Power and Intensity

- The waveform shows how sound pressure varies over time.
- Related to sound pressure are:
  1. **sound power** emitted by the source:
     - a fixed quantity, in Watts (W),
     - analogous to the wattage rating of a light bulb.
  2. **sound intensity** measured a distance from the source:
     - power per unit area carried by wave (W/m$^2$),
     - influenced by interference and environment,
     - analogous to light brightness at different positions in a room.

Intensity and Pressure

- **Intensity** is the power per unit area,
  
  \[ \text{Intensity} = \frac{\text{Power}}{A}, \]

  expressed in Watts/square meter (W/m$^2$).

- **Sound intensity** is
  - a measure of the power in a sound that actually contacts an area (e.g. eardrum);
  - a quantity influenced by environment surroundings/surfaces and interference from other sources;

- Intensity is related to pressure squared:
  
  \[ I = \frac{p^2}{\rho c}, \]

  where $\rho$ is the density of air (kg/m$^3$), and $c$ is the speed of sound (m/s).

Sound Range of Hearing

- Amplitude (pressure) range of hearing (humans)
  - Threshold of audibility: $0.00002$ N/m$^2$
  - Threshold of feeling (or pain!): $200$ N/m$^2$

- Sound intensity range (humans)
  - $I_0 = 10^{-12}$ W/m$^2$ (threshold of audibility)
  - $1$ W/m$^2$ (threshold of feeling)

- The intensity ratio between the sounds that bring pain to our ears and the weakest sounds we can hear is more than $10^{12}$. 
Linear vs logarithmic scales.

- Human hearing is better measured logarithmically.
- On a linear scale,
  - a change between two values is perceived on the basis of the difference between the values;
  - e.g.: a change from 1 to 2 would be perceived as having the same increase as from 4 to 5.
- On a logarithmic scale,
  - a change between two values is perceived on the basis of the ratio of the two values;
  - e.g.: a change from 1 to 2 would be perceived as having the same increase as a change from 4 to 8.
- Linear: moving one unit to the right adds 1.
- Logarithmic: moving right one unit multiplies by 10.

### Decibels (dB)

- The decibel (dB) is a unit named after telecommunications pioneer, Alexander Graham Bell.
- To understand decibels DON’T watch.
- The decibel is a logarithmic scale, used to compare two quantities such as
  - the power gain of an amplifier;
  - the relative power of two sound sources.
- A decibel is defined as one tenth of a bel,
  
  \( 1 \text{ B} = 10 \text{ dB} \)
  
  (to convert from B to dB, multiply by 10)
- To compare quantities A and B:
  
  \[
  \log_{10} \left( \frac{A}{B} \right) = \text{value (B)}
  \]
  
  \[
  10 \log_{10} \left( \frac{A}{B} \right) = \text{value (dB)}
  \]

### Comparing Power and Intensity

- The decibel difference between two power levels \( \Delta L \) is defined in terms of their power ratio \( W_2/W_1 \):
  
  \[
  \Delta L = L_2 - L_1 = 10 \log \frac{W_2}{W_1} \quad \text{dB}
  \]
- Since power is proportional to intensity, the decibel difference between two levels with intensities \( I_1 \) and \( I_2 \) is given by
  
  \[
  \Delta L = L_2 - L_1 = 10 \log \frac{I_2}{I_1} \quad \text{dB}
  \]

### Power and Intensity Levels

- Decibels are often used as absolute measurements.
- There is an implied fixed reference (e.g. the threshold of audibility).
- Sound power level of a source:
  
  \[
  L_W = 10 \log \left( \frac{W}{W_0} \right) \quad \text{dB}
  \]
  
  where \( W_0 = 10^{-12} \text{ W} \).
- Sound intensity level at a distance from the source
  
  \[
  L_I = 10 \log \left( \frac{I}{I_0} \right) \quad \text{dB}
  \]
  
  where \( I_0 = 10^{-12} \text{ W/m}^2 \).
Sound pressure Level (SPL or $L_p$)

