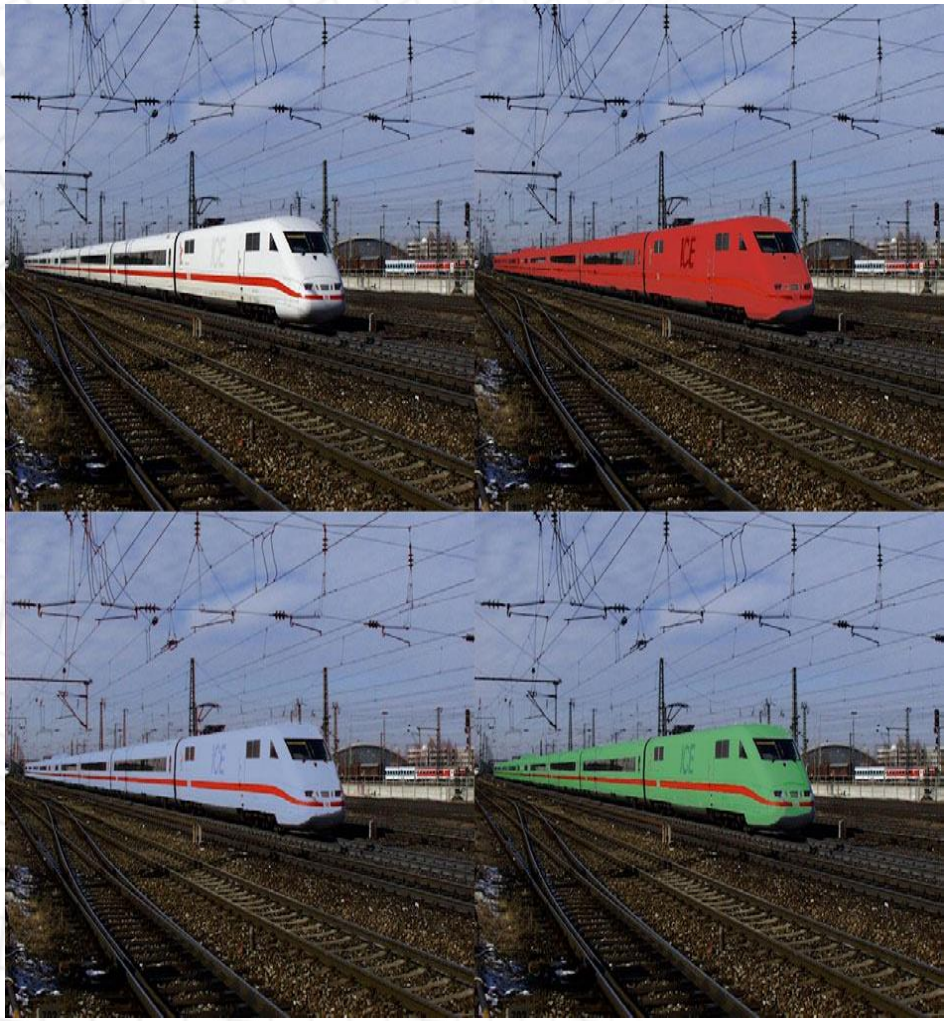
- complex instrumentation
- sound quality metrics
- confined by limited knowledge of sound perception



Subjective

- listen & judge
- most representative
- statistical analysis

Audio-Video Interaction



ICE trains with different colour (⊂)

Still Picture Effect on Loudness

❖ Modern-day Acoustics (Scopes of Acoustics)

● Transportation noise:

- Aviation Noise:
  - Sonic Boom
  - Turbo-fan Engine Noise
  - Jet noise: turbulent shear, screech tone
  - Airframe Noise (+Gear)
  - Helicopter noise: HSI, BVI, Broadband
  - V/STOL
  - Propeller
  - Rocket

❖ Modern-day Acoustics (Scopes of Acoustics)

● Transportation noise:

- (High Speed) Trains
  - Tunnel passing noise
  - Pantograph noise
  - Train-body noise
  - Underbody noise
- Automobiles
  - Power-train (engine) noise
  - Car-Body noise
  - Tire noise

❖ Modern-day Acoustics (Scopes of Acoustics)

- Military Noise
  - Shooting noise
    - Heavy Artilleries
    - Small guns
    - Propagation
  - Environmental noise
    - Sound quality
    - Human perception
    - Annoyance/ Sleep disturbance
    - Health effect assessment (Hypertension, cardiovascular)
    - Learning capability (School room noise)
    - Noise mapping with GIS

❖ Modern-day Acoustics (Scopes of Acoustics)

