# Physics and Neurophysiology of Hearing

H.G. Dosch, Inst. Theor. Phys. Heidelberg

I Signal and Percept

II The Physics of the Ear

III From the Ear to the Cortex

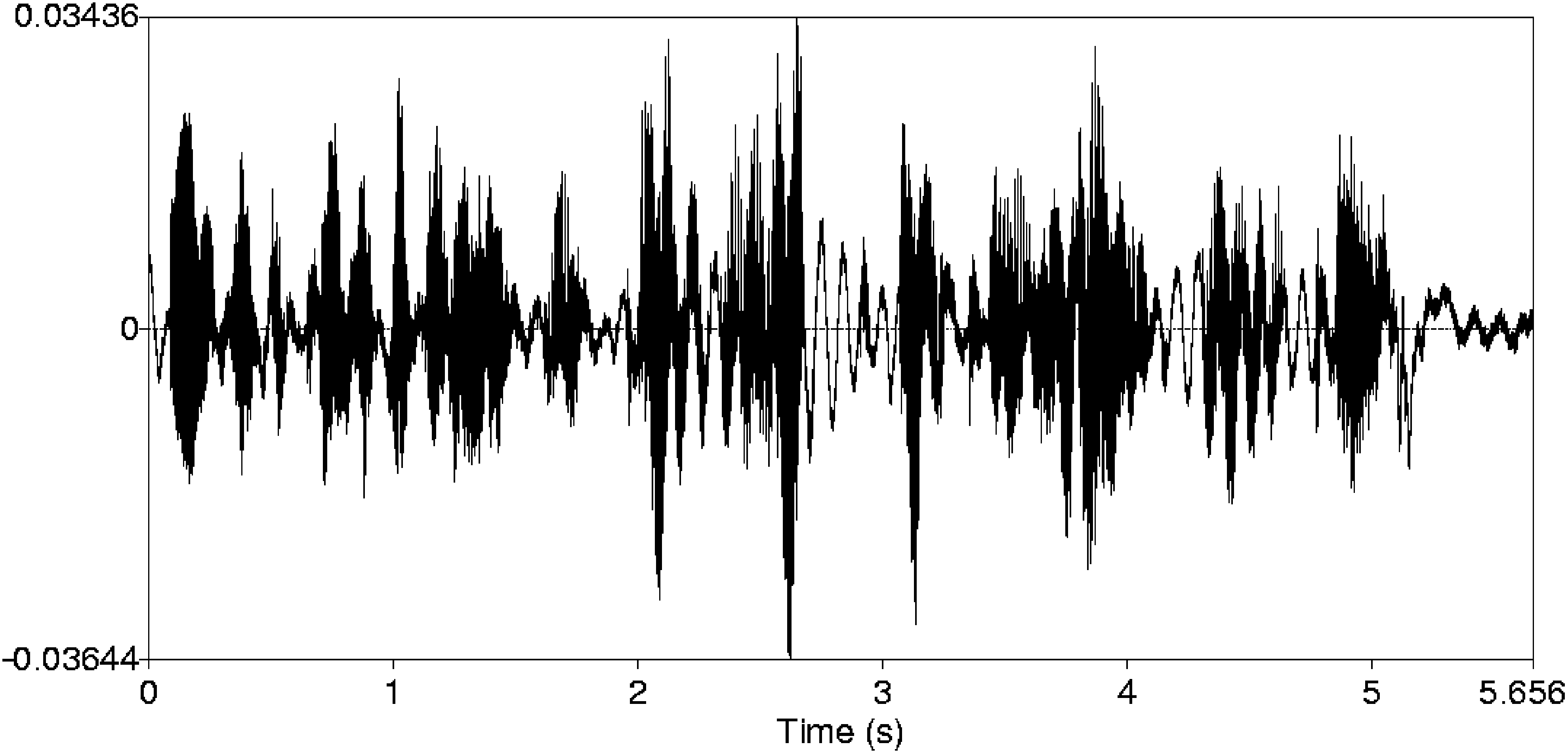
IV Electrophysiology

## Part I: Signal and Percept

1)The time scales in hearing
2)Relation between Physics and Sensation (Psychophysics)
   a) Propagation and Production of Sound
   b) The principal relations and caveats
   c) A Byte of Signal processing (mainly Fourier etc)
   d) Application to acoustics: Ohms Law
   e) Theory of Musical Consonance
   f) Fusion of Harmonics and Fundamental Tracking

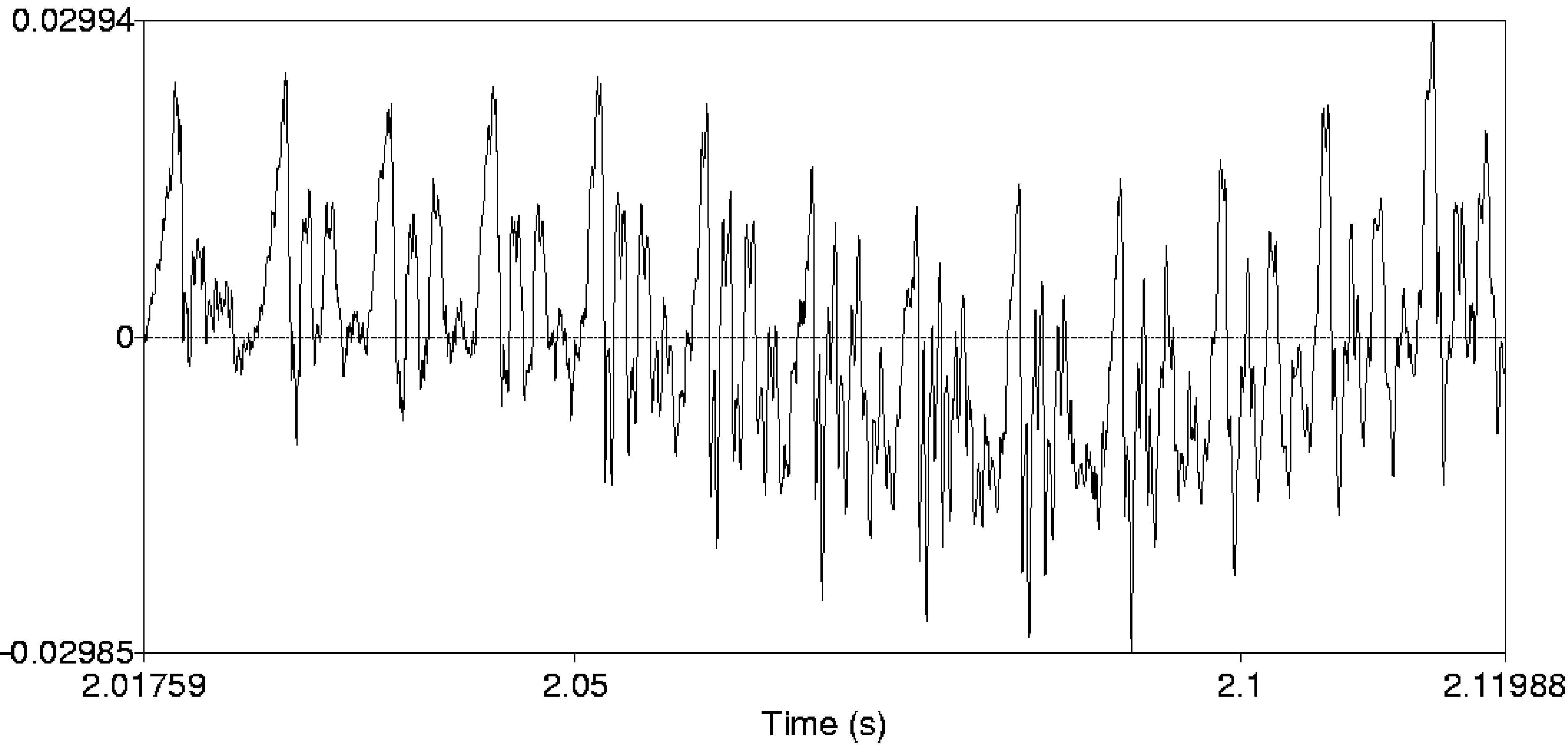
Sound pressure curve of the sentence:

**each acoustical signal can be mapped unto a sound pressure curve**




Typical time scale of variation 0.1 s and larger

sound-pressure-example.wav in praat1.collection selection of the previous sentence: mapped



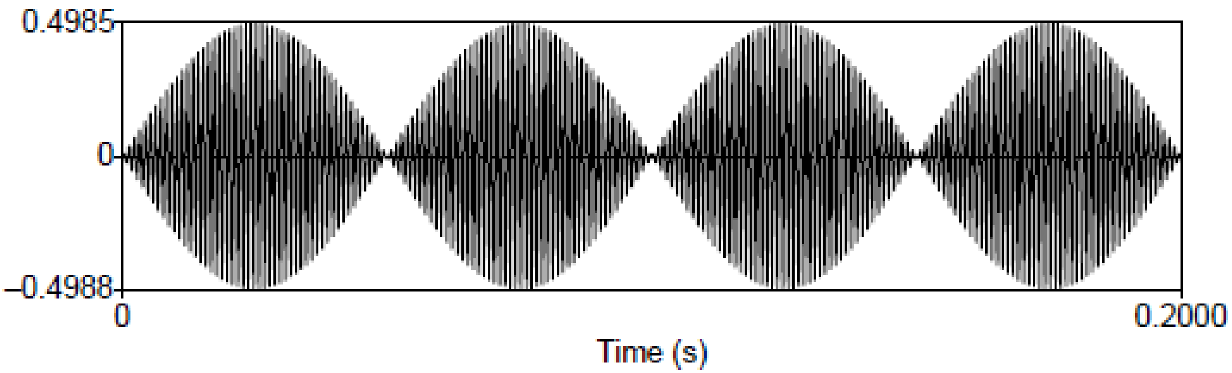

Typical time scale of variation: 10 ms

sound-pressure-selection.wav in praat1.collection

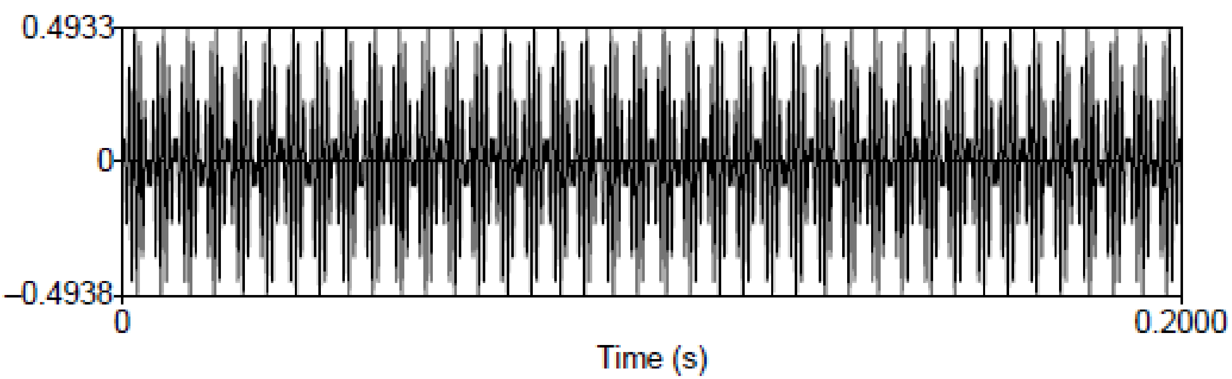
Amplitude-modulated sinusoidal tone with carrier frequency $\nu_0$ and modulation frequency $\nu_m$.

