Music 175: Sound Level

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Pressure, Power and Intensity

- The waveform of **sound** shows the time evolution of the *pressure* variations—its amplitude.
- Related to sound pressure are the
  1. sound **power** emitted by the source
  2. sound **intensity** measured some distance from the source.
- **Power**:
  - Watts (W) or Joules [1]/second (J/s),
  - equivalent to the amount of energy consumed per unit of time.
- **Sound power** is analogous to the wattage rating of a light bulb—**it's a fixed quantity**.

[1](Joule = force × distance)

Intensity

- **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;
  - analogous to the brightness of the light in a particular part of the room.

- Intensity is **related to pressure squared**:

$$I = p^2/(\rho c),$$

where ρ 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 on a *logarithmic* scale than a *linear* scale.
- 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 the same amount of 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 the same amount of increase as a change from 4 to 8 (also a ratio of 1:2).

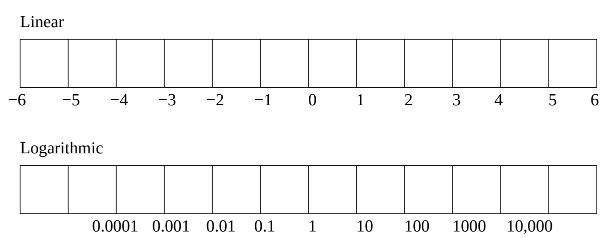

Figure 1: Moving one unit to the right increments by 1 on the linear scale and multiplies by a factor of 10 on the logarithmic scale.

Decibels

- The decibel (dB) is a unit named after Alexander Graham Bell, known as a telecommunications pioneer.
- 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 Bel to dB, multiply by 10.

- The decibel difference between two power levels ΔL is defined in terms of their power ratio W_2/W_1:

$$\Delta L = 10 \log W_2/W_1 \quad \text{dB}.$$

- Since power is proportional to intensity, the ratio of two signals with intensities I_1 and I_2 is given in decibels by

$$\Delta L = 10 \log I_2/I_1 \quad \text{dB}.$$

Sound Power and Intensity Level

- Though decibels are often used as absolute measurements, there is an *implied fixed reference*.
- The **sound power level** of a source is expressed using the threshold of audibility $W_0 = 10^{-12}$ as a reference:
$$L_W = 10 \log W/W_0 \text{ dB}.$$
- The **sound intensity level** (SIL) at some distance from the source can be expressed in dB by comparing it to the reference $I_0 = 10^{-12}$ W/m^2:
$$L_I = 10 \log I/I_0 \text{ dB}.$$

Sound pressure Level (SPL or L_p)

- Intensity is proportional to sound pressure amplitude squared
$$I = p^2/(\rho c),$$
where $\rho c \approx 400$.

- For a plane wave travelling down a tube or spherical wave traveling outward from a source (when $\rho c = 400$):
$$L_p = L_I.$$

- This can be used to express SPL in dB by:

$$\begin{aligned} L_p &= 10 \log I/I_0 \\ &= 10 \log p^2/(\rho c I_0) \\ &= 10 \log p^2/(4 \times 10^{-10}) \\ &= 10 \log \left(p/(2 \times 10^{-5})\right)^2 \\ &= 20 \log p/(2 \times 10^{-5}) \\ &= 20 \log p/p_0 \text{ dB.} \end{aligned}$$

where $p_0 = 2 \times 10^{-5}$ is the threshold of hearing for amplitude of pressure variations.

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

Increasing distance from a source

- A *point source* is one from which a spherical wave radiates in *free space* (equally in all directions) and in which:
  - the intensity decreases by $1/r^2$ with an increase in radius r (the surface area of a sphere is $4\pi r^2$)
  - the pressure decreases by $1/r$ (since pressure is proportional to the square root of intensity).
- In actual practice, sound sources wouldn't radiate so symmetrically as there is likely to be interference from other reflective objects.

SIL at a Distance from the Source

- **Problem**: Given the sound power level at a source, what is the SIL at a distance 1 m from that source in free field?
- **Solution**:
  - When a given amount of sound power is distributed over the surface of an expanding sphere, the intensity is
$$I = \frac{W}{4\pi r^2}.$$
  - The itensity at 1 m from the source is given by
$$I = \frac{W}{4\pi r^2} = \frac{W}{4\pi}.$$
  - The corresponding SIL is
$$\begin{aligned} L_I &= 10\log\frac{I}{10^{-12}} = 10\log\frac{W}{4\pi 10^{-12}}, \\ &= 10\log\frac{W}{10^{-12}} - 10\log(4\pi) \\ &= L_W - 11, \end{aligned}$$

    or 11 dB less than the sound power level at the source.