- Recall: intensity is proportional to pressure squared:
  \[ I = \frac{p^2}{(\rho c)} \]
  (where $\rho c \approx 400$).
- The sound pressure level $L_p$ (SPL) is equivalent to sound intensity level in dB:
  \[
  L_p = 10 \log \frac{I}{I_0}
  = 10 \log \frac{p^2}{(\rho c I_0)}.
  \]
- The product of $\rho$ and $c$ is often approximated by 400:
  \[
  L_p = 10 \log \frac{p^2}{(400 I_0)}
  = 10 \log \left( \frac{p}{2 \times 10^{-5}} \right)^2
  = 20 \log \frac{p}{2 \times 10^{-5}}
  = 20 \log \left( \frac{p}{p_0} \right) \text{ dB},
  \]
  where $p_0 = 2 \times 10^{-5}$ is the threshold of hearing for pressure variations.

Sound Intensity Level with a Doubling of Distance

- How does the sound level change with a doubling of distance?
  - intensity will drop by a factor of $1/2^2$ or $2^{-2}$ and
    \[
    L_I = 10 \log \left( \frac{I}{I_0} \right)^{2^{-2}}
    = 10 \log \left( \frac{I}{I_0} \right) + 10 \log(2^{-2})
    = 10 \log \left( \frac{I}{I_0} \right) - 20 \log(2)
    = 10 \log \left( \frac{I}{I_0} \right) - 20(.3)
    = 10 \log \left( \frac{I}{I_0} \right) - 6 \text{ dB}.
    \]
    - doubling the distance from a source causes a decrease of $6$ dB in the sound level.

Increasing distance from a source

- Assuming radiation in free space (and equally in all directions) and a distance $r$ from the source,
  - intensity decreases by $1/r^2$

- Question: If there is a doubling of distance from the source, by what factor will the intensity change?
- Solution:
  - Given an intensity at some initial distance:
    \[
    I_1 = \frac{P}{4\pi r^2},
    \]
  - doubling the distance from the source yields,
    \[
    I_2 = \frac{P}{4\pi (2r)^2} = \frac{P}{2^2 4\pi r^2} = \frac{1}{2^2} I_1,
    \]
    a change in intensity by a factor of of $1/2^2$.

SPL with a Doubling of Distance

- We should obtain the same result for pressure as with intensity.
- If intensity decreases by $1/r^2$,
  - pressure decreases by $1/r$,
  - (intensity is proportional to pressure squared).
- With a doubling of distance, pressure will drop by a factor of $1/2$ or $2^{-1}$,
  \[
  L_p = 20 \log \left( \frac{P}{p_0} \right)^{2^{-1}}
  = 20 \log \left( \frac{P}{p_0} \right) - 20 \log(2)
  = 20 \log \left( \frac{P}{p_0} \right) - 6 \text{ dB}.
  \]
Multiple sources

- When there are multiple sound sources, the total power emitted is the sum of the power from each source.
- By how much would the sound level increase when two sources sound simultaneously with equal power?
  - the sound power level would double, 
  \[ L_W = 10 \log \left( \frac{2W}{W_0} \right) \]
  \[ = 10 \log \left( \frac{W}{W_0} \right) + 10 \log(2) \]
  \[ = 10 \log \left( \frac{W}{W_0} \right) + 3 \text{ dB}, \]
  and there would be an increase of 3 dB.
- Similarly, there would be a 3 dB increase in the sound intensity level measured at some distance away from the source.
- This accounts for most cases; the actual result depends on correlation (and interference) of sound sources.

Example SPL Levels

- The following is taken from Dan Levitin’s, Your Brain on Music.
  - 0 dB: a mosquito flying in a quiet room, ten feet away from your ears
  - 20 dB: a recording studio
  - 35 dB: a typical quiet office with the door closed and computer off
  - 50 dB: typical conversation
  - 75 dB: typical comfortable music listening level (headphones)
  - 100-105 dB: Classical music concert during loud passages; the highest level of some portable music players
  - 110 dB: A jackhammer 3 feet away
  - 120 dB: A jet engine heard on the runway from 300 ft away; typical rock concert
  - 126-130 dB: Threshold of pain and damage; a rock concert by the Who
  - 180 dB: Space shuttle launch