$$p(t) = \sin(2\pi\nu_m t)\sin(2\pi\nu_0 t)$$

$\nu_0 = 1000$ Hz

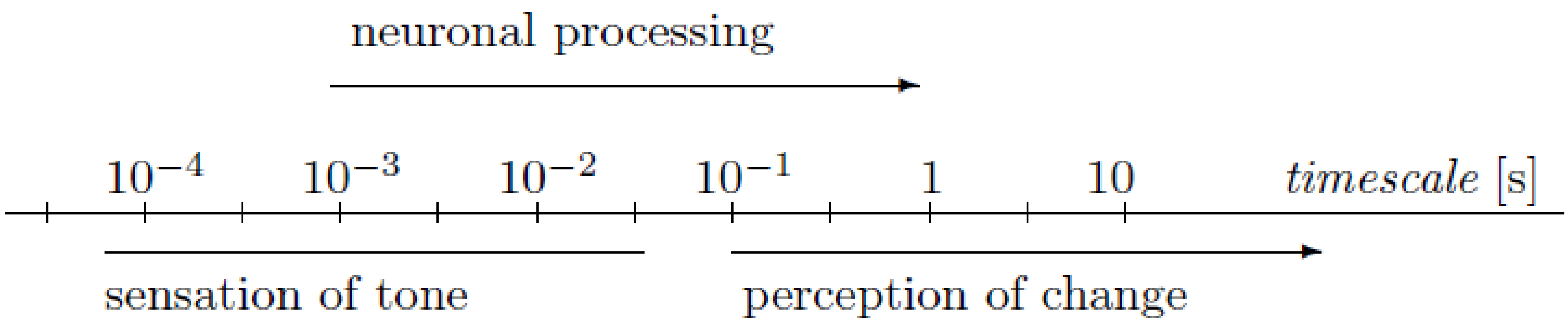



$\nu_m = 10$ Hz

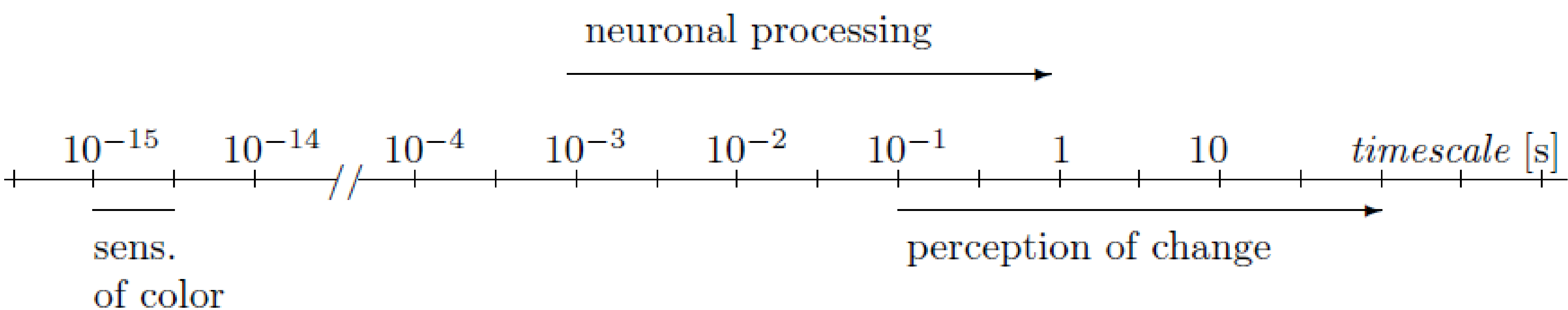



$\nu_m = 100$ Hz

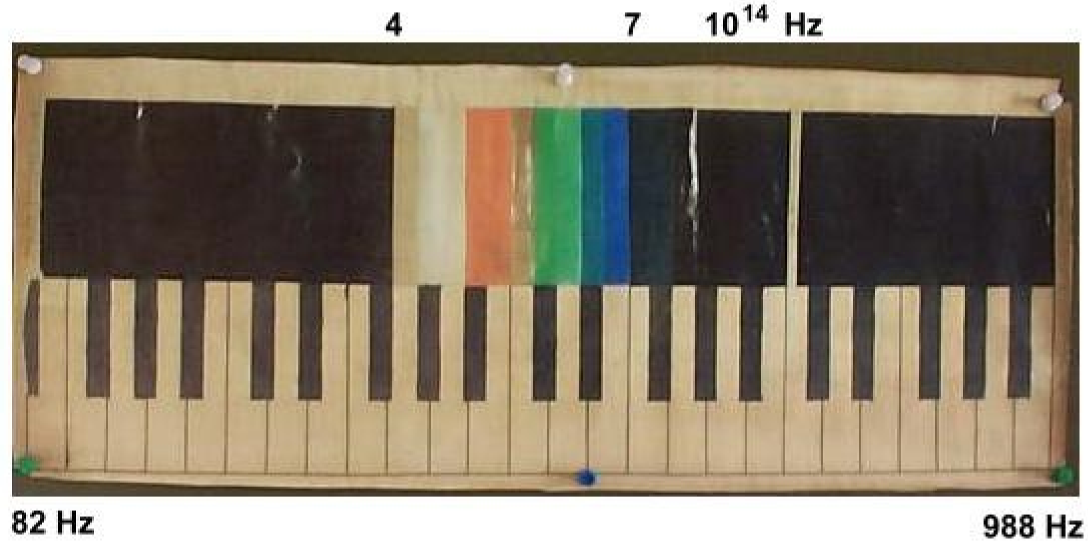
101praat:
sinfreqmod10.wav
sinfreqmod100.wav




Time scales in auditive processes




Time scales in visual processes

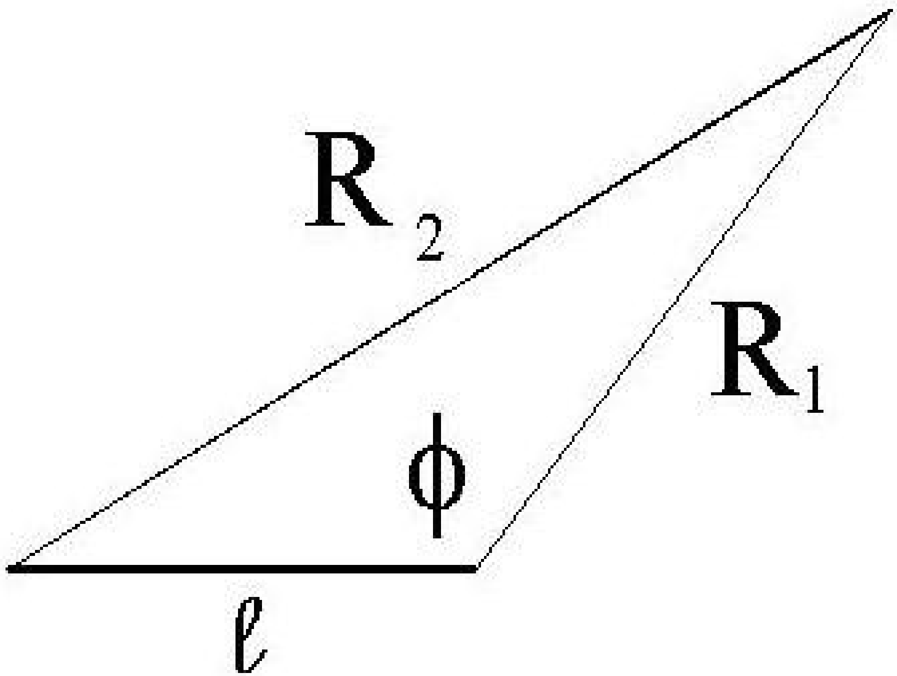



Original collage by Helmholtz to illustrate the optical and acoustical spectrum.

The red has faded away

The reception of sound waves in the ear is achieved by mechanical means on the basilar membrane,
the reception of light by chemical processes in the retina.

In the following only concerned on the time variations in the ms range.




$$R_2^2 = \ell^2 + R_1^2 - 2\ell R \cos\phi$$

$$d = R_2 - R_1 \approx \ell\cos\phi$$

$$\delta T = \frac{\delta d}{c_L} \approx -\frac{\ell}{c}\sin\phi\,\delta\phi$$

time reolution for angular resolution of 10 degrees

$$\frac{\ell}{c}\sin\phi\,\delta\phi \approx \frac{0.2}{330}\cdot\frac{2\pi}{360}\cdot 10 \approx 10^{-4}\ \text{s}$$

shorter than tact of neurons

101praat
gap01-005.wav in 1praat

# 2
# Relation between Physics and Sensation
# Signal-Percept

Psychophysics

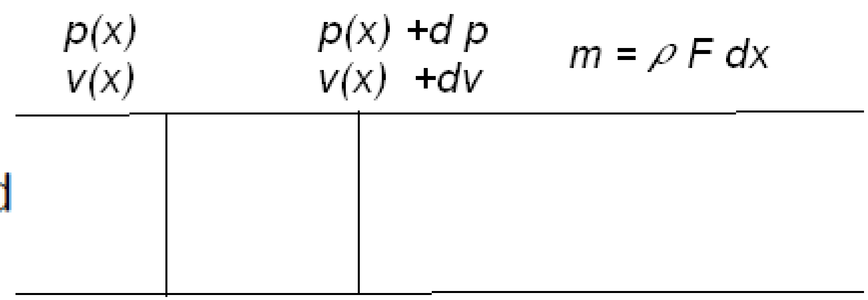
Principal perceived properties of sound:

Loudeness (volume)

Pitch

Timbre

# 2a




Propagation and generation of sound

| | |
|---|---|
| Newton's Law | $m\dot{v} = K$ |
| in our case | $\rho\,\dot{v} = -\partial_x p$ |
| Conservation of matter | $\partial_t \rho = -\partial_x(\rho v)$ |
| Compressibility (adiabatic) | $\frac{d\rho}{dp} = \frac{1}{c^2}$ |

$c$ turns out to be the speed of sound in the material.

For sound:

1) the variations of density and and pressure are small compared to the prevailing values:

$\Delta p \ll p_0$, $\Delta\rho \ll \rho_0$ (e.g. atmospheric conditions).

2) $\dot{v} = \partial_t v + \partial_x v\, v \approx \partial_t v$

Then we obtain:

$$\partial_t \rho = \frac{d\rho}{dp} \partial_t p = -\rho_0 \partial_x v$$

$$\frac{1}{c^2} \partial_t^2 p = -\rho_0 \partial_t \partial_x v = \partial_x^2 p$$

$$\frac{1}{c^2} \partial_t^2 p - \partial_x^2 p = 0$$

(Wave equation in 1+1 dimensions)

General solution (D'Alembert, ca 1750) :

$$p(x,t) = p_+(x + xct) + p_-(x - ct)$$

Also valid for strings, but there $c$ related to the properties of the string (tension, diameter etc).

Solution with harmonic time dependence, $\sim e^{i2\pi\nu t}$, **without** boundary conditions

$$p(x,t) = Ae^{-2\pi i\nu t + ikx + i\delta}$$

$\nu$ Frequency, $k = 2\pi/\lambda = 2\pi\nu/c$) wave number ($\lambda$ wave length).

**With** boundary conditions, e.g. $\rho(0,t) = \rho(L,t) = 0$
special solution

$$p(x,t) = \sin(\frac{n\pi}{L}x)\cos(\frac{n\pi c}{L}t)$$

organ pipe with two open ends or vibrating string

relation between variation of $p$ and $v$ for the wave solution:

$$\omega\rho_0 v = -k\,p \text{ or } p = -Zv$$

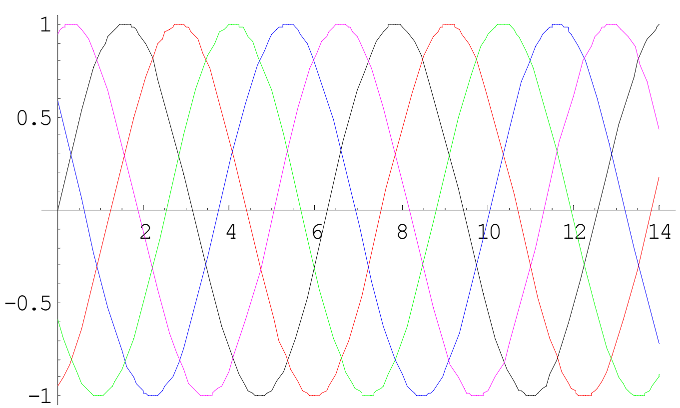
$Z = \rho_0 c$ is called the impedance (wave resistance) of the medium

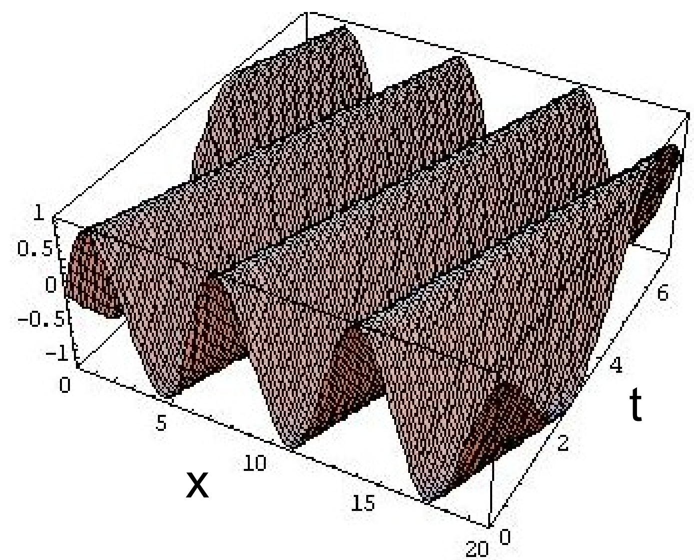
(cf with $U = IR$).

