1 Announcement: I want you for schlepping

• Volunteers needed for Wed, 9/14 class meeting
• 2 volunteers at room ____, 5 minutes before start of class
• 2 volunteers after class (please approach me after class)

2 Review

2.1 Written assignment 1 (wr1)

• How relevant is music really as an application of sound recording technology?
• Connection with the telephone: Consider [SOMALGET]

2.2 Reading assignment 1 (rd01)

• What is the physical principle that Christina Kubisch’s Electrical Walks are based on?
• Do the resulting sounds exhibit any similarities to existing musical genres? If so, how come?

3 Preview

3.1 Reading assignment 2 (rd02)

• 4 videos and one article on microphones

3.2 Production analysis 1 (pa1)

• Analysis of a commercially available music production
• Will be presented in class throughout the semester
• Please sign up for one of the available dates!
4 Syllabus, ctd.

- Lecture notes
- Online resources
- Assignment submission format
- Attendance policy
- Use of electronic devices
- Workload
- Academic integrity

5 What is sound?

- Ancient philosophical question: "If a tree falls in a forest, does it make a sound if no one is around to hear it?"

- Rather than answer this question, we will consider sound as both, a
  - physical phenomenon ("yes, it does") and a
  - perceptual phenomenon ("no, it doesn’t").

- Astonishing discrepancies between physics & perception of sound!

- For now (today), we will consider only the physics.

6 Wave propagation

6.1 Longitudinal vs. transverse waves

- Longitudinal waves: Wave travels in direction of particle oscillation
- Transverse waves: Wave travels perpendicularly to particle oscillation
- In real life, waves are often a mixture of both (e.g., water waves)
- Sound waves in air: longitudinal

6.2 Radiation patterns

- Two idealized sound sources: monopole (spherical wave), dipole
- Real-life radiation patterns much more complex and frequency-dependent

6.3 Spherical vs. plane waves

- Two idealized archetypes of wavefronts: spherical vs. plane
- Any spherical wavefront ‘looks plane’ from sufficient distance
6.4 Periodic vs. aperiodic waves

- Periodic waves repeat at regular intervals (by contrast to aperiodic ones)
- Periodicity is a fundamental concept in sound & acoustics
  - Temporal periodicity implies spectral harmonicity
  - Periodicity & harmonicity associated with perception of pitch

6.5 Visualization as a waveform

- Waves are always a temporal and spatial phenomenon – their amplitude is a function of time and location
- Any 2d visual representation must neglect either space or time
- E.g., a waveform plots amplitude over time (but for a single location)
- Common representation for audio editing purposes (e.g., Reaper)

7 Wave properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>$A$</td>
<td>$\mu$Pa, mV, ...</td>
</tr>
<tr>
<td>Period</td>
<td>$T$</td>
<td>s</td>
</tr>
<tr>
<td>Frequency</td>
<td>$f$</td>
<td>Hz</td>
</tr>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
<td>m</td>
</tr>
<tr>
<td>Speed of sound</td>
<td>$c$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>Phase</td>
<td>$\phi$</td>
<td>$^\circ$ or rad</td>
</tr>
</tbody>
</table>

Table 1. Wave properties

7.1 Amplitude

- Which physical unit is used to quantify a wave’s amplitude depends on propagation medium and respective application (more later)
- Different ways to measure amplitude:
  - As peak amplitude or peak-to-peak amplitude (implies periodicity)
  - Integrated over time as root mean square (e.g., sound level meter)
- The physical property of amplitude relates to (but is distinct from!) the perceptual quality of loudness.
  - Everything else being equal, a sound of higher amplitude tends to be perceived as louder.
  - However, amplitude-loudness relationship is non-linear, frequency-dependent, and highly complex!
- Roads (2015, p. 43) contrasts various terms to describe sound ‘magnitude’

$$\text{Equation 1. Root mean square amplitude in time window } \{T_1, T_2\}$$

$$A_{RMS} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} A(t)^2 \, dt}$$
7.2 Frequency & period

• Frequency $f$ is reciprocal of wave’s period $T$
  \[ f = \frac{1}{T} \]
  \[ \text{Equation 2. Frequency } f, \text{ period } T \]

• Both describe wave’s *temporal* behavior (periodicity in time)

• The physical property of frequency relates to (but is distinct from!) the perceptual quality of *pitch*.
  – Everything else being equal, higher frequencies tend to be perceived at a higher pitch.
  – However, frequency-pitch relationship is similarly complex as amplitude-loudness relationship!