- Industrial noise :
  - Turbo-machinery noise
    - Fan
    - Blower
    - Pump
    - Compressor
    - Turbine
  - Silencer Design
  - Combustion noise & Instability

❖ Modern-day Acoustics (Scopes of Acoustics)

- Underwater acoustics:
  - Submarine
  - Military Ships
  - Torpedo
  - Civil Ships (여객선 55dB, 객실기준 2014.7 IMO)
  - Propulsion system (single, ducted, multi-staged)
  - Sonar System
  - Long-range propagation
  - Sound channel
  - Fishing
  - Marine Biological Acoustics

❖ Modern-day Acoustics (Scopes of Acoustics)

- Infrasound :
  - Vibration coupling
  - Effect on Human
  - Artillery
  - Seismic wave
- Ultrasonics :
  - Medical diagnostics
  - Structural integrity
- Active noise control :
  - Duct application
  - 3-D application
  - Signal processing

❖ Modern-day Acoustics (Scopes of Acoustics)

- Infrasound :
  - Vibration coupling
  - Effect on Human
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❖ Classification by Sources

- Structure-borne Noise : Vibro-acoustics
- Airborne Noise : Aeroacoustics
- Liquid-borne Noise : Hydro-acoustics

❖ Computational Aeroacoustics (CAA)

- Broad Definition :
  - Hybrid methodology (CFD + acoustic module)
- Narrow Definition :
  - Direct calculation of sound generation and propagation using high-order schemes (low dispersion)

The Nature of Sound

- Sound propagates as a wave
  - 340 m/sec in air
  - 1500 m/sec in water
- Sound transports energy with it, and vibrates our eardrums
- Audible range
  - 20 ~ 20,000 Hz (cycles/sec)
- Sensitive range
  - 1000 ~ 5000 Hz

The Nature of Sound

- Sound source supplies energy (Acoustic power)
  - Human whisper : 10^{-10} watts
  - Human shout : 10^{-5} watts
  - Large jet transport : 10^{5} watts
    = 10^{-5}watts $\times$ 10^{10}(world population)
  - Rocket launch : 10^{7} watts

  - Total acoustic energy during an exciting baseball game
    = energy for frying an egg !! (acoustic energy is usually small)

The Nature of Sound

- Sound is a linear motion
- When a sound wave propagates, it disturbs the fluid from its mean state.
  - $p = p_0 + p'(\boldsymbol{x}, t)$
  - $\rho = \rho_0 + \rho'(\boldsymbol{x}, t)$
  - $\boldsymbol{v} = \boldsymbol{v}(\boldsymbol{x}, t)$
- Viscosity is unimportant in sound waves
  - Stress by pressure $\gg$ Stress by viscosity
  - Ratio of two stress = Reynolds number = $2\pi c\lambda/\nu = \omega\lambda^2/\nu$
  - If long distance propagation is involved, viscosity can be important (after the wave travels about $\omega\lambda^2/\nu$ wavelengths)

The Nature of Sound

- Sound waves are classified as
  - longitudinal waves : a local vibration in gas or liquid
  - transverse waves : string vibration
  - water surface wave (has both longitudinal & transverse components)

- Simple Harmonic Waves
  - Speed(c), Frequency(f), Period(T), Frequency in radian(ω)
  - Wave number(k), Wave length(λ), Particle velocity(u)
  - $T=1/f$, $\lambda=cT=c/f$
  - $\omega=2\pi f=2\pi/T$, $k=\omega/c=2\pi f/c=2\pi/\lambda$
  - $\boldsymbol{u=p'/\rho_0 c}$

❖ Units of Noise

- Description of Sound Strength
  - Power : $W=dE/dt$ (watts)
  - Intensity : $\boldsymbol{I} = dW/d\boldsymbol{A}$ (watts/m^2)
  - Sound energy density

- Sound Power Level (PWL)
  - taken the log scale due to enormous range

$$\mathrm{PWL} = 10\log_{10}\left(\frac{\text{sound power output}}{10^{-10}\ \text{watts}}\right)$$

$$= 10\log_{10}\left(\text{sound power in watts}\right) + 120\,\mathrm{dB}$$

❖ Units of Noise

- Sound Pressure Level (SPL)

$$\text{SPL in dB} = 20\log_{10}\left(\frac{p'_{rms}}{0.0002\,\mu\text{bar}}\right)$$

