PHY 103: Loudness and Amplification

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Reading

- Heller, Ch. 7
- Fletcher and Rossing, Ch. 9 and 12 (advanced)
Midterm Exam

‣ In class, Thursday October 20

‣ Will be largely conceptual with some basic arithmetic and logarithms

‣ Topics:
  • Properties of waves
  • Normal modes of strings and air columns
  • Scales and tuning systems
  • Loudness and amplification
Need for Amplification

- Instruments produce sound by vibrating some element (a string, a drumhead, a reed, your lips, …)

- There is typically very little energy in this vibration

  - For plucked string, total energy is \( E = \frac{1}{4} \mu \omega_n^2 A_n^2 L \)
  
  - First E string on a guitar: \( \omega_1 = 2\pi \times 329.63 \text{ Hz} \)
  
  - \( \mu = 0.4 \text{ g/m} \)
  
  - \( L = 0.6 \text{ m}, A = 3 \text{ mm} \)
  
  - Energy is about 2 mJ. Energy required to lift an apple (100 g) vertically by 1 meter against gravity: 1 J
Amplification

- In order to actually hear an instrument and project its sound we have to amplify it.
- Acoustic resonators have been used for thousands of years for this purpose.
- Now we can couple instruments to electroacoustic transducers, amplifiers, and loudspeakers.
- Before we get into acoustic amplification, let’s talk about sound power (a physical quantity) and loudness (a perceived quantity)…
Relative Power: dB

- **Energy** in an oscillating wave: $E \sim A^2$ [Joules]
- **Power**: $P = \text{energy per unit time}$ [Joule/sec = Watts]
- **Intensity**: $I = \text{power per unit area}$ [W/m$^2$]
- **Relative sound level** between two sounds is given in decibels [dB]
  - Sound 1 has power $P_1$ and sound 2 has power $P_2$
  - Relative difference: $10 \log(P_2 / P_1)$ dB
  - $P_2 = 2 \, P_1 \rightarrow 10 \log 2 = 3$ dB difference
The Decibel Scale

- Sample: noise decreased in steps of 6 dB
- Sample: noise decreased in steps of 3 dB
- Sample: speaker moving away from microphone. The sound intensity decreases as $1/r^2$, where $r$ is the distance to the microphone.

Image from hyperphysics

Samples from Auditory Demonstrations by Houtsma, Rossing, and Wagenaars
Time-Averaged Power

- Note: when we talk about power in this context, we don’t mean the instantaneous power at one time $t$

- We are talking about the **time-averaged power** of an oscillating pressure wave

\[ p(t) = A \cos(\omega t) \]

\[ P(t) \propto p(t)^2 \]

\[ \langle P_{\text{avg}} \rangle = \frac{1}{\tau} \int_{0}^{\tau} P(t) \, dt \propto \frac{1}{\tau} \int_{0}^{\tau} A^2 \cos^2(\omega t) \, dt = \frac{A^2}{2} \]

\[ \propto P_{\text{max}} / 2 \]
Sound Intensity Reference

- Decibels measure a relative power (or intensity) ratio between two sounds

- So when we talk about a sound being 60 dB (for example), what is the reference point we are using?

- Remember that sound corresponds to pressure variations propagating through air in longitudinal waves

- Reference point: \( p_0 = 0.02 \, \mu\text{Pa} \) or about \( 2 \times 10^{-10} \, \text{atm} \)

- So you can think of dB as the amplitude variation of sounds (in pressure) relative to this reference point

  - sound level = \( 10 \log(p / p_0)^2 = 20 \log(p / p_0) \) dB
# Power of Common Sounds