7.3 Wavelength

• Wavelength $\lambda$ describes wave’s *spatial* behavior (periodicity in space)

7.4 Speed of sound

• Speed of sound $c$ connects wave’s temporal ($f$) and spatial ($\lambda$) behavior
  \[ c = \lambda \cdot f \]
  \[ \text{Equation 3. Speed of sound} \]

• Refers to speed of wavefront (not particle velocity)

• Increases rapidly with density $\rho$ of propagation medium
  – Higher in liquids than in gases
  – Yet higher in solids

• Depends less heavily on temperature, e.g.: $c_{\text{air}} \approx 331.3 + 0.606 \cdot \theta$

• But for music recording purposes can be regarded as a constant

• Let’s memorize the following value: $c_{\text{air}, 15^\circ C} \approx 340 \text{ m s}^{-1}$

<table>
<thead>
<tr>
<th>Medium</th>
<th>$c$/m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (20°C; 0% hum.)</td>
<td>343.2</td>
</tr>
<tr>
<td>Water (fresh; 25°C)</td>
<td>1497</td>
</tr>
<tr>
<td>Steel</td>
<td>4597</td>
</tr>
</tbody>
</table>

7.5 Phase

• Phase $\varphi$ of a wave: an elusive concept blamed for all sorts of problems in audio (not unlike parasitic capacitance in electrical engineering)

• Probably because it yields the complex phenomenon of *interference*
  – Occurs whenever two or more waves are superimposed
  – Example: Mixing signals recorded by two microphones in same room
  – *Constructive interference* occurs when waves are in phase
  – *Destructive interference* (phase cancellation) occurs when two waves are anti-phase
  – *Mixed interference* occurs when two waves are out-of-phase
8 Acoustic quantities

8.1 Field quantities vs. energy quantities

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
<th>Nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound pressure</td>
<td>( p )</td>
<td>Pa</td>
<td>Field quantities</td>
</tr>
<tr>
<td>Particle displacement</td>
<td>( \xi )</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Particle velocity</td>
<td>( v )</td>
<td>m s(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Sound power</td>
<td>( P_{ac} )</td>
<td>W</td>
<td>Energy quantities</td>
</tr>
<tr>
<td>Sound intensity</td>
<td>( I )</td>
<td>( W ) m(^{-2})</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Acoustic quantities

• Note distinction between field vs. energy quantities
• Will become important for discussion of decibel (section 9)

8.2 Inverse square law & inverse distance law

• Experience tells that sound decays with distance from its source. Why?
  • Two equivalent laws that describe sound decay with distance:
    – Sound pressure \( p \) decreases linearly with distance \( r \) from source
    – Sound intensity \( I \) decreases with square of distance \( r \) from source

  “Time and again, it is claimed that the sound pressure decays with the square of the distance \( r \) from the sound source. One hears that so often that one is almost tempted to believe it.” (Sengpiel 2004, own transl.)

• Validity of either law restricted by two assumptions:
  – Free field (i.e., neither too close nor too far from source in a room)
  – Spherical wave (but radiation of real instruments is more complex)

• Illustration of inverse square law:
  – General relationship: intensity is power over area: \( I = \frac{P_{ac}}{A} \)
  – \( P_{ac} \) is property of source, not sink (hence constant with regards to \( r \))
  – But surface area \( A \) changes with distance \( r \) from source
  – Assuming surface of a sphere (monopole): \( I(r) = \frac{P_{ac}}{4\pi r^2} \propto \frac{1}{r^2} \)

9 The decibel (dB)

• The decibel (or dB) is a logarithmic unit to express a ratio of two values.
• Since the dB expresses a ratio
  – It has the dimension 1
  – One can use it to compare two values of any physical quantity\(^1\)
There always is a reference value (which is often implicitly assumed).

