21M.380 Music and Technology
Sound Design

Lecture №5
Physics of sound

Wednesday, February 17, 2016

1 Archetypal sound objects

Mouth harp, straws, glass bottles, strings (guitar, violin), drums

2 Wave properties

- Amplitude A
- Frequency f
- Wavelength λ
- Phase φ
- Speed of sound $c = \lambda \cdot f$

3 Simple harmonic oscillators

- Mass-spring system
- Pendulum
- Solved by means of differential equations

4 Complex harmonic oscillators

4.1 Concept of harmonicity

- A sound is *harmonic* if its partials are multiples of a *fundamental frequency*
- Terminology: Fundamental vs. harmonics vs. overtones
- Periodicity in the time domain means harmonicity in the frequency domain
- Harmonicity is related to pitch perception
  - Harmonic sounds favor perception of a specific pitch
  - Inharmonic sounds are not perceived as pitch
- But harmonicity is a fluid concept (no clear-cut line between harmonic vs. inharmonic sounds)

- Demo: Pd patch
  - Harmonic sound whose partials are not perfect integer multiples
  - Still sounds pitched

4.2 Oscillation of a string

- YouTube video that goes with slides
- Bridge video (recommendation by Peter P.): https://upload.wikimedia.org/wikipedia/commons/1/19/Tacoma_Narrows_Bridge_destruction.ogg
- Harmonics (cf., Farnell 2010, eq. 4.12):

$$f_n = \frac{n}{2l}\sqrt{\frac{T}{\mu}}$$

  - f_n … modes (Hz)
  - n … mode number ($n \in \mathbb{N} = 1, 2, 3, \ldots$)
  - l … string length (m)
  - T … linear tension (N)
  - μ … linear density ($\mathrm{kg\,m^{-1}}$)
- Demo: Karplus-Strong plucked string synthesis implemented in Pd vanilla by Colin Barry: http://blog.loomer.co.uk/2010/02/karplus-strong-guitar-string-synthesis.html

4.3 Pipe closed on one end

- Russell animation
- Distinguish particle displacement vs. sound pressure distribution!
- Why do pressure nodes and peaks *have to* be distributed that way?

4.4 Pipe open on both ends

- What would we expect the distribution to look like?
- In groups of 2 or 3, derive an equation for the expected harmonics of an open pipe

4.5 Helmholtz resonator

$$f = \frac{c \cdot d}{4\pi}\sqrt{\frac{\pi}{V \cdot l}}$$

- f … resonant frequency (Hz)
- c … speed of sound in air ($\mathrm{m\,s^{-1}}$)
- d … neck diameter (m)
- V … resonator volume ($\mathrm{m^3}$)
- l … neck length (m)

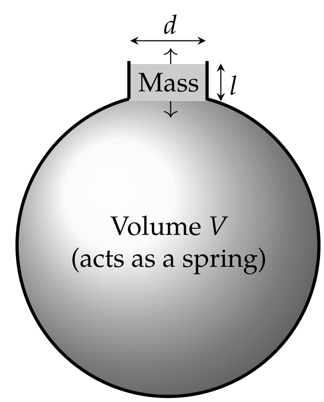

Figure 1. Helmholtz resonator

4.6 Bar clamped at one end

$$f_1 = \frac{0.5596}{l^2}\sqrt{\frac{ER^2}{\rho}}$$

- f_1 … fundamental frequency (Hz)
- l … bar length (m)
- E … Young's modulus (Pa)
- R … radius of gyration (m)
- ρ … material density ($\mathrm{kg\,m^{-3}}$)

Material	E / 10^{10}Pa	ρ / $10^3\mathrm{kg\,m^{-3}}$
Aluminium	7.05	2.7
Brass	10.05 ± 0.35	8.48
Copper	12.98	8.79
Gold	7.8	19.29
Iron	21.2	7.87
Lead	1.62	11.35
Silver	8.27	10.5
Steel	21.0	7.82
Zinc	9.0	7.12
Glass	6.1 ± 1.0	2.6 ± 0.2
Rosewood	1.4 ± 0.2	0.86 ± 0.04

Table 1. Young's modulus E and density ρ of different materials (Benson 2008, p. 117)

5 Group work

A	B	C	D
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

Table 2. Student groups

5.1 Group A (glass bottle)

- Try to predict the glass bottle's fundamental frequency
- Compare the result to reality
- How could we synthesize this in Pd?

5.2 Group B (mouth harp)

- Try to predict the mouth harp's fundamental frequency
- Compare the result to reality

5.3 Group C (straw closed on one end)

- Cover the far end of a straw your blowing into with your hand
- What happens to the pitch?
- Derive the equations for the harmonics of the closed straw
  - Remember how sound pressure behaves at open and closed end
  - How does this change the relationship between the straw's length l and the resulting wavelengths λ_n?
  - What about the fundamental frequency?
  - Which harmonics would you actually expect to occur?
  - How would that change our *perception* of that sound?
- Use the equations to predict the straw's fundamental frequency
- Compare the result to reality

5.4 Group D (violin)

- Determine the fundamental frequency of an open A string on the violin.
- Do online research to find reasonable estimates for any missing quantities.
  - ______________________________
  - ______________________________
  - ______________________________
- How does your result compare to reality?

6 Group discussion

- Differences between open and closed pipes?
- Is end correction relevant also for glass bottle?

References and further reading

Benson, Dave (2008). *Music: a Mathematical Offering*. URL: https://homepages.abdn.ac.uk/mth192/pages/html/music.pdf (visited on 03/07/2015).

Farnell, Andy (2010). *Designing Sound*. Cambridge, MA and London: MIT Press. 688 pp. ISBN: 978-0-262-01441-0. MIT LIBRARY: 001782567. Hardcopy and electronic resource.