Session 6
The Human Voice and Fourier Analysis!
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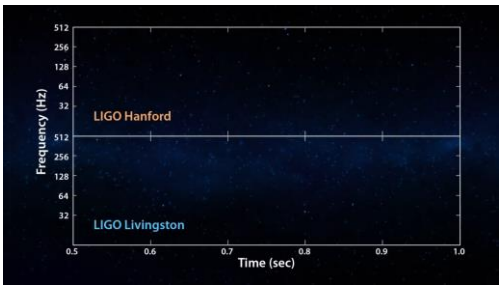
Science of Music

Today's session

We want to learn about
- The acoustics of the human voice instrument
- The analysis of signals via Fourier series
- The appreciation of human singing
- The sound generation in our voice box
- How what we say, determines how we sing

The sound of two colliding black holes



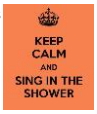
Camille Saint-Saëns' *Samson et Dalila*

- ***Samson and Delilah*** (French: *Samson et Dalila*), Op. 47, is a grand opera in three acts and four scenes by Camille Saint-Saëns to a French libretto by Ferdinand Lemaire. It was first performed in Weimar at the Grossherzogliches (Grand Ducal) Theater (now the Staatskapelle Weimar) on 2 December 1877 in a German translation.
- The opera is based on the Biblical tale of Samson and Delilah found in Chapter 16 of the Book of Judges in the Old Testament. It is the only opera by Saint-Saëns that is regularly performed. The second act love scene in Delilah's tent is one of the set pieces that define French opera. Two of Delilah's arias are particularly well known: "Printemps qui commence" and "Mon cœur s'ouvre à ta voix" ("My heart opens itself to your voice", also known as "Softly awakes my heart"), the latter of which is one of the most popular recital pieces in the mezzo-soprano/contralto repertoire.

From Wikipedia, the free encyclopedia

History of the Singing Voice

- Humans have probably always been singing, earliest recall is from the Bible.
- Important in Ancient Greece, the same as reading poetry.
- Scaled down during early Christianity, instruments, female and popular singing forbidden. Instead, Gregorian chants. https://youtu.be/D5ubvYqOh1M?t=22m12s
- Up until 500 A.D. no polyphonic singing, and only after that did profane singing win ground.
- High voice and tenors until Johannes Ockeghem 'invents' basses.
- 1500's: Earliest music still played today, Palestrina Caccini and Monteverdi. (Music clip from The Coronation of Poppea) https://youtu.be/_isL0E-4TsQ?t=13s
- Female voices 'discovered'.
- Four different voice ranges: Soprano, alto, tenor and bass
- Baroque era, Bach and Händel, music is complex and sung like a flute. https://youtu.be/MUolx9EdSjw?t=2m41s
- Women was not allowed in churches so instead they castrated boys to keep their high voice, instead of having their voices break in puberty.
- They had bigger lungs and very flexible larynx which made them able to do things we can't replicate today. https://youtu.be/lQo2PNnwOww?t=16s



History of the Singing Voice part 2

- **Bel Canto** to sing like an instrument, with precision, high virtuosity, clarity and agility.
- The singer was the creator of emotions and music.
- Vienna Classicism, singers developed bigger range as shown in the Magic Flute. https://youtu.be/463jDvbw3LQ?t=2m11s
- With Rossini the relationship between singer and composer starts to change. He writes music hard enough for the singers not to improvise. https://youtu.be/ZbOMO_IfJCs?t=5m8s
- 1800's – a new way of singing, biggest change for centuries. The new voice was dramatic. More volume, more emotions, not as precise as Bel Canto.
- 'Projection': a technique which allows singers to unaided be heard over a hundred piece orchestra. https://youtu.be/N8lD9ZmYHhE?t=2m34s
- New voice types: Mezzo-soprano and Bass-Baritone.
- The plot of the opera was more important than the individual singers chance to show off. https://youtu.be/K2snTkaD64U
- Wagner took they art of singing to new extremes, requiring skills that are on the edge of what the human voice can do. https://youtu.be/owFdFRoFKHk
- During early 20th century the microphone was invented, giving space to new ways of singing such as jazz and blues.
- Opera - a dying art form? https://youtu.be/OV3xp5ZXSYA?t=26s

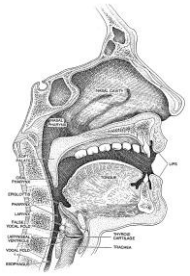
The "voicebox"

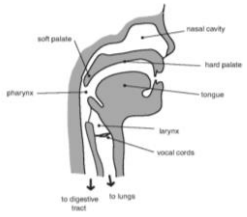
- The voice organ is an instrument consisting of a power supply (the lungs), an oscillator (the vocal folds/chords) and a resonator (the larynx, the pharynx and mouth).
- Singers use the resonator in special ways.