Special solution, **without** boundary conditions (propagation of sound in space):

$\rho(x,t) = A/c^2 \sin(2\pi\nu\, t - k\, x)$

$\nu$ Frequency, $k = 2\pi/\lambda = 2\pi\nu/c$) wave number ($\lambda$ wave length). Wave propagating to the right.



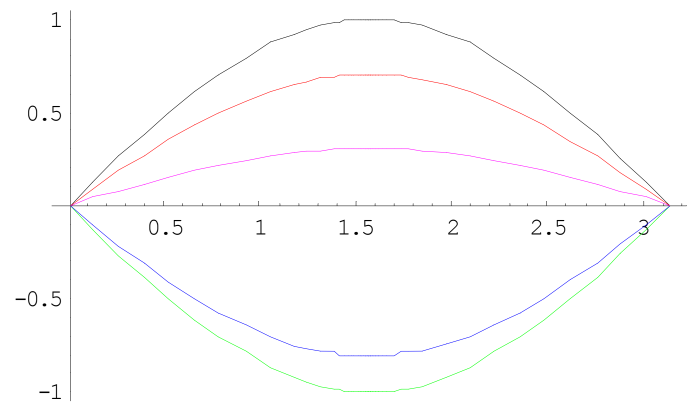

$$\partial_t p = c^2 \rho_0 \partial_x v = -c^2 \rho_0 \frac{k}{\nu} \partial_t v = -Z \partial_t v$$

$Z = \rho_0 c$ is called the impedance (wave resistance) of the medium

(cf with $U = \dot{I} R$).

**With** boundary conditions, e.g. $\rho(0,t) = \rho(L,t) = 0$
special solution

$$\rho(x,t) = \sin(\frac{n\pi}{L}x)\cos(\frac{n\pi c}{L}t)$$




organ pipe with two open ends or vibrating string

101praat sin440

## 2b Relation between acoustical signal (sound pressure) and perception

(to be refined later)

Amplitude of sp Loudeness

If the change of the sensation, $ds$, is proportinal to the relative change of the physical stimulus $R$

$$ds = \frac{dR}{R} \qquad \text{then } s = \log \frac{R}{R_0}$$

$R_0$ is the threshold of sensation.

Therefore in acoustics the measure of the energy of sound pressure level is the decibel (dB).

If $R_0$ is amplitude (actually rms) of the sound pressure level at hearing threshold (at 2000 Hz) then dB (SPL) is given as

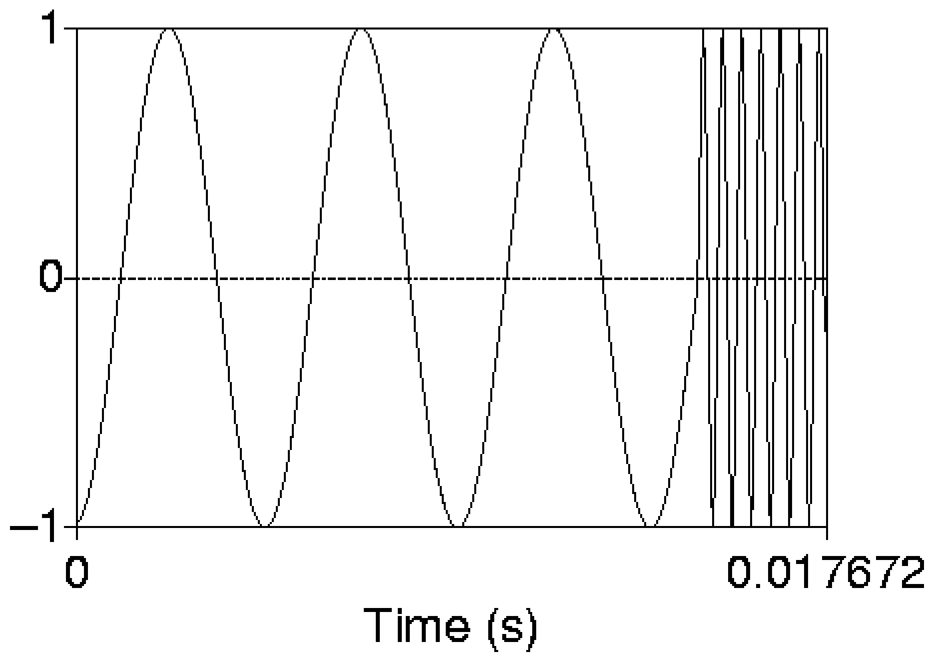
$$10 \log[10, \frac{R^2}{R_0^2}] = 20 \log[10, \frac{R}{R_0}]$$

Relation Energy-loudeness not so simple

101praat: chain leise-mittel-laut

101praat: karm1,harm3,harm7

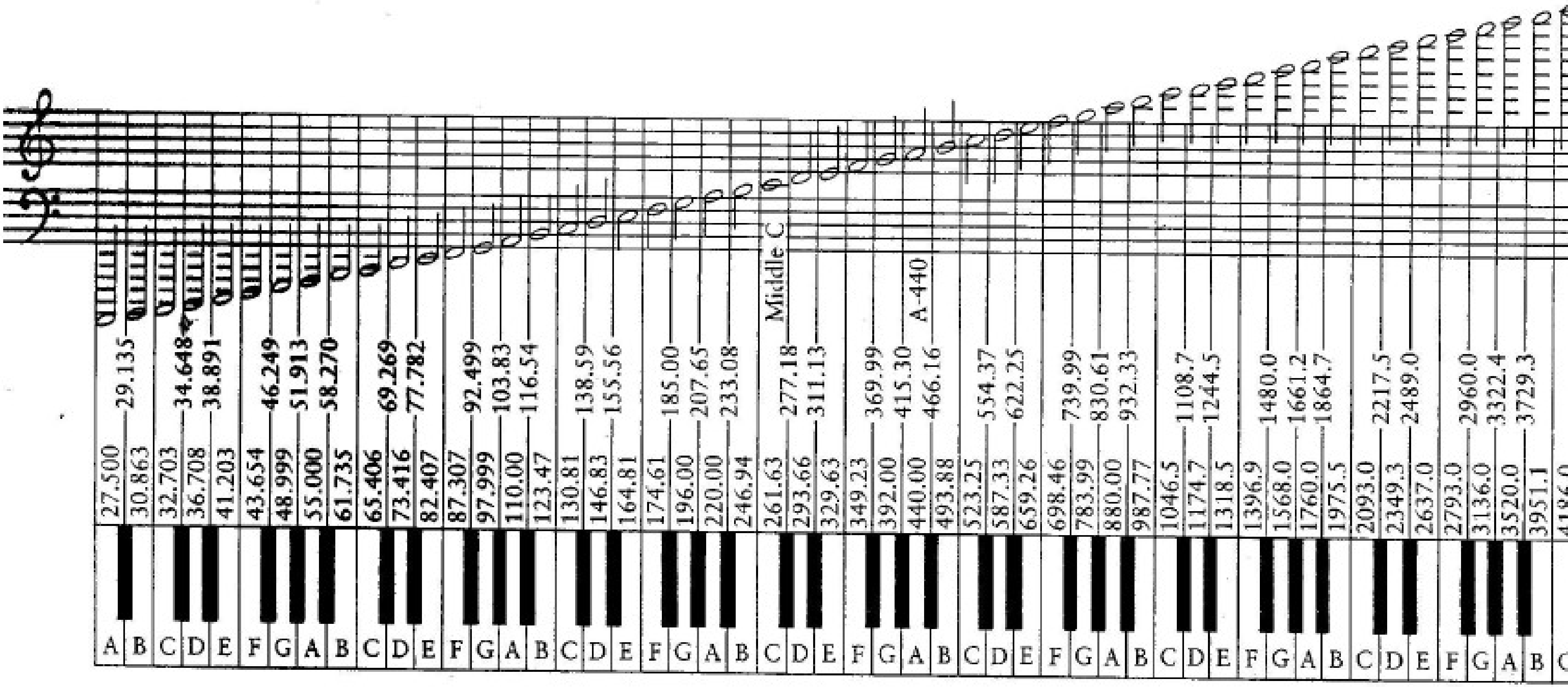
Periodicity pitch of the tone




101praat: tief-hoch.wav

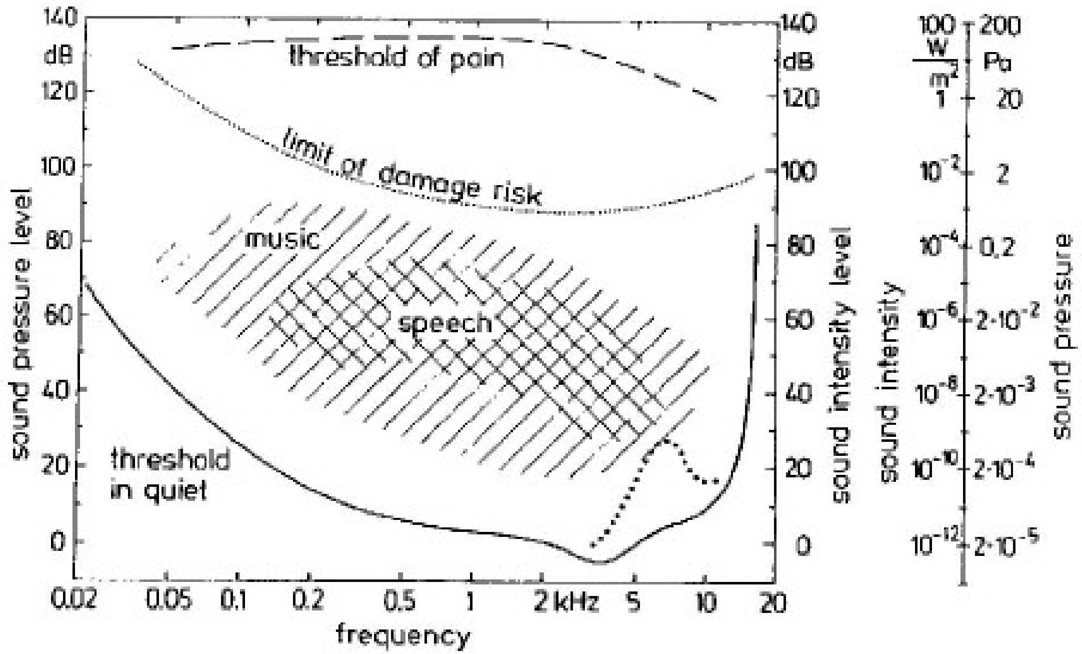
again: real life is a bit more complicated