$$= 20\log_{10}\left(\frac{p'_{rms}}{2\times10^{-5}\,\text{N/m}^2}\right)$$

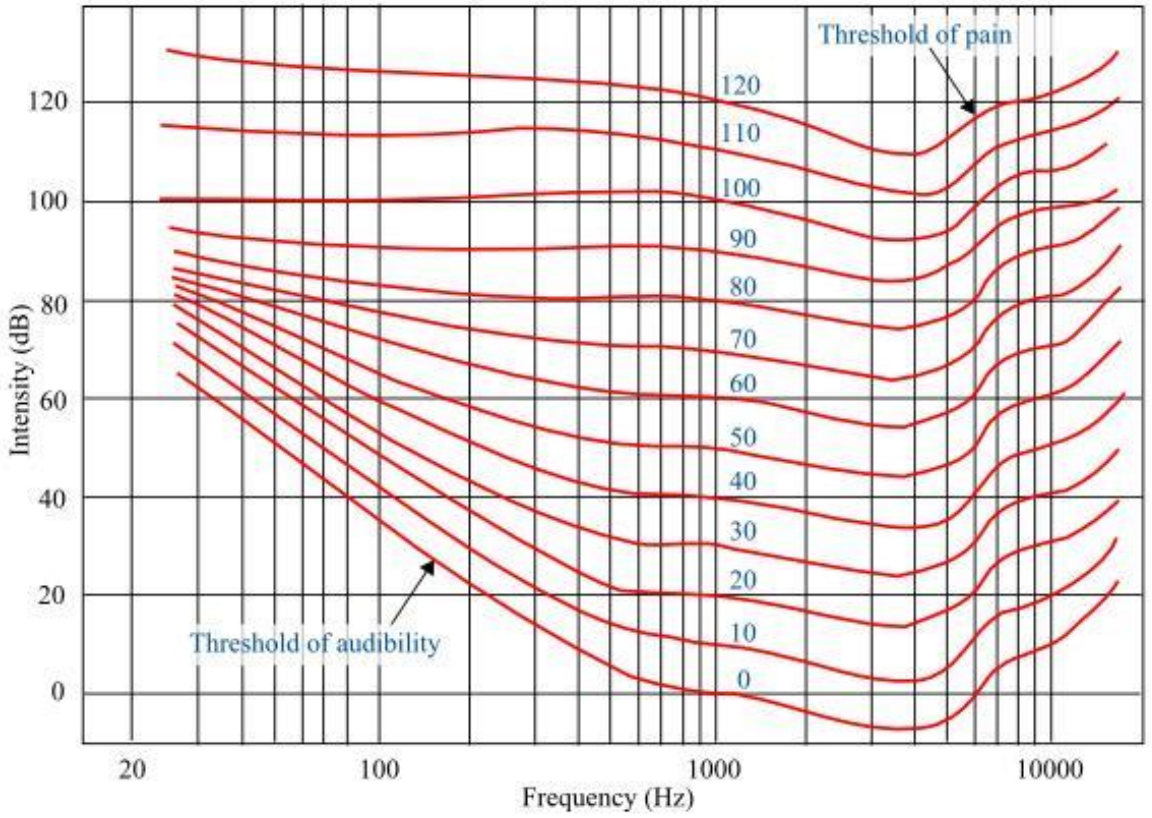
  - 1 atm pressure fluctuation = 194 dB
  - Threshold of pain = 130~140 dB ☞ $p'/p_0 \sim 10^{-3}$
  - Threshold of hearing = 0 dB ☞ $p'/p_0 \sim 10^{-10}$
  - P_{ref} = threshold of hearing

- Sound Intensity Level(IL)
  - IL (L_I) = 10 log10(I/I_{ref}) in dB where $I_{ref} = 10^{-12}$ watts/m^2

❖ Subjective Units of Noise

- Loudness Level (phons)

  : defined as loud as a pure tone of frequency 1kHz



❖ Subjective Units of Noise

- Loudness Level (sones)

  : linear measure of loudness (DL_p=40, DL_s=1)