John Sundberg, "Acoustics of the Singing Voice", Scientific American, March 1977

The resonator of the"voicebox": vocal tract

- Vocal tract acts like a resonant chamber such as tube of a horn or body of violin.
- Boundary conditions are set by lips, jaw, tongue, larynx.





Audience participation A

- Finding your own <u>personal</u> singing voice
  - Soprano: C4–C6
  - Mezzo-soprano: A3–A5
  - Contralto: F3–F5
  - Countertenor: E3-E5
  - Tenor: C3–C5
  - Baritone: G2–G4
  - Bass: E2-E4

Fourier analysis: basics

- Nearly any function $f(t)$ can written as

$$f(t) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\frac{n\pi t}{L} + b_n \sin\frac{n\pi t}{L}\right)$$

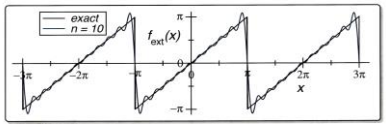
with

$$a_n = \frac{1}{L}\int_{-L}^{L} dx \cos(\omega_n t)\, f(t), \qquad \omega_n = \frac{n\pi}{L}$$

$$b_n = \frac{1}{L}\int_{-L}^{L} dx \sin(\omega_n t)\, f(t).$$

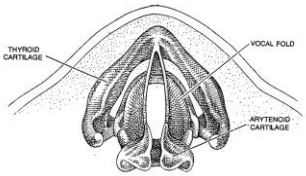
$f(x) = x$

$\forall x \in [-\pi, \pi]$

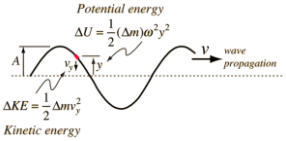


Our vocal cords

- https://youtu.be/P2pLJfWUjc8
- Audience participation B: balloons



Fourier analysis: energy of waves and power spectrum



- Energy in (small segment of) string:

$dU = \frac{1}{2}\mu y^2\omega^2 dx, \quad \mu = \frac{dm}{dx}$

$dT = \frac{1}{2}\mu v_y^2 dx$

$y = A\sin(kx - \omega t)$

$\frac{dy}{dx} = v_y = A\omega\cos(kx - \omega t)$

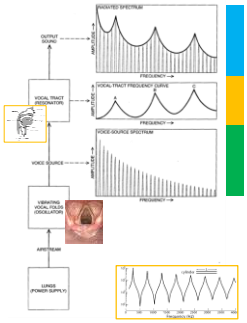
$$P(\omega) = \frac{E}{\tau} = \frac{1}{2}\mu\omega^2 A^2 v$$

$E = \int_0^{\lambda} dU + dT = \frac{1}{2}\mu\omega^2 A^2 \int_0^{\lambda} \sin^2(kx - \omega t)dx + \frac{1}{2}\mu A^2\omega^2 \int_0^{\lambda} \cos^2(kx - \omega t)$

$= \frac{1}{2}\mu\omega^2 A^2\lambda \qquad @\ t = 0$

An air column in our throat

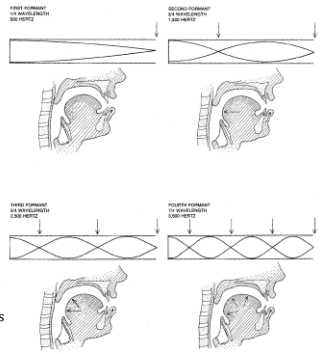
- Air stream from lungs is periodically interrupted by the vibrating vocal folds
- Resulting sound has a spectrum, containing a large number of harmonic partials, amplitude of which is decreasing with increasing frequency
- Air column in vocal tract has characteristic modes of vibration (resonances) call formants (A, B, C)
- Sound is modulated according the distance from formants
- Formant frequencies are peaks in the final output sound