101praat: sound-440_3-5, 366_4_6

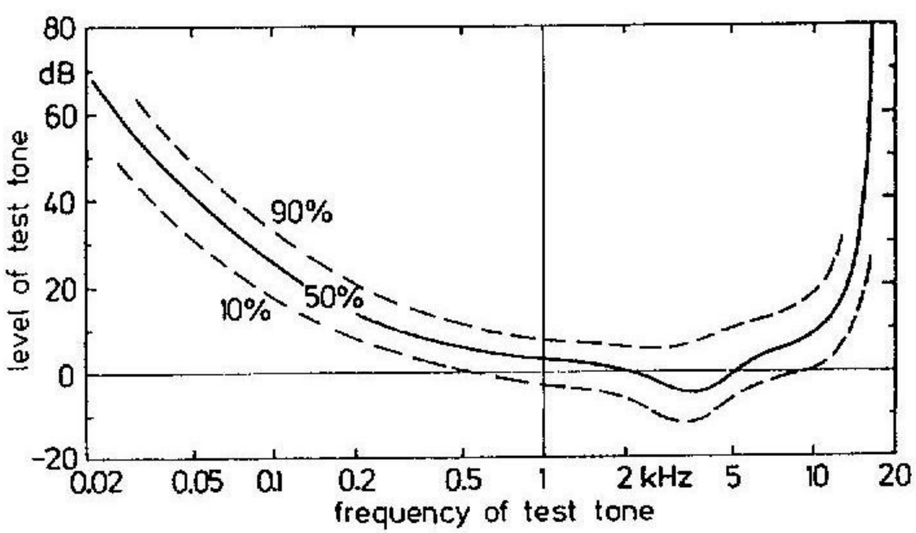


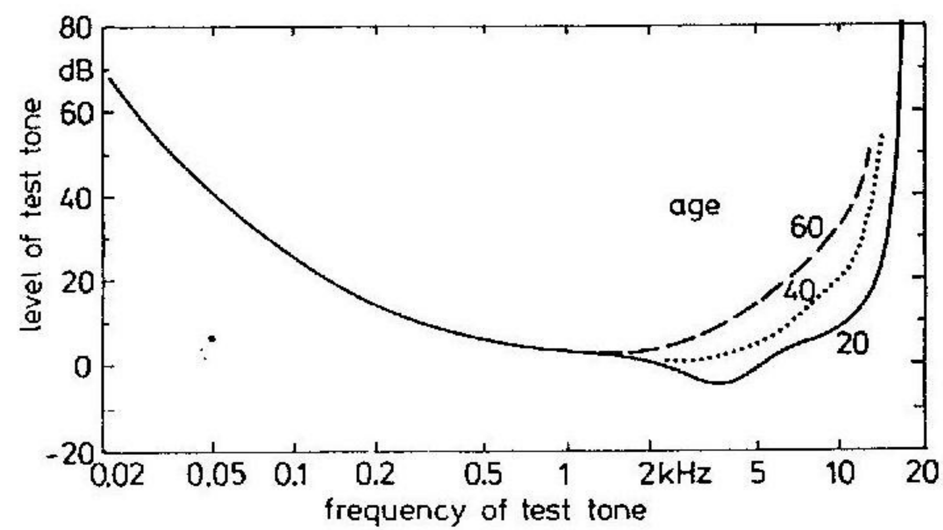
Middle C
A-440
27.500
29.135
30.863
32.703
34.648
36.708
38.891
41.203
43.654
46.249
48.999
51.913
55.000
58.270
61.735
65.406
69.269
73.416
77.782
82.407
87.307
92.499
97.999
103.83
110.00
116.54
123.47
130.81
138.59
146.83
155.56
164.81
174.61
185.00
196.00
207.65
220.00
233.08
246.94
261.63
277.18
293.66
311.13
329.63
349.23
369.99
392.00
415.30
440.00
466.16
493.88
523.25
554.37
587.33
622.25
659.26
698.46
739.99
783.99
830.61
880.00
932.33
987.77
1046.5
1108.7
1174.7
1244.5
1318.5
1396.9
1480.0
1568.0
1661.2
1760.0
1864.7
1975.5
2093.0
2217.5
2349.3
2489.0
2637.0
2793.0
2960.0
3136.0
3322.4
3520.0
3729.3
3951.1
4186.0
A B C D E F G A B C D E F G A B C D E F G A B C D E F G A B C D E F G A B C D E F G A B C D E F G A B C


A2 A1 A a a' a'' a''' a''''

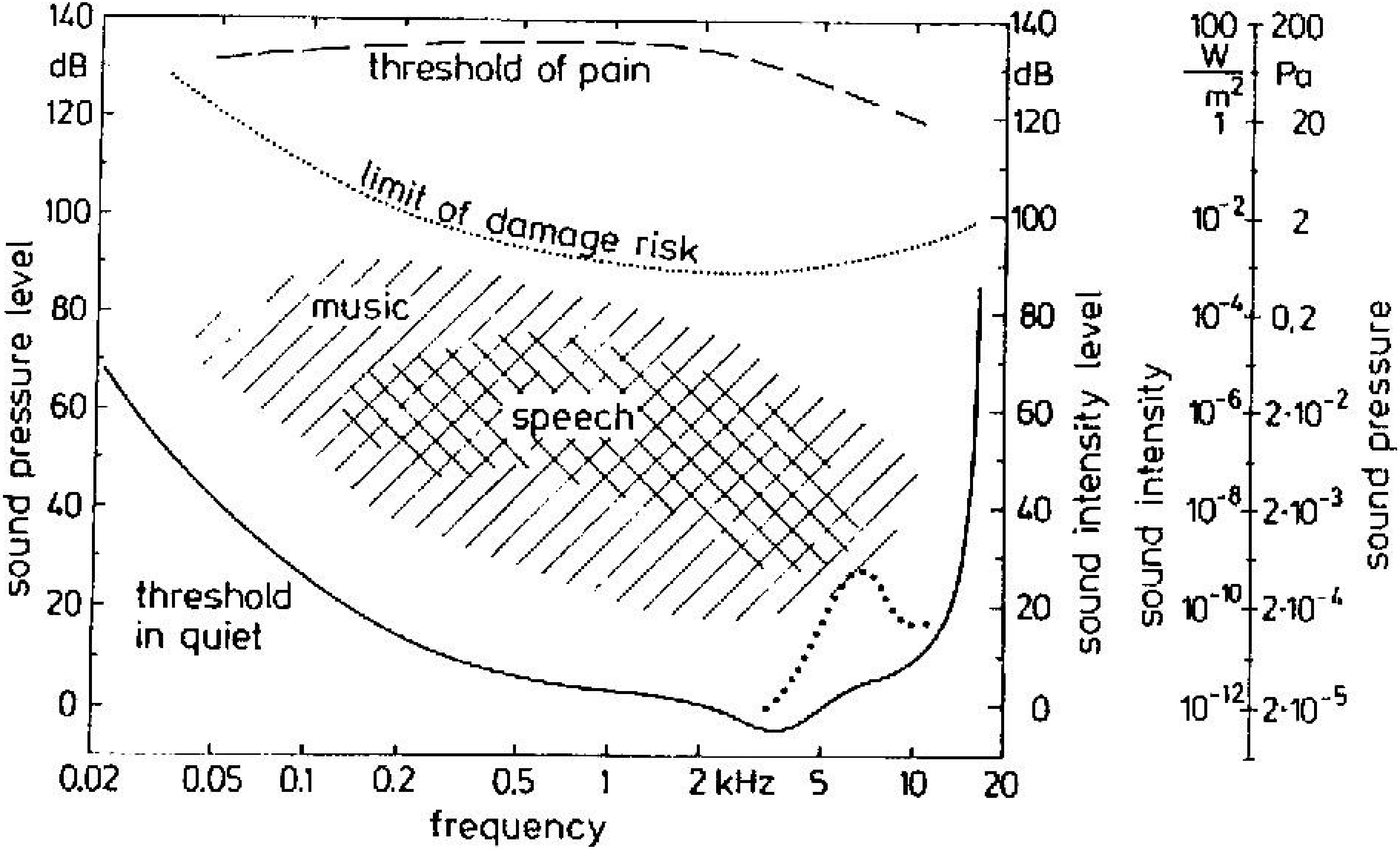



| Intensität W/cm$^2$ | Lautstärke |
| --- | --- |
| $10^{-4}$ | Schmerzgrenze |
| $10^{-7}$ | *fff* |
| $10^{-10}$ | *mf* |
| $10^{-13}$ | *ppp* |
| $10^{-16}$ | Hörschwelle |




101praat: sound440- sound 13_75c (pitch-range.collection)



threshold of pain
limit of damage risk
music
speech
threshold in quiet
sound pressure level
140 dB
120
100
80
60
40
20
0
0.02
0.05
0.1
0.2
0.5
1
2 kHz
5
10
20
frequency
140 dB
120
100
80
60
40
20
0
sound intensity level
100 W/m²
1
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
10⁻¹²
sound intensity
200 Pa
20
2
0,2
2·10⁻²
2·10⁻³
2·10⁻⁴
2·10⁻⁵
sound pressure

Most complicated sensation: timbre

not (approximately) 1 dimensional like volume and pitch
but many properties:

full, thin, soft, harsh .............

general relation:

form of the SP curve timbre

A very important distinction is the different timbre of different vowels

# The human vocal tract

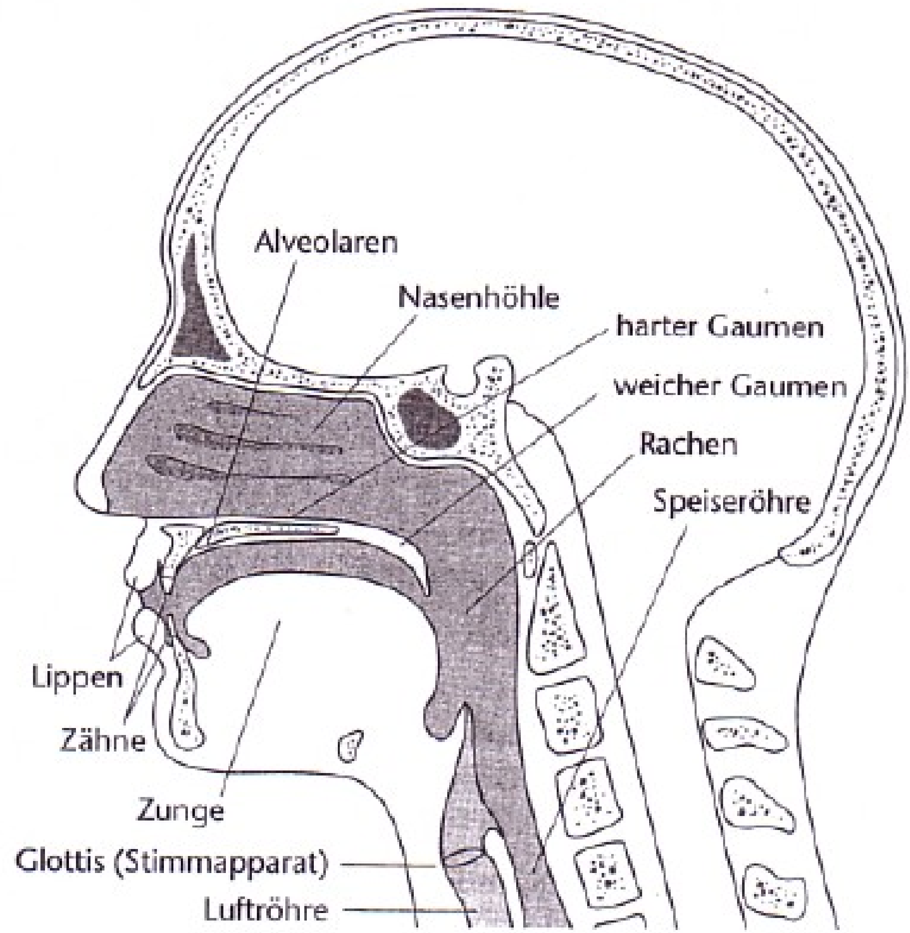
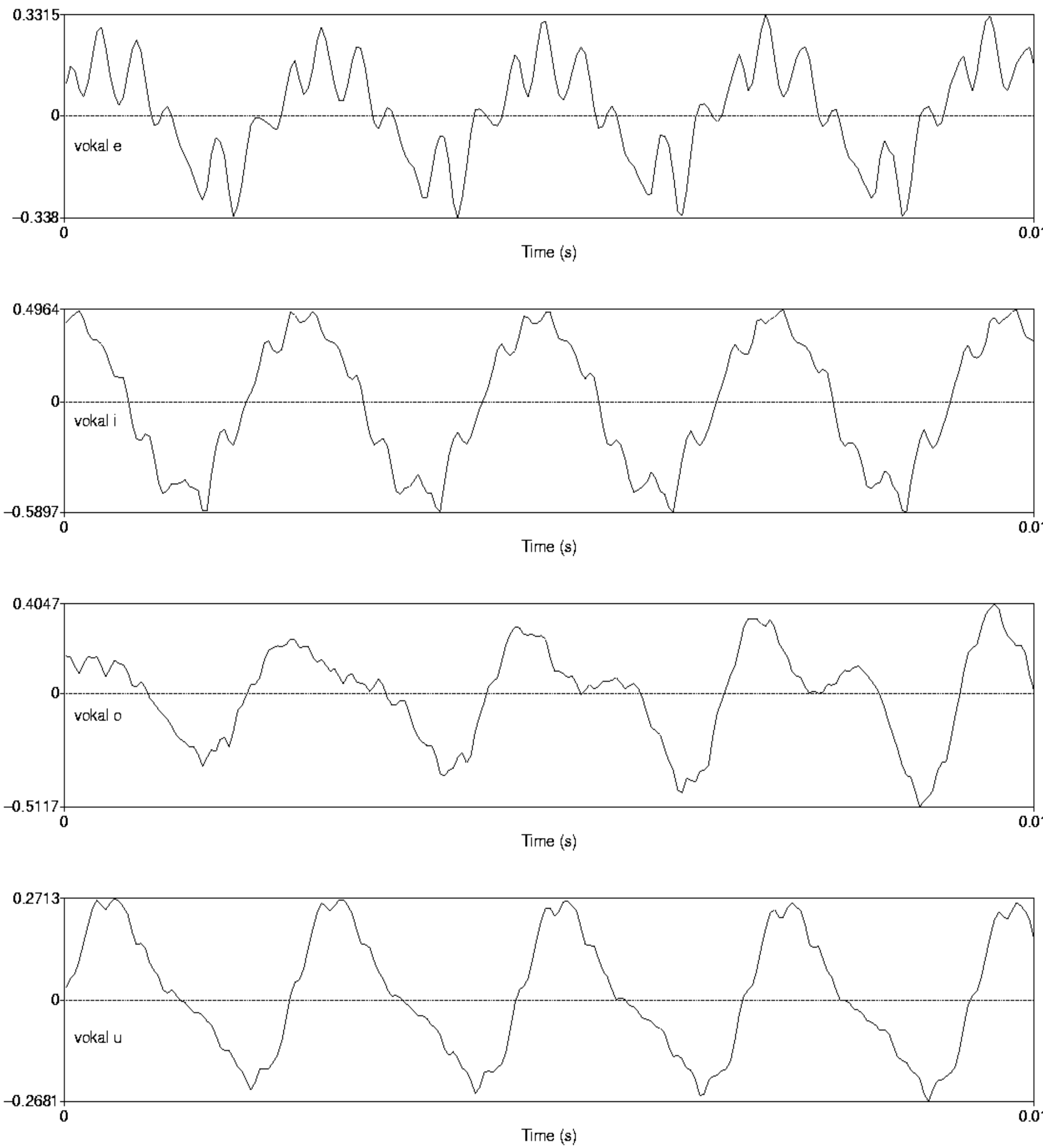
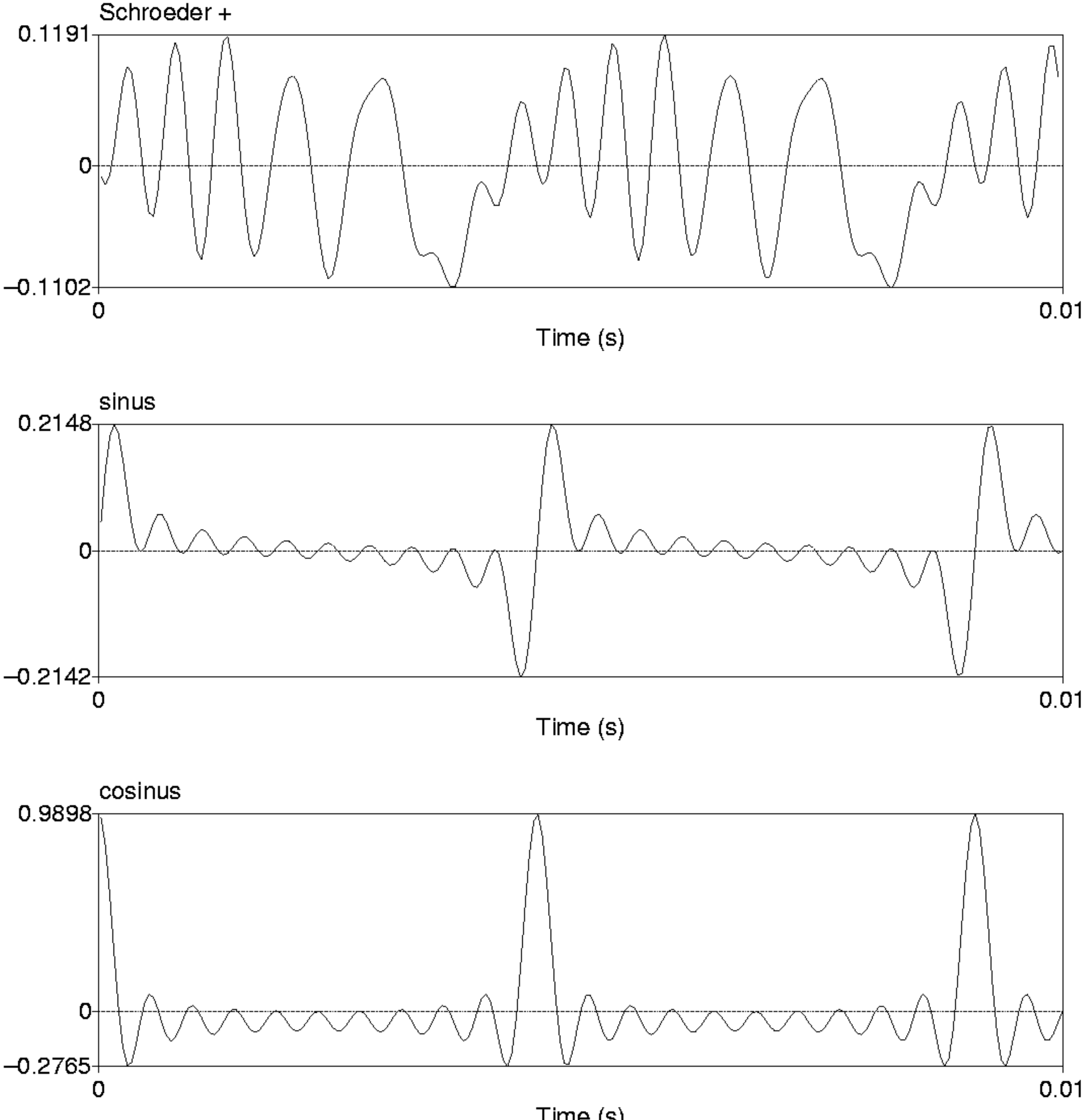



***Abb. 12.1*** *Zum Stimmtrakt gehören Nasen- und Mundhöhle und der Rachen sowie Bestandteile, die sich bewegen, etwa Zunge, Lippen und Stimmbänder.*

The vowels sound very different, though the sp curves look similar:




101praat: e_reg - u_reg




The sound pressure curves look different, but the sounds are practically indistinguishable

101prat:
schroederplus10,
sin10,cos10

# Fourier and wavelet transforms

Fourier transform:

$$\tilde{f}(\omega) = \int_{-\infty}^{\infty} dt \; f(t) e^{i\omega t}$$

magic formula

$$\int \frac{d\omega}{2\pi} e^{i\omega\alpha} e^{-i\omega t} = \delta(t-\alpha)$$

$$f(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \; \tilde{f}(\omega) e^{-i\omega t}$$

The squared modulus

$$|\tilde{f}(\omega)|^2$$

is called *power spectrum.*

The Fourier transform is linear: $\alpha\, f(t) + \beta\, g(t) \rightarrow \alpha \tilde{f}(\omega) + \beta \tilde{g}(\omega)$

If the function $f(t)$ is real, i.e. if f(t) = f*(t), then $\tilde{f}(\omega) = \tilde{f}^*(-\omega)$.

Convolution:

$$(f * g)(\tau) = \int_{-\infty}^{\infty} dt dt' \; f(t) g(t') \delta(t + t' - \tau) = \int_{-\infty}^{\infty} dt \; f(t) g(\tau - t) = \int_{-\infty}^{\infty} dt \; f(\tau - t) g(t)$$

$$\Rightarrow \quad \int_{-\infty}^{\infty} dt\, f(t)\, g(t) e^{i\omega t} = \frac{1}{2\pi} (\tilde{f} * \tilde{g})(\omega)$$

# Signal Processing

$t$ time; $\omega = 2\pi\nu$ circular frequency;
$\nu$ frequency

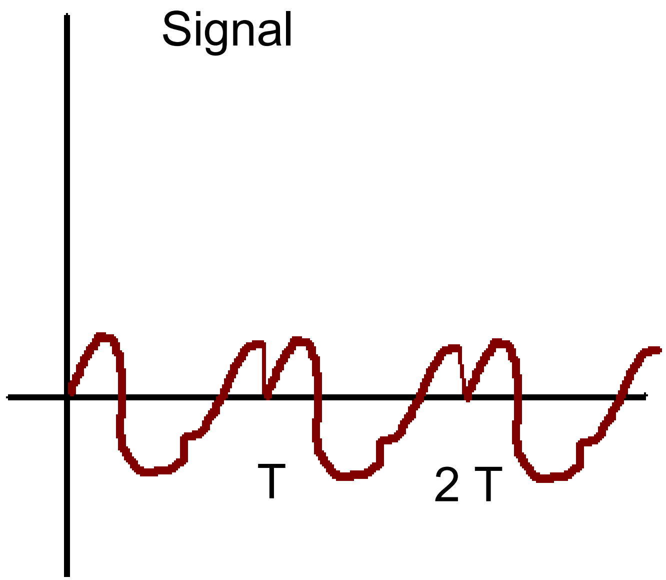
$p(t)$ Signal (e.g. sound pressure as function of time)

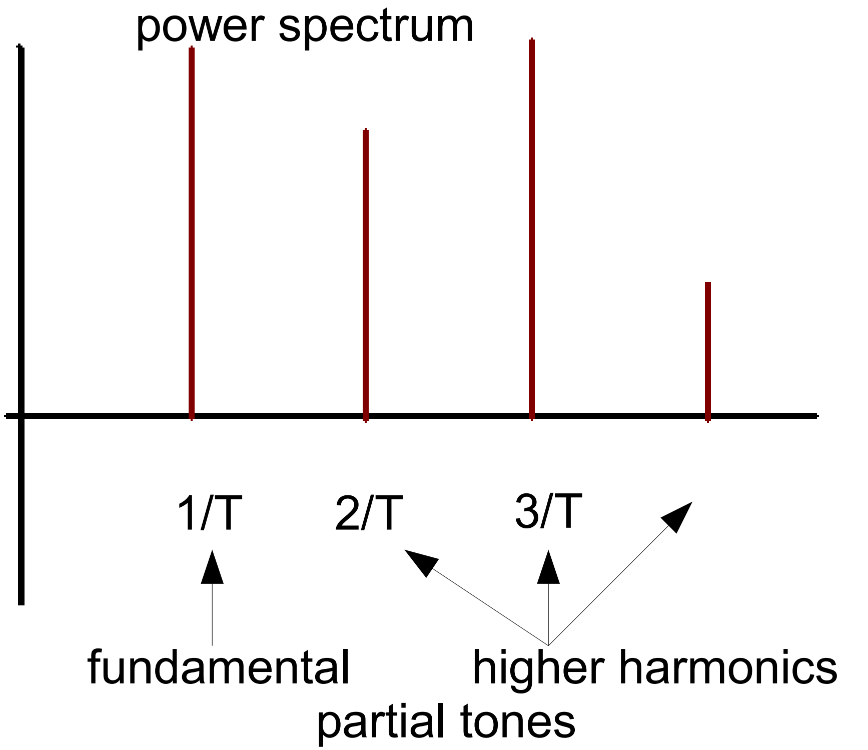
$\tilde{p}(\nu) = \int dt\, p(t)\, e^{i2\pi\nu t}$ spectral function

$|\tilde{p}(\nu)|^2$ (power) spectrum, normally displayed in logarithmic scale (dB) 10 db a factor 10 in power ($\sqrt{10}$ in amplitude)

# Essential Theorem:

If the signal is periodic with period $T$, then the spectral function is different from zero only at $n/T$, $n$ integer. Harmonic spectrum



$$p(t) = p(t+T) \Rightarrow \tilde{p}(\nu) = \sum_n c_n \delta(\nu - \tfrac{n}{T})$$

Proof:

$$p(t) = \int dt \tilde{p}(2\pi\nu) e^{i2\pi\,\nu\,t} = \int dt \tilde{p}(2\pi\nu) e^{i2\pi\,\nu\,(t+T)}$$

$$\Rightarrow \quad 2\pi\,\nu\,T = n$$

Only valid if $\nu\,T = n$ (integer).