$$LL_s = 2^{(LL-40)/10}$$

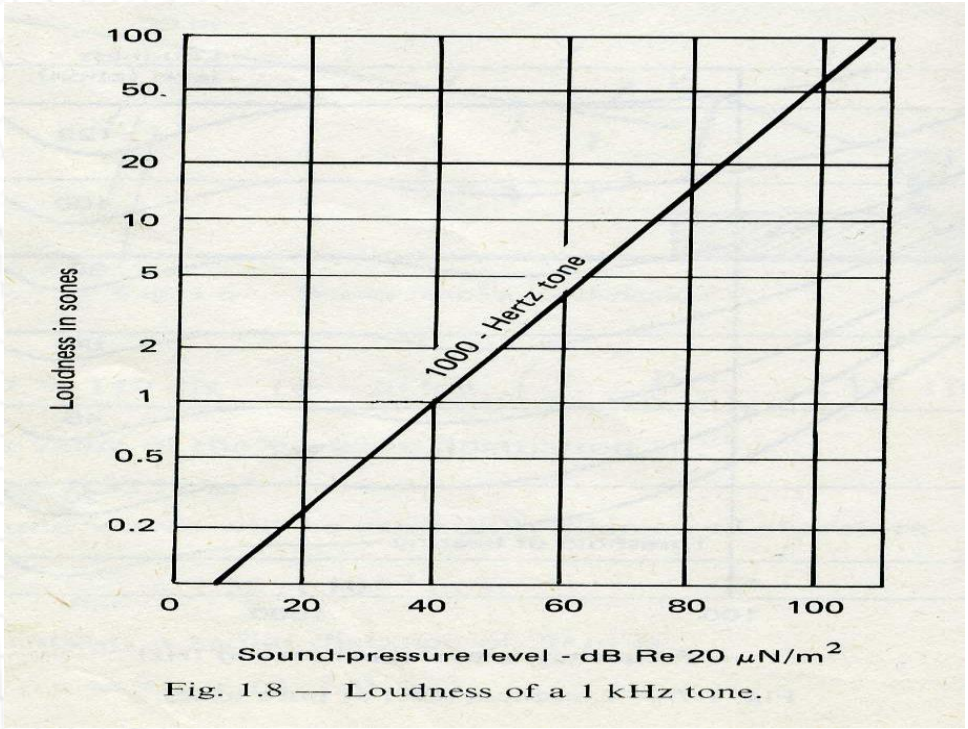
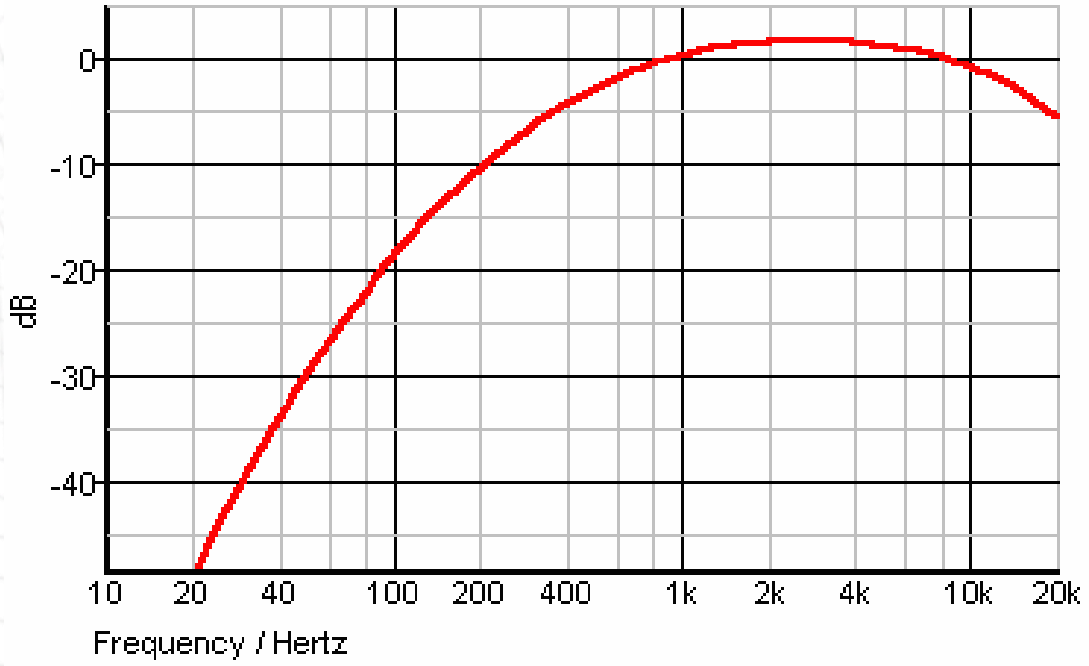


Fig. 1.8 — Loudness of a 1 kHz tone.

❖ Subjective Units of Noise

- 'A-weighting' Sound Pressure Level (dBA)
  - weighting SPL in each frequency level by taking into account the ear's sensitivity. Internationally accepted.

(Note) 'B & C weightings' are rarely used.