Since the dB is a logarithmic unit,
- It can express larger ratios than a linear measure.
- It suits the somewhat logarithmic nature of human perception.

However, the dB still measures physical quantities (e.g., $p$, $V$, etc.)!
- It does not measure perceptual qualities (such as loudness).
- But people misleadingly use dB to say “how loud” a sound is.

### 9.1 Mathematical definition

\[
L = 20 \cdot \log_{10} \left( \frac{A}{A_0} \right) = 10 \cdot \log_{10} \left( \frac{A^2}{A_0^2} \right)
\]

$L$ level dB

$A$ some field quantity $\mu$Pa, mV, ...

$A^2$ some energy quantity $W$, $W m^{-2}$, ...

$A_0$ reference field quantity $\mu$Pa, mV, ...

$A_0^2$ reference energy quantity $W$, $W m^{-2}$, ...

### 9.2 Sound pressure level (sPL)

- Pressure is a field quantity, so use ‘20 version’ of decibel equation.
- Common reference: $p_0 = 20 \mu$Pa $\equiv 0$ dBsPL (threshold of hearing).

### 9.3 Sound intensity level (sIL)

- Intensity is an energy quantity, so use ‘10 version’ of decibel equation.
- Common reference: $I_0 = 10^{-12} W m^{-2} \equiv 0$ dBsIL (threshold of hearing at 1 kHz).

### 9.4 Sound power level (sWL)

- Power is an energy quantity, so use ‘10 version’ of decibel equation.
- Common reference: $P_0 = 10^{-12} W = 1 pW \equiv 0$ dBsWL.

\[
L_I = 10 \cdot \log_{10} \left( \frac{I}{I_0} \right)
\]

Equation 8. Sound intensity level $L_I$.

\[
L_W = 10 \cdot \log_{10} \left( \frac{P_{ac}}{P_0} \right)
\]

Equation 9. Sound power level $L_W$. 

6 of 8
10 Complex sounds

- So far we have considered only very simple (and rather dull) sounds:
  - Pure sine tones whose spectrum contains only a single frequency
  - Stationary sounds that do not change over time
- But the sounds we are interested in recording are more complex:
  - Contain multiple frequencies
  - Change over time

10.1 Visualization as a spectrum

- Waveform = amplitude as function of time
- Spectrum = amplitude as function of frequency
- Another 2D visual representation of sound
- Shows a sound’s frequency content within a given time window (ignoring any changes within that window)
- Useful for analysis (e.g., to determine *harmonicity* of a sound)

10.2 Harmonic sounds

- Periodicity in the time domain (waveform) implies harmonicity in the frequency domain (spectrum).
  \[ f_N = N \cdot f_1 \]
- Harmonic sounds *are perceived as pitched*
  - Fundamental frequency determines perceived pitch
  - Spectral composition determines perceived *timbre* (sound color)
- Examples: Sine waves, square waves, triangle waves, sawtooth waves

10.3 Inharmonic sounds

- Sounds that are aperiodic in time have an inharmonic spectrum and are perceived as unpitched.
- Examples: Noise of different colors (e.g., white, pink)²
- Again, spectral composition determines perceived *timbre*

10.4 Envelopes

- The *envelope* of a sound describes its amplitude profile over time
- Different frequency components tend to exhibit quite distinct envelopes!
- E.g., high frequencies on a piano note decay faster than low frequencies

² Roads (2015, p. 103) provides an extensive overview of different noise colors.
10.5 Visualization as a spectrogram

- 3D representation: Amplitude as function of time and frequency
- Shows temporal behavior of different frequency components
- Great for analytical purposes:
  - Baudline: [http://www.baudline.com/](http://www.baudline.com/)
  - Sonic Visualiser: [http://sonicvisualiser.org/](http://sonicvisualiser.org/)
- Less common as an editing paradigm (exceptions: [Spear], [Audiosculpt])

References & further reading