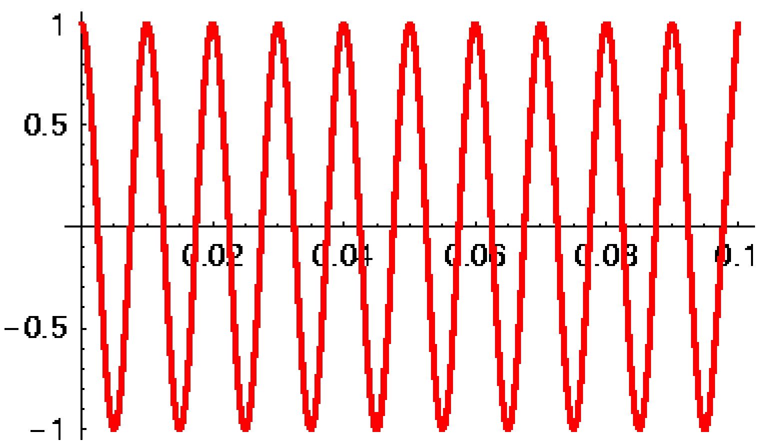
Fourier transform

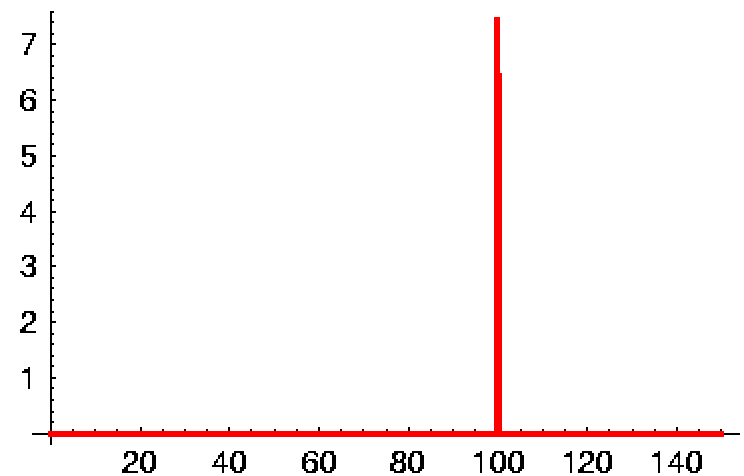
signal

spectral function

$$p(t) = \cos(2\pi\nu_0 t) \qquad \tilde{p}(\nu) = \pi\,\delta(\nu - \nu_0) + \pi\,\delta(\nu + \nu_0)$$
$$p(t) = \sin(2\pi\nu_0 t) \qquad \tilde{p}(\nu) = i\,\pi\,\delta(\nu - \nu_0) - i\,\pi\,\delta(\nu + \nu_0)$$

$\nu_0 = 100$ Hz



Fourier transform

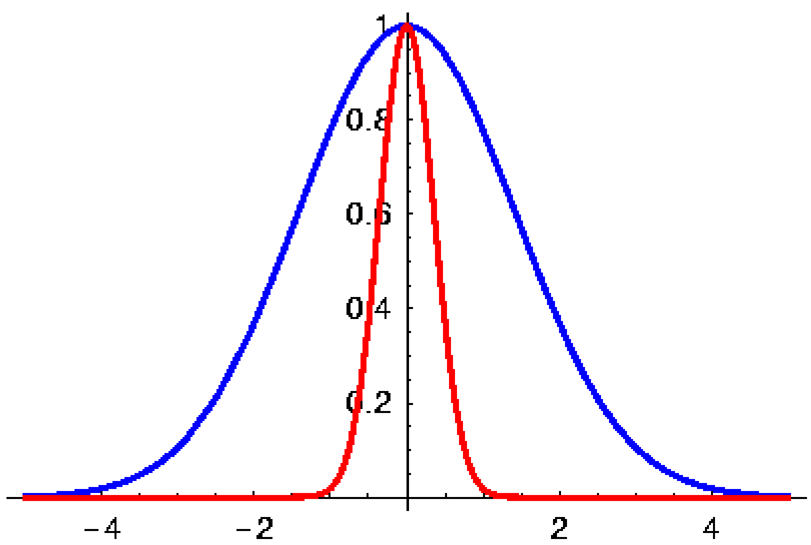
signal

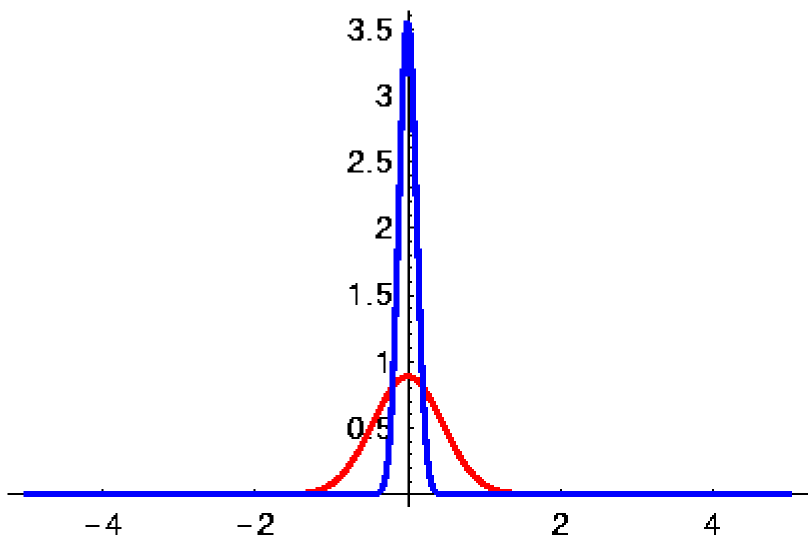
$$p(t) = e^{-(t-c)^2/b^2}$$

spectral function

$$\tilde{p}(2\pi\nu) = e^{i2\pi\nu c}\, b\sqrt{\pi} e^{-b^2(2\pi\nu)^2/4}$$

b=0.5 b=2



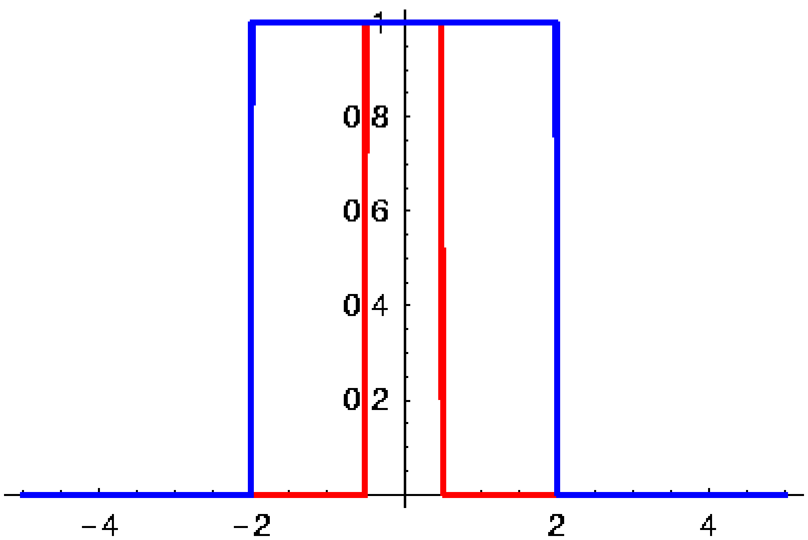
signal

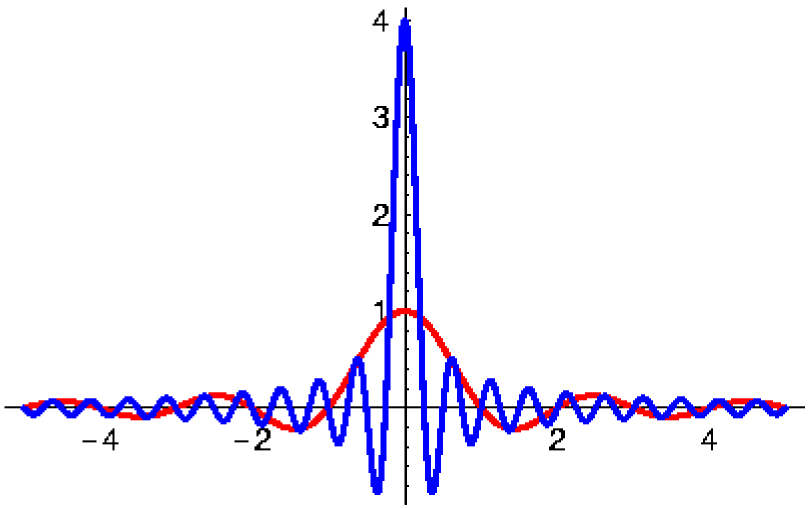
spectral function

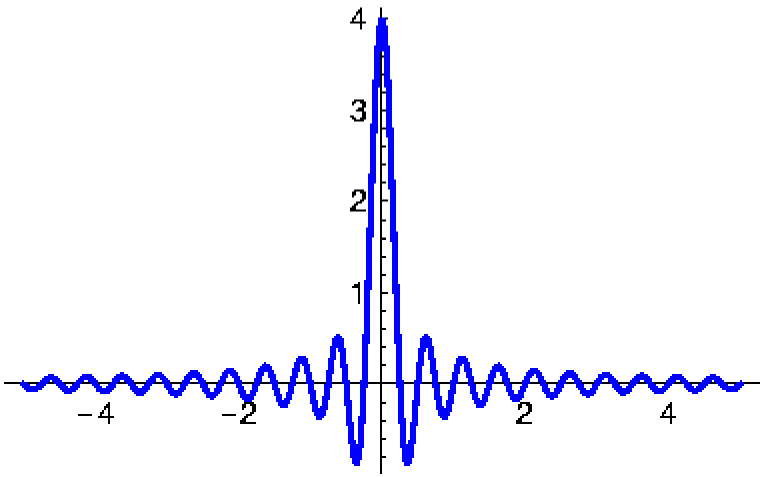
$$p(t) = \theta(t - c + b) \cdot \theta(c + b - t)$$

$$\tilde{p}(\nu) = e^{i2\pi\nu c}\, 2\frac{\sin(b2\pi\nu)}{2\pi\nu}$$

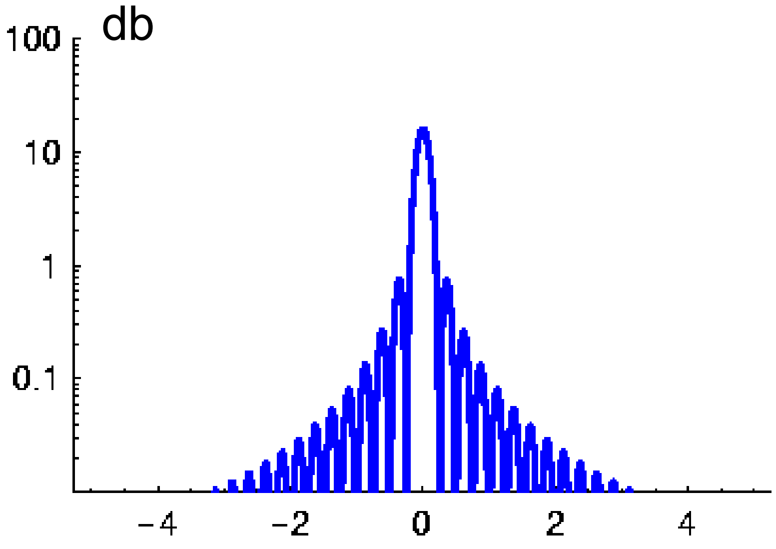
c=0 b=0.5 b=2






spectral function




power spectrum

Windowed Fourier Analysis, Wavelet analysis

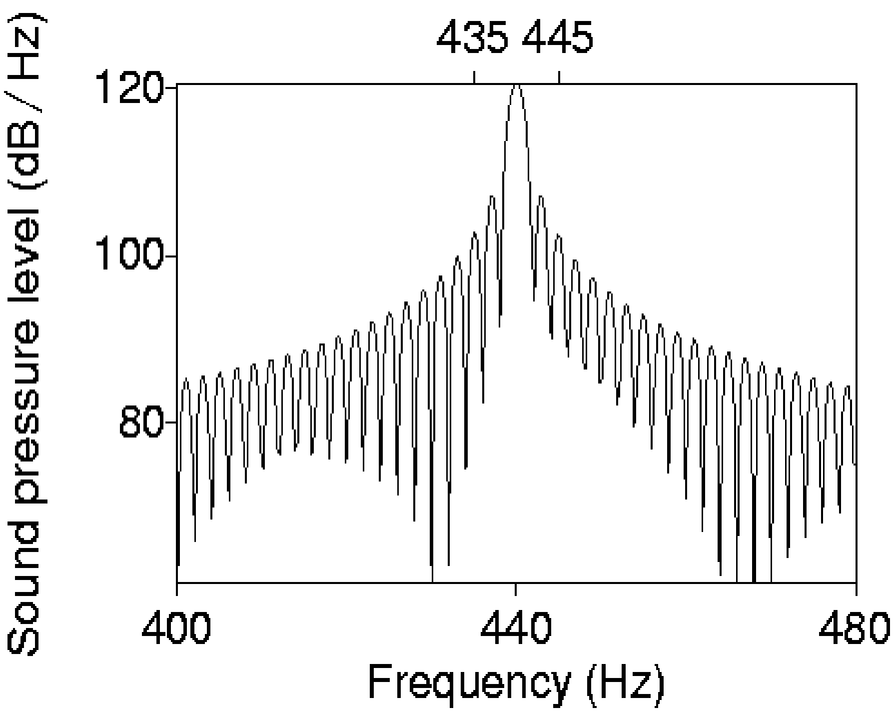
Fourier analysis over a time window, *g(t)* :