Subjective Units of Noise

- Directivity Index (DI) & Q-factor

$$DI = SPL_i - \overline{SPL} = 10 \log_{10} Q$$

- Perceived Noise Level (PNdB) - unit:(noy)
  - mainly for aircraft noise by taking account for high frequency components of jet noise; use different weighting; typically 12-16 dB higher than dB_A

- Effective Perceived Noise Level (EPNL)
  - weighting the pure tones in noise signal (turbo-machinery)

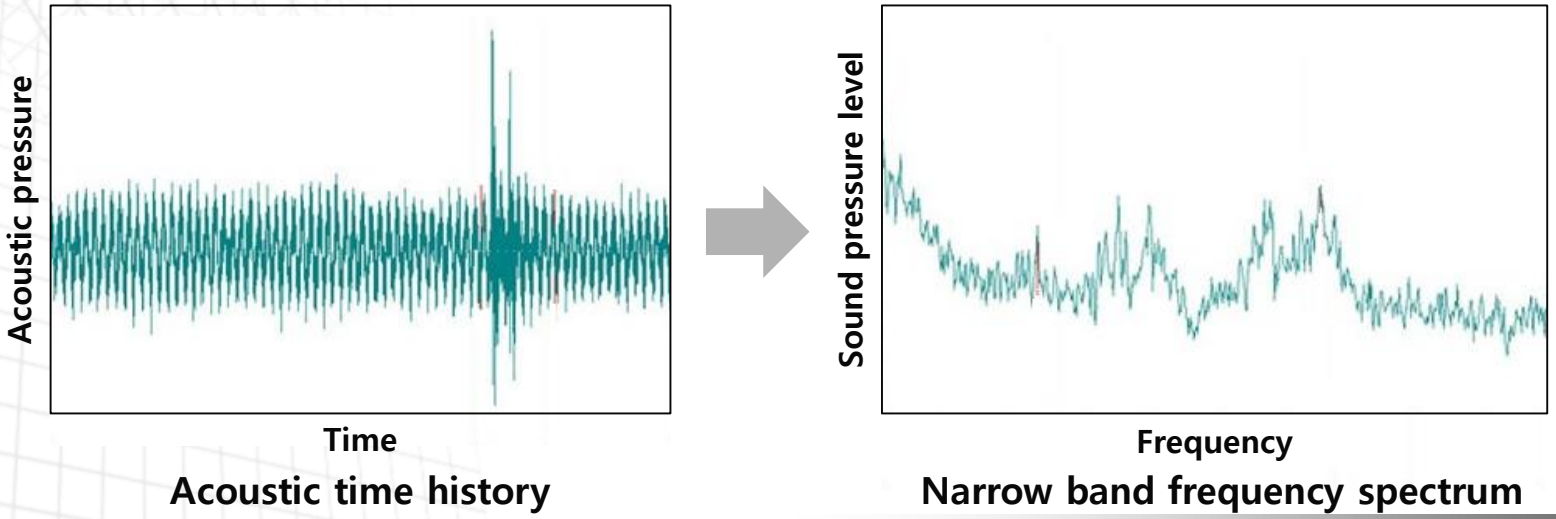
❖ Subjective Units of Noise

- Total Noise Exposure Level (TNEL)
  - consider the number of aircraft.
- Equivalent Continuous Perceived Noise Level (ECPNL)
  - the average of EPNL
- Weighted ECPNL (WECPNL)
  - taking account for the effect of night time. (add 10dB)

❖ Narrow band spectrum

- A narrow band spectrum is the sound source spectrum represented by very small bandwidth and high resolution.

- It is usually obtained by using FFT (Fast Fourier Transform) from an acoustic time history.



❖ Octave / One-third octave band spectrum

- In Engineering applications, the sound source spectrums are usually represented in octave or one-third octave frequency bands.

- An octave refers to the interval between one frequency and its double or its half

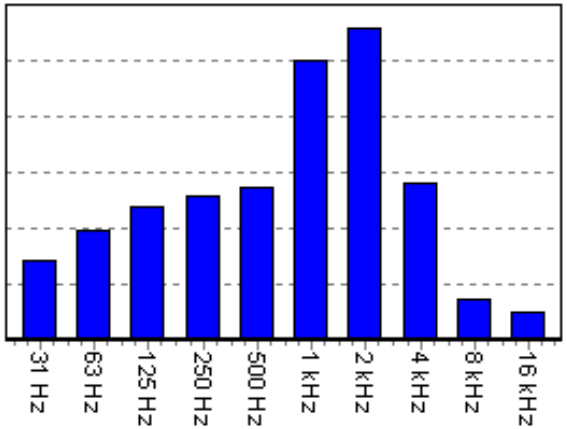
- Center frequency : $f_c = \sqrt{f_u f_l}$

