21M.380 · Music and Technology
Recording Techniques & Audio Production

Physics of sound

Session 2 · Monday, September 12, 2016

1 Announcement: I want *you* for schlepping

- Volunteers needed for Wed, 9/14 class meeting
- 2 volunteers at room [redacted], 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

Property	Symbol	Unit
Amplitude	A	µPa, mV, …
Period	T	s
Frequency	f	Hz
Wavelength	λ	m
Speed of sound	c	$\mathrm{m\,s^{-1}}$
Phase	φ	° or rad

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'

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

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

7.2 Frequency & period

- Frequency f is reciprocal of wave's 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!

$$f = \frac{1}{T}$$

Equation 2. Frequency f, period T

7.3 Wavelength

- Wavelength λ describes wave's *spatial* behavior (periodicity in space)

7.4 Speed of sound

- Speed of sound c connects wave's temporal (f) and spatial (λ) behavior
- Refers to speed of wavefront (*not* particle velocity)
- Increases rapidly with density ρ of propagation medium
  - Higher in liquids than in gases
  - Yet higher in solids
- Depends less heavily on temperature, e.g.: $c_{\text{air}} \approx 331.3 + 0.606 \cdot \vartheta$
- But for music recording purposes can be regarded as a constant
- *Let's memorize the following value:* $c_{\text{air, 15 °C}} \approx 340\,\text{m}\,\text{s}^{-1}$

$$c = \lambda \cdot f$$

Equation 3. Speed of sound

Table 2. c increases with density ρ

Medium	$c/\text{m}\,\text{s}^{-1}$
Air (20 °C; 0 % hum.)	343.2
Water (fresh; 25 °C)	1497
Steel	4597

7.5 Phase

- Phase φ of a wave: an elusive concept blamed for all sorts of problems in audio (not unlike parastic 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

Quantity	Symbol	Unit	Nature
Sound pressure	p	Pa	
Particle displacement	ξ	m	Field quantities
Particle velocity	v	$\mathrm{m\,s^{-1}}$	
Sound power	P_{ac}	W	Energy quantities
Sound intensity	I	$\mathrm{W\,m^{-2}}$	

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

$$p \propto \frac{1}{r}$$

Equation 4. Inverse distance law

$$I \propto \frac{1}{r^2}$$

Equation 5. Inverse square law

  "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]

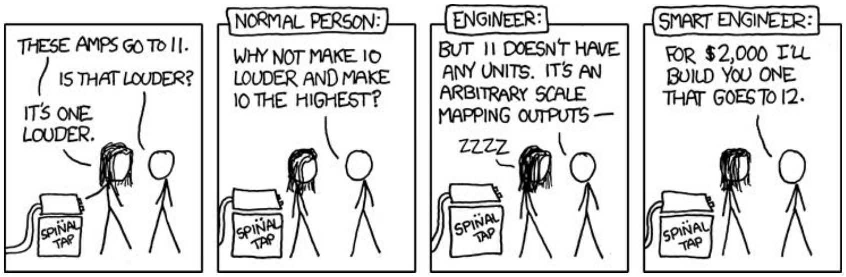

Figure 1. Spinal Tap Amps (Courtesy of Randall Munroe.)

  - 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

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

Equation 6. Definition of some physical quantity's level L in decibel

L	level	dB
A	some field quantity	μPa, mV, …
A^2	some energy quantity	W, W m⁻², …
A_0	reference field quantity	μPa, mV, …
A_0^2	reference energy quantity	W, W m⁻², …

9.2 Sound pressure level (SPL)

$$L_p = 20 \cdot \log_{10}\left(\frac{p}{p_0}\right)$$

Equation 7. Sound pressure level L_p

- Pressure is a *field* quantity, so use '20 version' of decibel equation
- Common reference: $p_0 = 20\,\mu\text{Pa} \equiv 0\,\text{dB}_{\text{SPL}}$ (threshold of hearing)

9.3 Sound intensity level (SIL)

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

Equation 8. Sound intensity level L_I

- Intensity is an *energy* quantity, so use '10 version' of decibel equation
- Common reference: $I_0 = 10^{-12}\,\text{W}\,\text{m}^{-2} \equiv 0\,\text{dB}_{\text{SIL}}$ (threshold of hearing at 1 kHz)

9.4 Sound power level (SWL)

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

Equation 9. Sound power level L_W

- Power is an *energy* quantity, so use '10 version' of decibel equation
- Common reference: $P_0 = 10^{-12}\,\text{W} = 1\,\text{pW} \equiv 0\,\text{dB}_{\text{SWL}}$

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).

$$f_N = N \cdot f_1$$

Equation 10. Harmonic spectrum

- 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

[2] Roads (2015, p. 103) provides an extensive overview of different noise colors.

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

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/`
  - Sonic Visualiser: `http://sonicvisualiser.org/`
- Less common as an editing paradigm (exceptions: Spear, Audiosculpt)

References & further reading

Fouad, Hersham (2004). "Understanding the decibel." In: *Audio Anecdotes: Tools, Tips, and Techniques for Digital Audio*. Ed. by Ken Greenebaum and Ronen Barzel. Vol. I. Natick, MA: A K Peters, pp. 13–7. MIT LIBRARY: 001253727.

Howard, David M. and James Angus (2001). "Introduction to sound." In: *Acoustics and Psychoacoustics*. 2nd ed. Oxford and Woburn, MA: Focal Press. Chap. 1, pp. 1–64.

Roads, Curtis (2015). *Composing electronic music. A new aesthetic*. Oxford: Oxford University Press. 480 pp. ISBN: 9780195373233. MIT LIBRARY: 002385875. Acompanying sound examples available from http://www.mat.ucsb.edu/~clang/news_files/RoadsCEMASoundexamples(155).zip (1.5GB!). Hardcopy on course reserve at the Lewis Music Library. Also available through MIT libraries as an electronic resource.

Sengpiel, Eberhard (2004). *Wie ist es richtig? Teil 8. Audio-Fachbüchern entnommen und in Vorlesungen aufgeschnappt*. URL: http://www.sengpielaudio.com/WieIstEsRichtig08.pdf (visited on 08/14/2014).