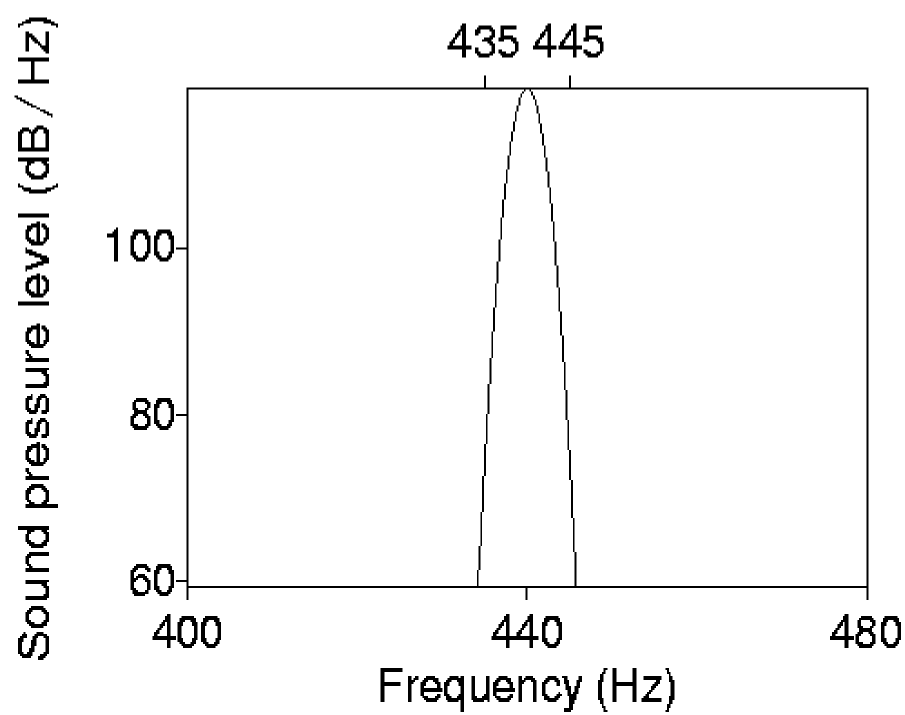
$$\tilde{f}(t,\omega) := \int_{-\infty}^{\infty} dt'\, g(t-t') f(t') \exp[-i\omega t']$$

possible time windows rectangular $g(t-t') = \theta(t-t')\theta(\Delta - (t-t'))$.

Gaussian window $g(t-t') = \frac{1}{\Delta\sqrt{\pi}} \exp[-\frac{(t-t')^2}{\Delta^2}]$.

Power spectrum of $\sin(2\pi\, 440\, t)$ for rectangular and Gaussian window ($\Delta = 0.5s$)



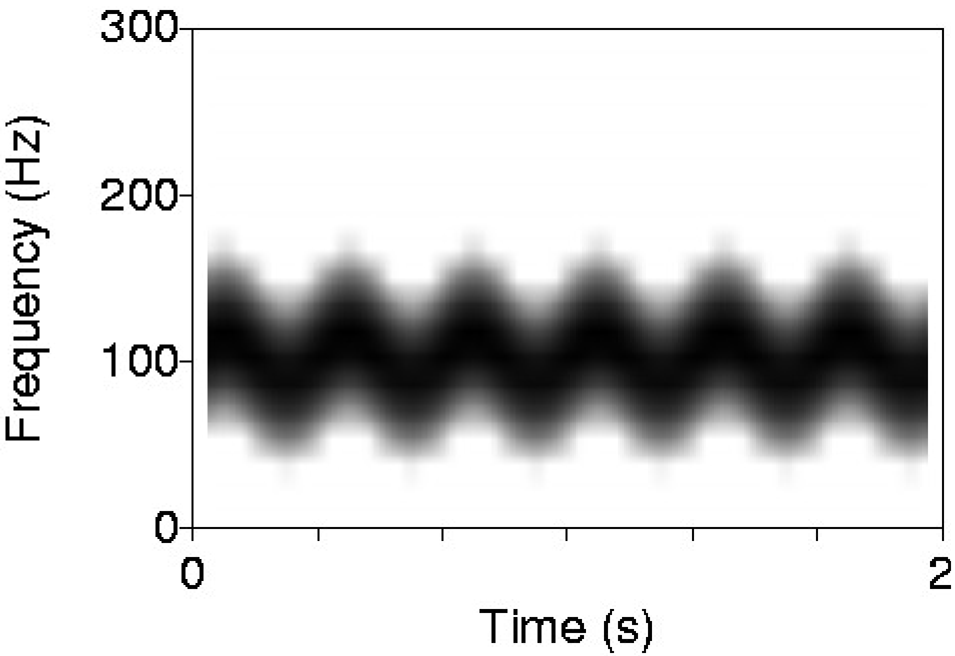
Representaion windowed Fourier transform by Spectrogramm:

time as x-Axes,   frequency as y axis and intensity as  gray value

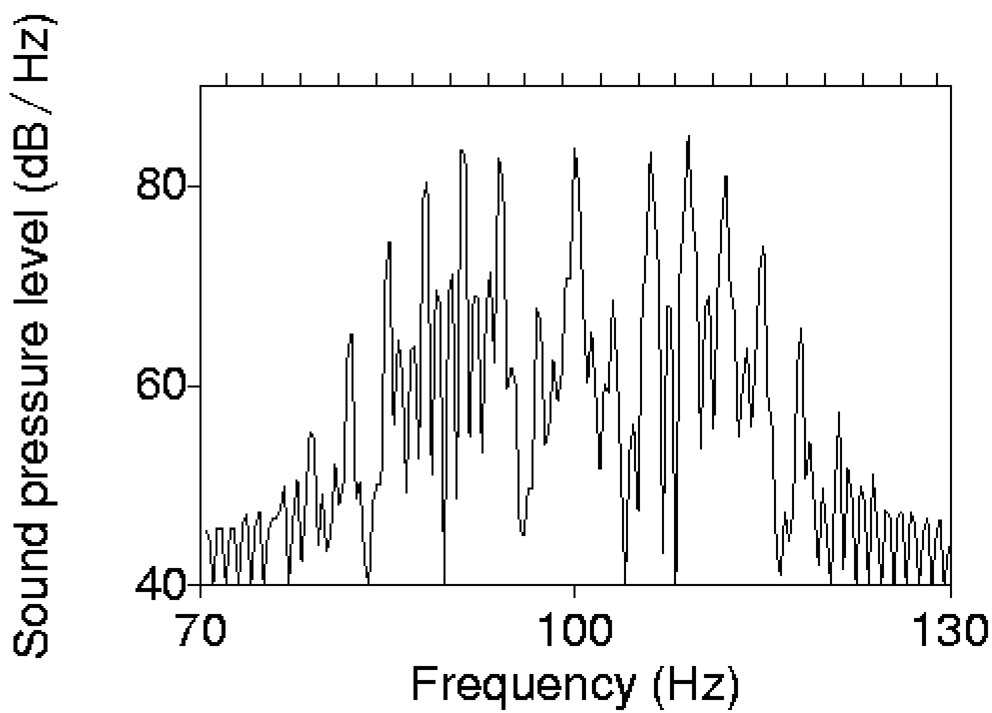
Example: tone with modulated frequency: modulation frequency 3 Hz

```
sin(2*pi*100*x-4*cos(2*pi*3*x))
```