- Bandwitdth : $f_u - f_l$ where $f_u = 2^m f_l$ for an m-octave band

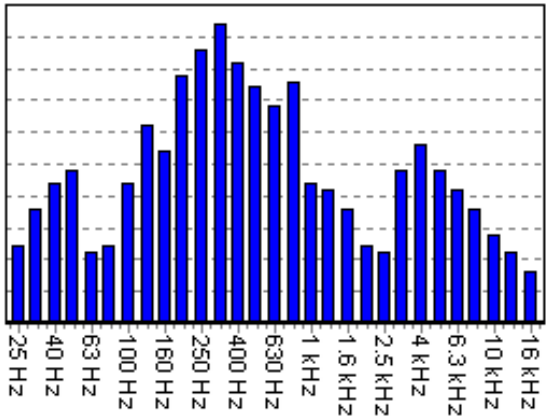
❖ Octave / One-third octave band spectrum

- Ten octave bands are commonly used in the octave band analysis : 31.5, 63, 125, 250, 500, 1k, 2k, 4k, 8k and 16kHz

- In the one-third octave band analysis, octave band is split into three, giving a more detailed description of the frequency content of the noise.



Octave band spectrum



1/3 octave band spectrum

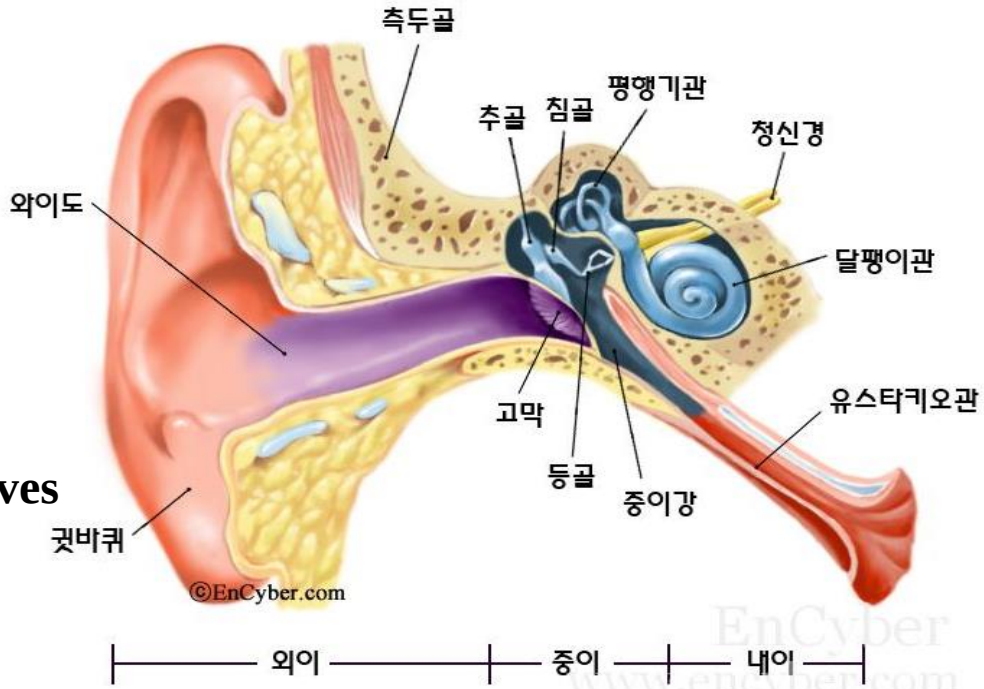
❖ Structure of Ear

1. 외이(外耳) : collecting sound

- 외이도 : 직경 약 10mm, 길이 약 27mm로 일종의 공명기 역할. Resonant frequency는 3kHz.

2. 중이(中耳) : Amplification of waves

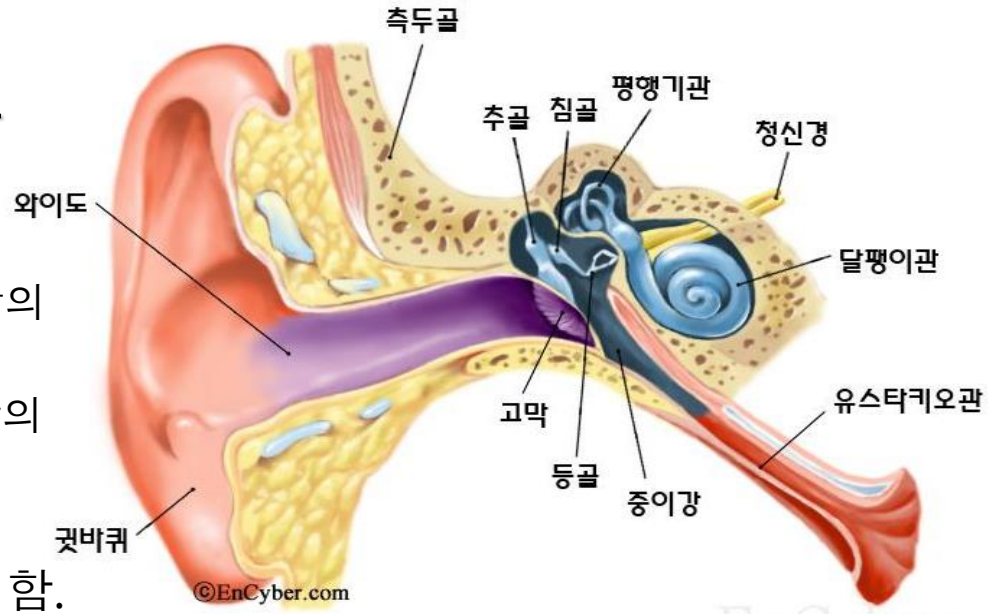
- 고막 : 두께 약 0.1mm, 실효면적 약 0.3~0.5cm2
- 청소골 : 망치뼈, 모두뼈, 등자뼈로 구성되어 고막에 전달된 음압을 약 20배 증폭