Forming formants

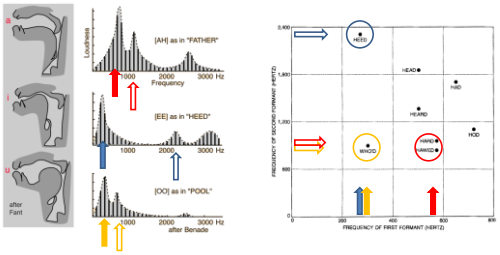
- Formants: standing waves of air-pressure oscillations
- Picture shows vocal tract approximated via cylindrical tube
- pressure waves as in open wind instruments, pressure differential large at vocal fold (glottis), close to zero at lips
- ¼ of wave lengths inside vocal tract for 1st formant
- 250-700Hz for adult male in first formant

$4 \times 17.5\text{cm} \times 500\text{Hz} = 350\ \text{m/s}$



Speech formants

- Audience participation C: Aa, ee, oo

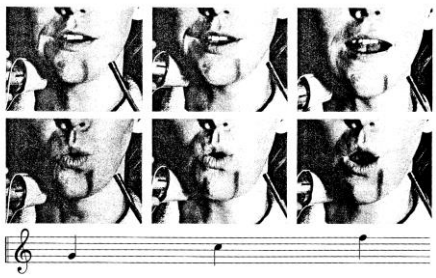


How to sing

- Singers of high pitch (sopranos, etc.) open mouth wider with rising pitch

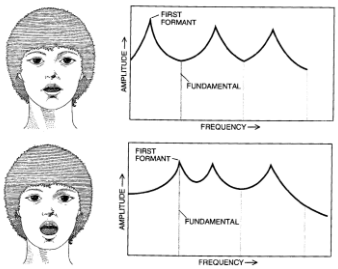
"heed"

"who'd"



"How to sing" explained

- High-tone singer often sing at frequencies beyond closed-lips formant, leads to reduction in sound
- Opening lips raises 1st formant to higher frequencies, giving better sound



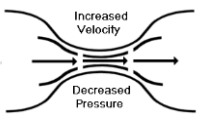
Bernoulli's principle

$$E_{\text{Lungs}} = E_{\text{Larynx}}$$

$$\frac{1}{2}Mv_{LU}^2 = \frac{1}{2}Mv_{LX}^2 \quad :/V$$

$$\frac{1}{2}\rho_{LU}v_{LU}^2 = \frac{1}{2}\rho_{LX}v_{LX}^2 = \frac{E}{L^3} = \frac{F}{L^3}\frac{L}{L^2} = \frac{F}{A} = P$$

$$P_{LU} + \frac{1}{2}\rho_{LU}v_{LU}^2 = \frac{1}{2}\rho_{LA}v_{LX}^2 + P_{LX}$$

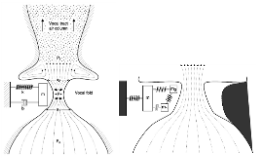


Closed vocal folds:

$v_{LU} = v_{LX} = 0$: $P_{LU} > P_{LA}$

Open vocal folds:

$v_{LU} < v_{LX}$: $P_{LU} < P_{LA}$



Pressure oscillations, aka SOUND!

Fourier analysis:

- Jo's singing:
  - Middle sound
  - Lower sound
  - Higher sound
  - Falsetto
  - Sotto voce

Singing formants

- What to do with a hundred piece orchestra and only your voice?
- Humans can naturally do a very piercing sound – a reflex. Opera singers have learnt to do so at will. They call it projection.
- Instruments and untrained singers decrease in amplitude as frequency increases above 200Hz
- An opera singer has a pronounced peak between 2000-3000Hz. **< The Singing Formant**
- Opera singers access this 'extra volume' by relax in the muscles and lowering the lowering the voice box.
- The negative side effect is that it distorts vowels, to an untrained ear, completely.

A thousand kinds of singing.

- Yodeling, https://youtu.be/vQhqikWnQCU
- Kulning, https://youtu.be/IJtW8CiGiEk
- Screamo, https://youtu.be/InRMwptcgAo?t=17s
- Carl Jenkins, Call for Prayer, A Mass for Peace. https://youtu.be/Dw3kRv6SVN0

Closing: Why I sing!

It ain't over until the fat lady sings!

Soprano/Mezzo-soprano [A3-C6]

Maria Callas

Leona Lewis

Cecilia Bartoli

Renée Fleming

Birgit Nilsson

Contralto/Countertenor [F3-F5]

Marian Anderson

Adele

Philippe Jaroussky

Tenor [C3-C5]

Jussi Björling

Justin Timberlake

Jonas Kaufmann

Luciano Pavarotti

Baritone-Bass [E2-G4]

David Bowie

Peter Mattei

Bryn Terfel