<table>
<thead>
<tr>
<th>Sound Source</th>
<th>Sound Level</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hearing threshold</td>
<td>0 dB</td>
<td>1 pW/m²</td>
</tr>
<tr>
<td>Whispering in library, 2 m distance</td>
<td>30 dB</td>
<td>1 nW/m²</td>
</tr>
<tr>
<td>Normal conversation, 1 m distance</td>
<td>60 dB</td>
<td>1 μW/m²</td>
</tr>
<tr>
<td>City traffic noise inside a car</td>
<td>85 dB</td>
<td></td>
</tr>
<tr>
<td><strong>Hearing loss threshold (sustained exposure): 90 dB</strong></td>
<td></td>
<td>1 mW/m²</td>
</tr>
<tr>
<td>Jackhammer at 20 m distance</td>
<td>95 dB</td>
<td></td>
</tr>
<tr>
<td>Hand drill</td>
<td>98 dB</td>
<td></td>
</tr>
<tr>
<td>Power mower</td>
<td>107 dB</td>
<td></td>
</tr>
<tr>
<td>Rock concert</td>
<td>115 dB</td>
<td></td>
</tr>
<tr>
<td><strong>Pain threshold: 120 dB</strong></td>
<td></td>
<td>1 W/m²</td>
</tr>
<tr>
<td>Pneumatic riveter at 1 m</td>
<td>125 dB</td>
<td></td>
</tr>
<tr>
<td><strong>Permanent damage threshold (short exposure)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet engine at 30 m</td>
<td>140 dB</td>
<td>100 W/m²</td>
</tr>
<tr>
<td>12 gauge shotgun blast</td>
<td>165 dB</td>
<td></td>
</tr>
<tr>
<td>Death of hearing tissue</td>
<td>180 dB</td>
<td>1 kW/m²</td>
</tr>
<tr>
<td>Loudest undistorted sound at 0C, 1 atm</td>
<td>194 dB</td>
<td></td>
</tr>
</tbody>
</table>

From gcaudio.com
What Happens >194 dB?

- 194 dB corresponds to a pressure amplitude of 1 atm
- Sound levels >194 dB require sound pressures >1 atm
- Sound waves become distorted (like a shock wave), with valleys clipped at 0 Pa (vacuum)
# Sound Safety

- **OSHA guidelines for sound level exposure:**

<table>
<thead>
<tr>
<th>Sound Level [dB]</th>
<th>Power/Intensity difference</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>—</td>
<td>8 hr/day</td>
</tr>
<tr>
<td>92</td>
<td>1.58</td>
<td>6 hr/day</td>
</tr>
<tr>
<td>95</td>
<td>3.16</td>
<td>4 hr/day</td>
</tr>
<tr>
<td>97</td>
<td>5.01</td>
<td>3 hr/day</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>2 hr/day</td>
</tr>
<tr>
<td>102</td>
<td>15.85</td>
<td>90 min/day</td>
</tr>
<tr>
<td>105</td>
<td>31.62</td>
<td>60 min/day</td>
</tr>
<tr>
<td>110</td>
<td>100</td>
<td>30 min/day</td>
</tr>
<tr>
<td>115</td>
<td>316.23</td>
<td>&lt;15 min/day</td>
</tr>
</tbody>
</table>

**Q: how did I go from dB to intensity difference?**
Combining Sound Levels

Suppose you have a 70 dB speaker and you add a second 70 dB speaker. How loud is the combined set?

Consider two possible cases:

1. Coherence: signals have same frequency and are in phase
2. Incoherence: signals have different frequencies
Combining Sound Levels

- If the speakers are in phase (coherent) where you are sitting, then the amplitudes of the waves add.

- Power ~ Energy ~ Amplitude$^2$

  \[
  p(t) = A \cos(\omega t)
  \]
  \[
  P(t) \propto [p(t) + p(t)]^2
  \]
  \[
  = 4 A^2 \cos^2(\omega t)
  \]

  \[
  \langle P_{\text{avg}} \rangle = \frac{1}{\tau} \int_0^\tau P(t) dt = \propto 2 A^2
  \]

- Average power is 4x the power of one signal ($A^2/2$)
Combining Sound Levels

- If the two speakers aren’t playing the same frequency, they are incoherent and the calculation changes.