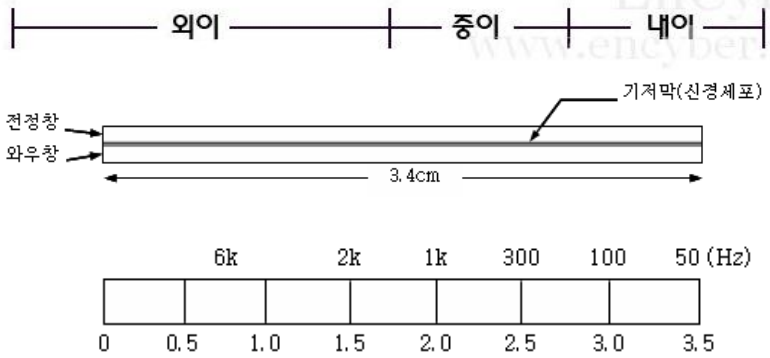


❖ Structure of Ear

3. 내이(內耳) : 소리를 분석하고 분석된 소리를 뇌로 전달

- 달팽이관
  - Amplitude of sound : 기저막의 진동 크기
  - Frequency of sound : 기저막의 진동 위치
- Eustachian tube : 기압조정, 목과 연결, 진동을 용이하게 함. Large vibration은 근육이 수축하여 damping