Sound Level with a Doubling of Distance

- **Problem**: How does the SIL change with a doubling of distance?
- **Solution**:
  - We know that the intensity will drop by $1/r^2$ which is a factor of $1/2^2$ for a doubling of distance. Thus,

$$\begin{aligned} L_I &= 10\log(\frac{1}{2^2} \times \frac{I}{I_0}) \\ &= 10\log(I/I_0) + 10\log(1/2^2) \\ &= \text{SIL} - 10\log(2^2) \\ &= \text{SIL} - 20\log(2) \\ &= \text{SIL} - 6, \end{aligned}$$

corresponding to a decrease of 6 dB.

Multiple Sources

- When there are multiple *independent* sound sources, the total power emitted is the *sum* of the power from each source.
- **Problem**: By how much would the sound level increase when two independent sources with equal power sound simultaneously?
- **Solution**:
  - The sound power level (at the source) would double, yielding the sound power level

$$\begin{aligned} L_W &= 10\log(2W/W_0) \\ &= 10\log(W/W_0) + 10\log(2) \\ &= 10\log(W/W_0) + 3 \text{ dB}, \end{aligned}$$

    which corresponds to an increase of 3 dB.
- This is the case most of the time. However, there is an exception...

Multiple Correlated Sound Sources

- If the sound sources emit waveforms that are strongly *correlated*, there will be *interference*.
- When two waves of the same frequency reach the same point, they may interfere *destructively* or *constructively*.
- The resulting overall amplitude can be anywhere from
  - 0 (complete *destructive* interference) to
  - the sum of the individual amplitudes (complete *constructive* interference).

Complete Constructive Interference

- Summing two in-phase sinusoids at the same frequency and amplitude doubles the pressure, yielding

$$\begin{aligned} SPL &= 20 \log \frac{2p}{p_0} \\ &= 20 \log \frac{p}{p_0} + 20 \log(2) \\ &= 20 \log \frac{p}{p_0} + 6, \end{aligned}$$

  which is an increase of 6 dB.

Listening to Sound Level's

- db.pd
- What does an increase in 1 dB sound like? (not much impact)
- A 6 dB difference (a factor of 4 in power or 2 in pressure) is easy to hear, but would not have a tremendous musical impact.

Loudness Level and Frequency

- Loudness is a subjective quality that depends on SPL, but also on frequency and other factors.
- Dependency on frequency is shown by Fletcher and Munson's **equal loudness curves**: the required SPL for different frequencies to sound equally loud.

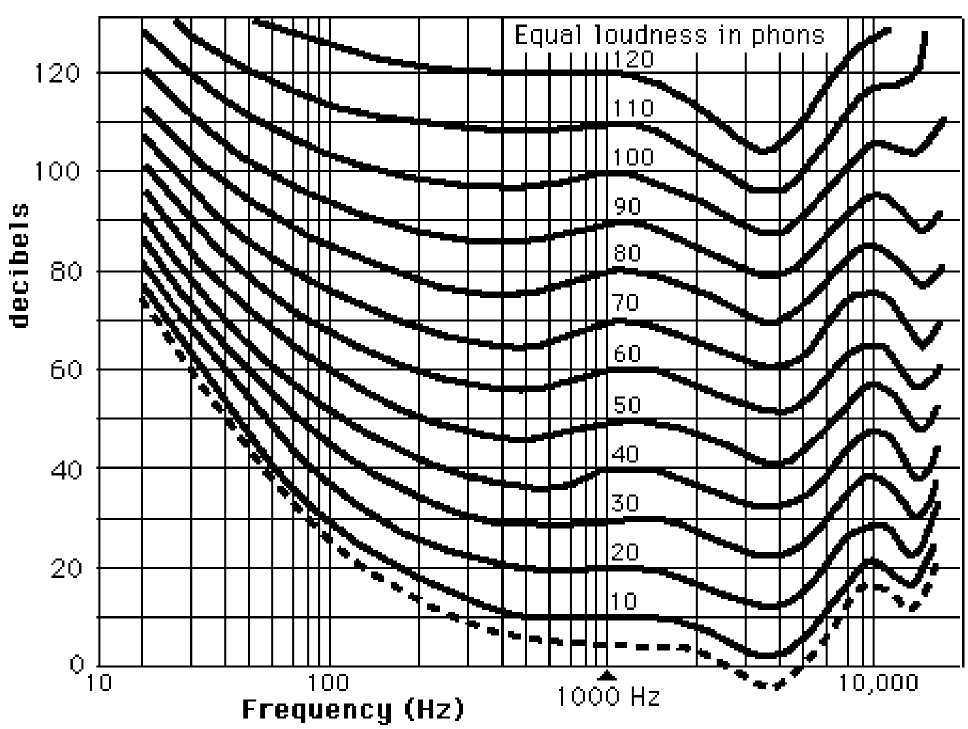

Figure 2: Equal-loudness curves for pure tones (expressed in phons).

- The equal-loudness curves are expressed in **phons**:

$$\text{phon} \triangleq \text{SPL in dB at a frequency of 1000 Hz.}$$