- Remember that we’re dealing with time-averaged power when we combine the signals:

\[ p_1(t) = A \cos(\omega t), \quad p_2(t) = A \cos(\Omega t) \]

\[ P(t) \propto [p_1(t) + p_2(t)]^2 \]

\[ = A^2 \cos^2(\omega t) + A^2 \cos^2(\Omega t) + 2A \cos(\omega t) \cos(\Omega t) \]

- Time average: \( A^2/2 \)
- Time average: \( A^2/2 \)
- Time average: 0

\[ \left< P_{\text{avg}} \right> \propto A^2 \quad \text{2x the power of 1 signal alone} \]
Combining Sound Levels

- Coherent case:
  - Difference in sound level = \(10 \log (4) = 6 \text{ dB}\)
  - Therefore, the total sound power of the two speakers is \(70 \text{ dB} + 6 \text{ dB} = 76 \text{ dB}\)

- Incoherent case:
  - Difference in sound level = \(10 \log (2) = 3 \text{ dB}\)
  - Therefore, the total sound power of the two speakers is \(70 \text{ dB} + 3 \text{ dB} = 73 \text{ dB}\)
Loudness Perception

- dB gives us an objective measurement of sound level power, but we don't perceive loudness equally at all frequencies.

![Diagram showing equal-loudness contours](image)

- Equal-loudness contours (red) (from ISO 226:2003 revision)
- Original ISO standard shown (blue) for 40-phoniers

frequency [Hz]
dB and Phons

- **Phon**: psychophysical loudness measure
- At 1 kHz, phon scale = dB
- Everywhere else, phons are tuned to subjective response
- Equal-loudness curve: at a given frequency, what dB sound produces same loudness w.r.t. 1 kHz?
- We have a strong frequency-dependent response to sounds
Amplification by Reflection

- If you hold a sound source next to a wall, the waves will be reflected off the wall back at you.
- You can get amplification, as if there were a second source behind the wall.

From Why You Hear What You Hear, E. Heller
Reflection from a Corner

- If wavelength is large compared to the distance between the source and its $N-1$ images, the power in the physical region goes up by $N^2$. 
Reflection from a 30° Wedge
Amplification: the Guitar

- A guitar is a fretted board of strings coupled to two flat vibrating panels

From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing
Soundboard Bracing

- Designs for bracing a guitar soundboard: Torres, Bouchet (France), Ramirez (Spain), crossed bracing

- Bracing affects the vibrational modes of the board

From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing
Guitar Schematic

- Different pieces of the guitar resonate in different frequency regimes

From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing
Guitar Plate Modes

Vibrational modes of a guitar plate blank without braces

Lines = nodes
Gaps = antinodes

From The Physics of Musical Instruments, N. Fletcher and T. Rossing
Effect of Braces

- Vibrational modes of guitar top plate with traditional fan bracing

From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing
Full Guitar Modes

- The whole guitar cavity has vibrational modes that are combinations of the modes of the plates and sides put together.

From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing
The Piano

- The piano also uses an acoustic resonator: the **soundboard**

![Diagram of a piano](image)

- The soundboard opposes the vertical components of the string tension (lots of force: 20 N per string)
- Acoustically, it’s also the main **radiating component**

*From* *The Physics of Musical Instruments*, N. Fletcher and T. Rossing
Upright Piano Soundboard

- An upright piano has a vertically oriented rectangular soundboard

- Frame members restrict the vibrations to a trapezoidal section where the bridges run diagonally

From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing
Upright Piano Modes

Vibrational modes of the upright piano soundboard

Lines = nodes
Gaps = antinodes

From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing
Rectangular Membrane Modes

1,1 mode

1,2 mode

2,1 mode

2,2 mode

Courtesy Dan Russell, Grad. Prog. in Acoustics, PSU
Horns

From *Why You Hear What You Hear* by Eric Heller
Horns

- Horns are built in a cone + bell shape, usually with the width of the cone growing exponentially towards the end of the bell

- The narrow end of the horn “loads the source”
  - Lots of constructive interference of certain wavelengths
  - Sound is confined to a small space, reducing $1/r^2$ losses

- The wide end of the horn lets all vibrations with wavelength $< \text{bell diameter}$ escape without strong reflections. Technical: no impedance mismatch
Ripple Tank Simulation
Horns in Reverse

From Why You Hear What You Hear by Eric Heller
Summary

- Decibel scale: logarithmic ratio of sound level power or intensity with respect to a reference point
  - sound level = 10 log \( \frac{P_1}{P_2} \) dB

- We perceive loudness differently depending on the frequency of the sound

- Amplification can be achieved by reflection from a surface, if the distance between the surface and sound source is much bigger than the wavelength of the sound

- In musical instruments, amplification is achieved by coupling vibrating elements to a resonator with low impedance — sound effectively transmitted into the air