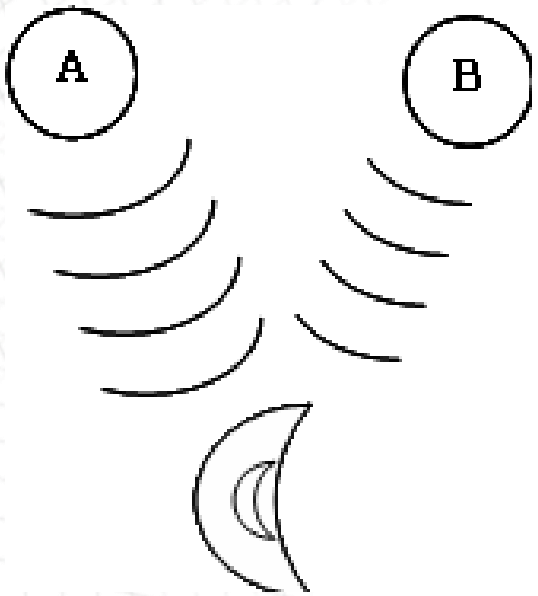


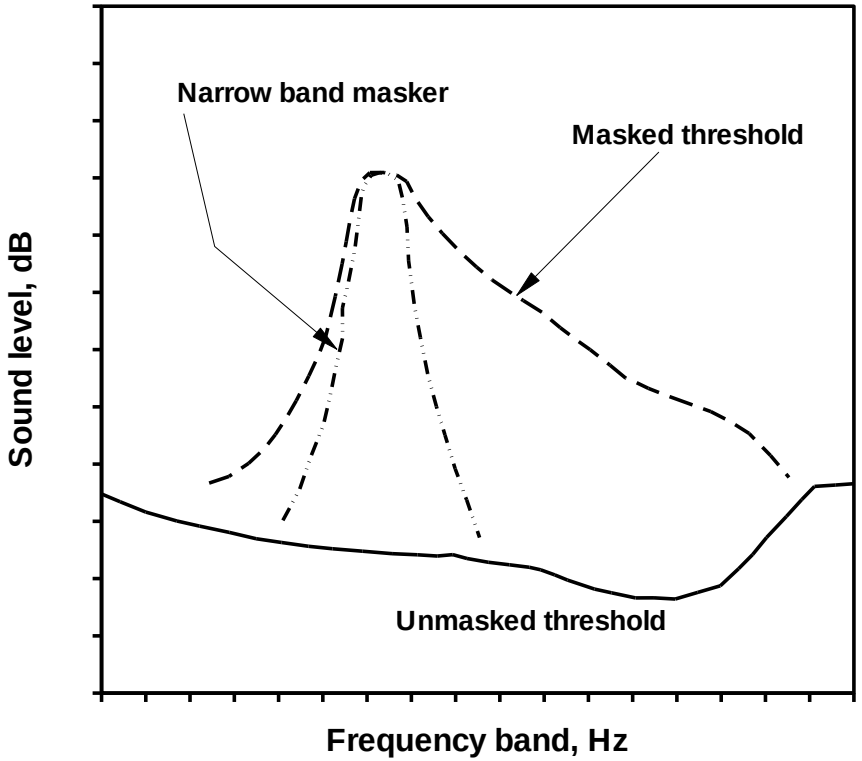


❖ Masking effect

- ‘B’ sound is masked by sound ‘A’

  → Physiological effect by increasing the threshold of hearing



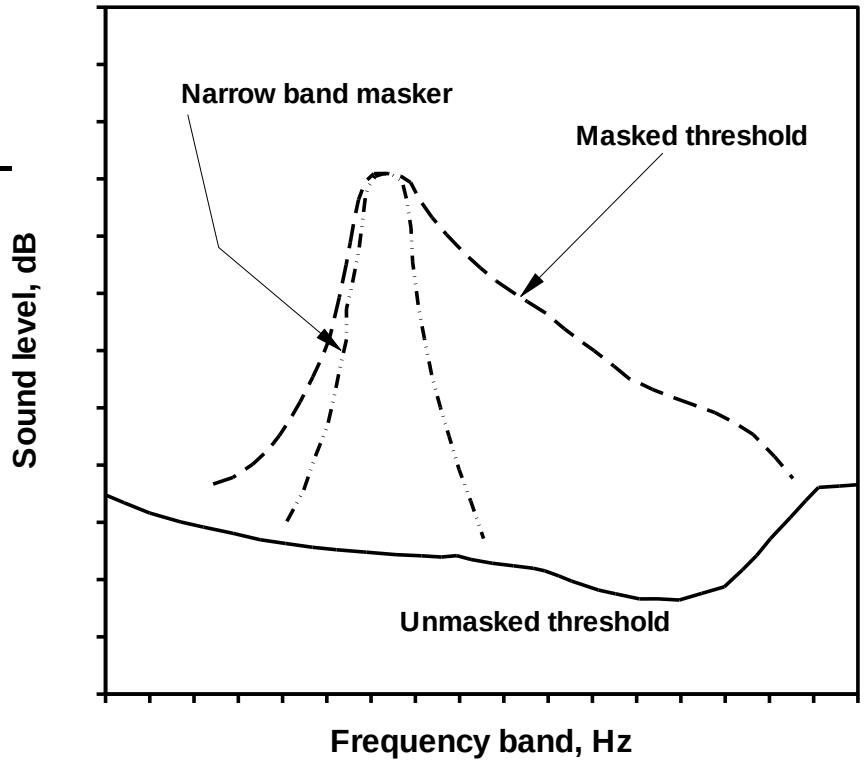


❖ Masking effect

- Generally masking has a bad effect. If you utilize BGM(Back Ground Music), you can mask the noise.

- If a person stays too long at very silent place, he/she will come unstable psychologica-lly.

  → A little bit of noise is good for human



❖ Influence of Noise

- Definition

  : Noise is unpleasant sound

- TTS & PTS : serious at 3-6 kHz
  - TTS (noise-induced temporary threshold shift):
  - PTS (noise-induced permanent threshold shift):
  - Measurement of hearing level : Audiometer
  - ISO standard : 10-15 dB normal, 25dB or higher PTS
- NER (Noise Exposure Rating)
- SIL (Speech Interference Level)

❖ Influence of Noise

- Infrasound (<16 Hz)
  - Tides, earthquakes, thunder, AirCon, Jet Aircraft ...
  - Make people sleepy & tired, Potential weapon
- Ultrasound (>20kHz)
  - Jet engine, High-speed drill, Washing machine
  - Medical Purpose, should be < 105 dB (EPA)
- Sonic Boom
  - N-wave, Boom carpet, Rising time (0.1~16 ms)
  - Should be less than 55 dB (EPA)

Three-dimensional wave equation

- **Sound waves are classified as**
  - Longitudinal waves – a local vibration in gas or liquid
  - Transverse waves – string vibration
  - Water surface wave (has both longitudinal & transverse components)