Spectrogram   $\Delta=0.05$ s

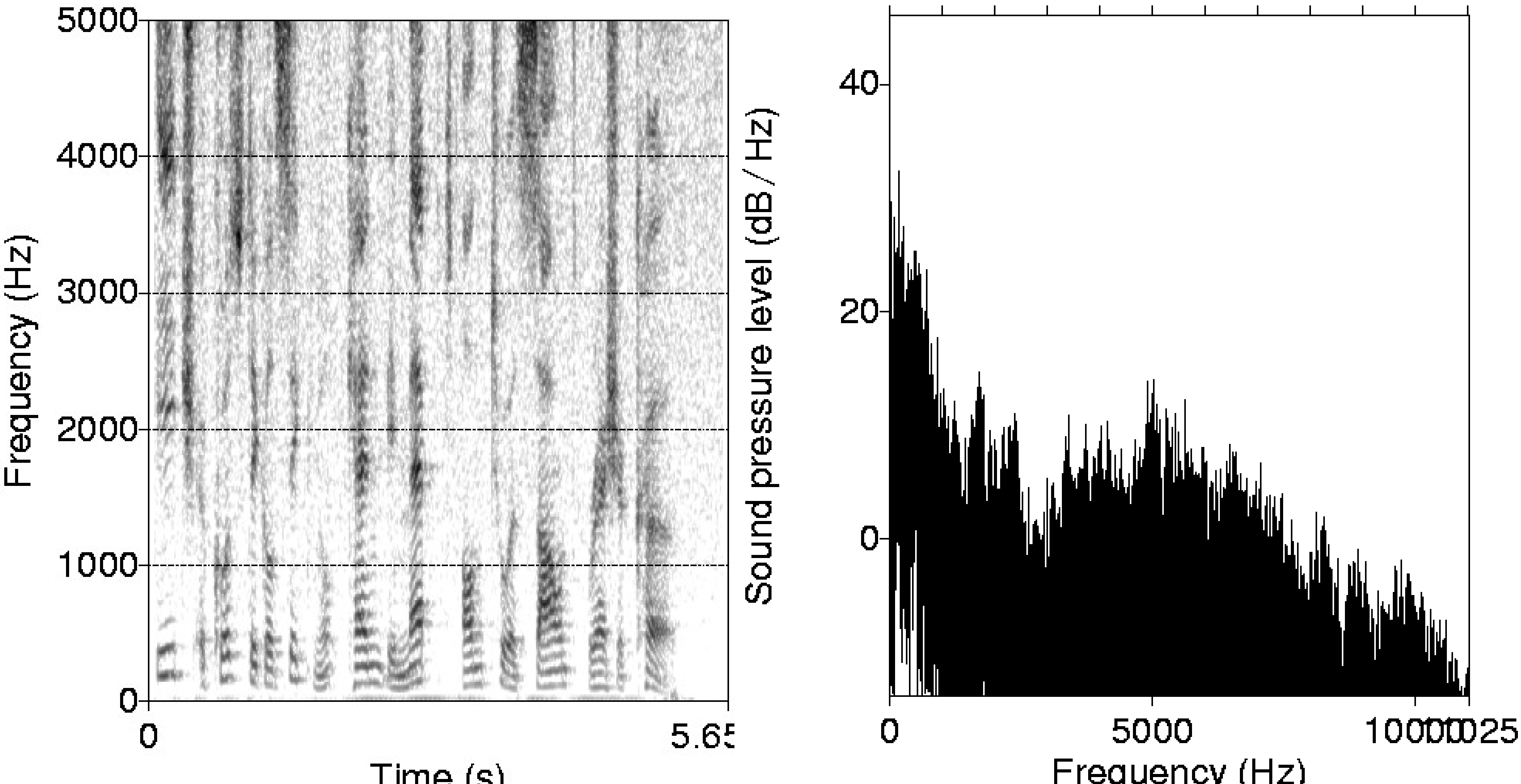



Spectrum

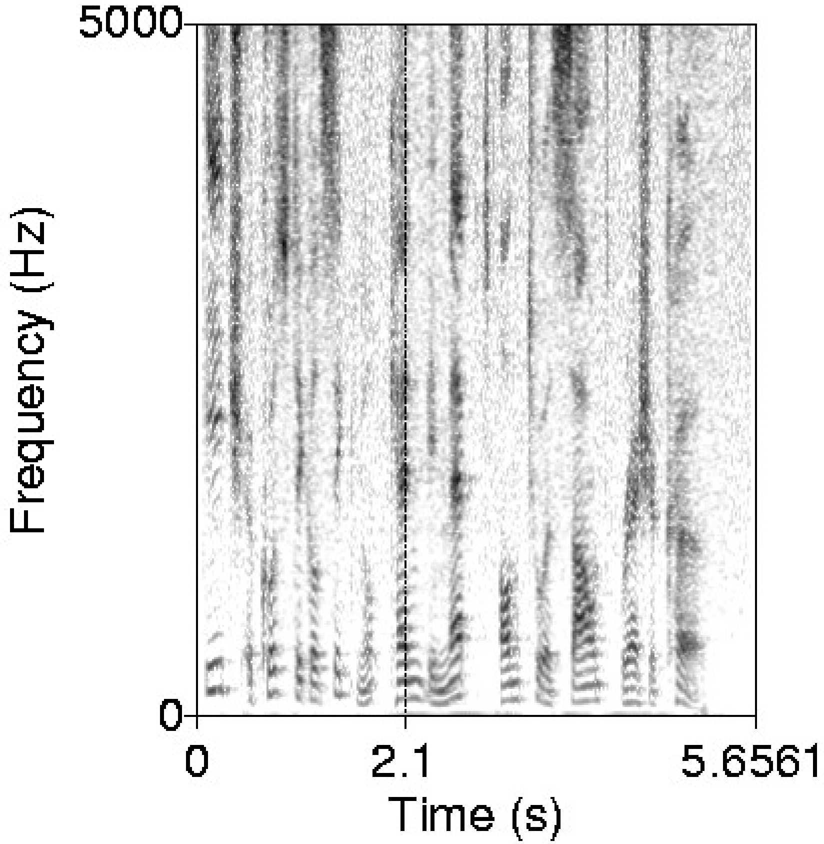


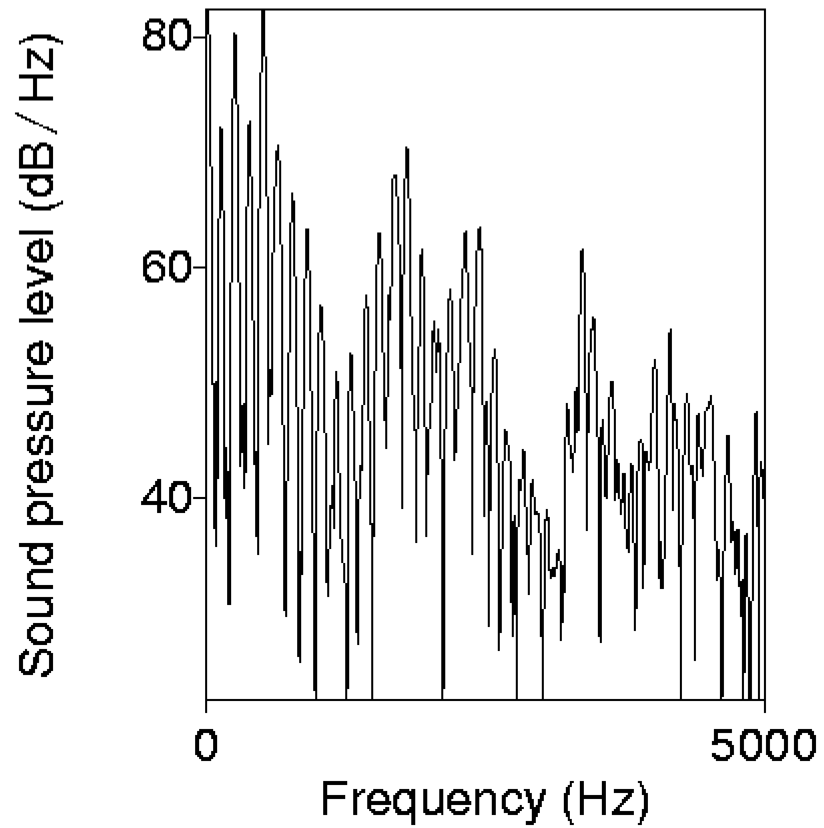

102praat: frequency-modulated.wav

Spectrogram and spectrum of
``Each acoustical signal can be mapped onto a sound pressure curve''



Spectrogram and spectrum taken at 2.1 s with gaussian window 0.05 s



# Wavelet analysis

wavelet analysis is a windowed Fourier analysis, where the time window $g(t)$ depends on the frequency, such that the number of wiggles is always the same:

$$\tilde{p}(t,\nu) = \int dt'\, g((t-t')\nu,\nu) e^{i\,2\pi\,\nu\,(t-t')} p(t')$$

$$\tilde{p}(t,\nu) = \int du\, h(u) p(u + \frac{t}{2\pi\nu})$$

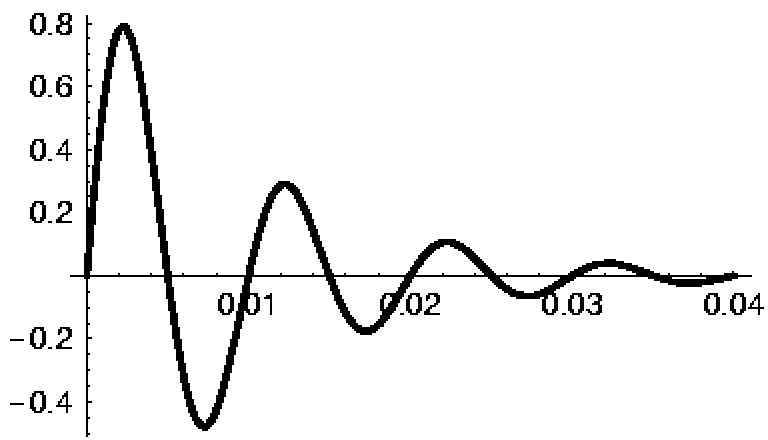
$$u = 2\pi\nu(t'-t), \qquad h(u) = g(u) e^{iu}$$

# Examples for wavelet: Gaussian damped hamonics:

$$h(u) = e^{iu-u}$$

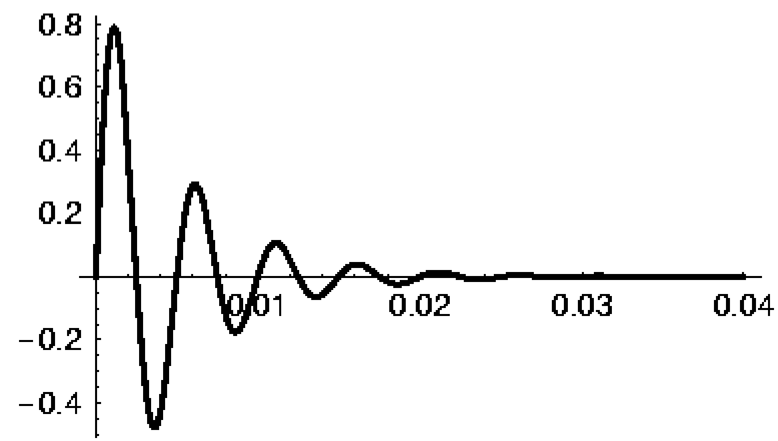
$\nu = 100/(2\pi)$

$\mathrm{Im}\, h(u)$




$\nu = 200/(2\pi)$

$\mathrm{Im}\, h(u)$



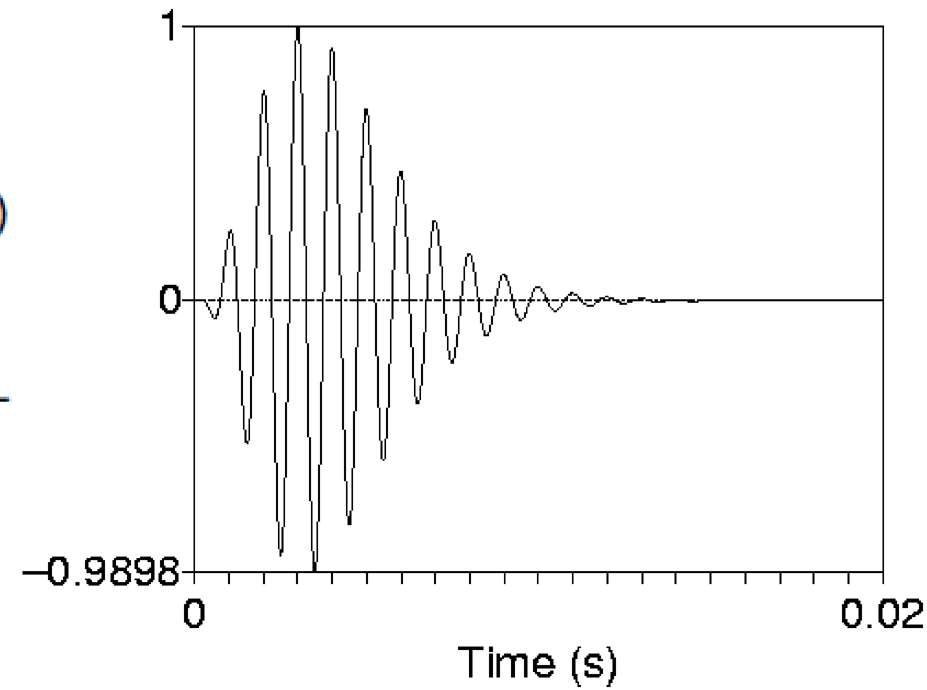

*h(u)* is called a ``note'' :

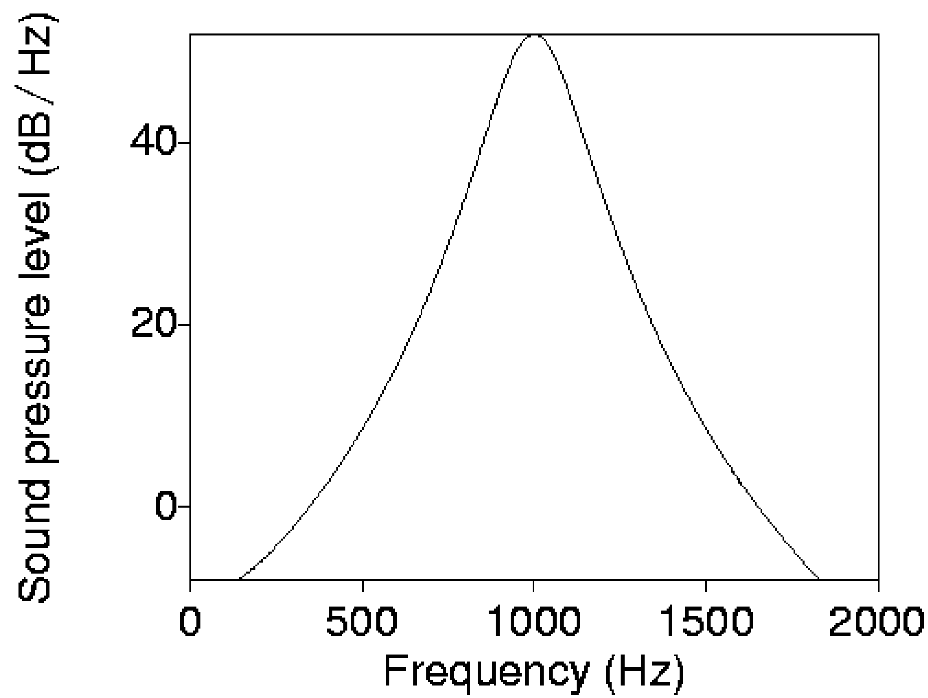
102praat note.wav

In acoustics the gamma-tone is a particularly popular wavelet

$$p_\gamma(t) = t^{\gamma-1} e^{-2\pi\, b(\nu_0)\, t} \cos(2\pi\, \nu_0\, t)$$

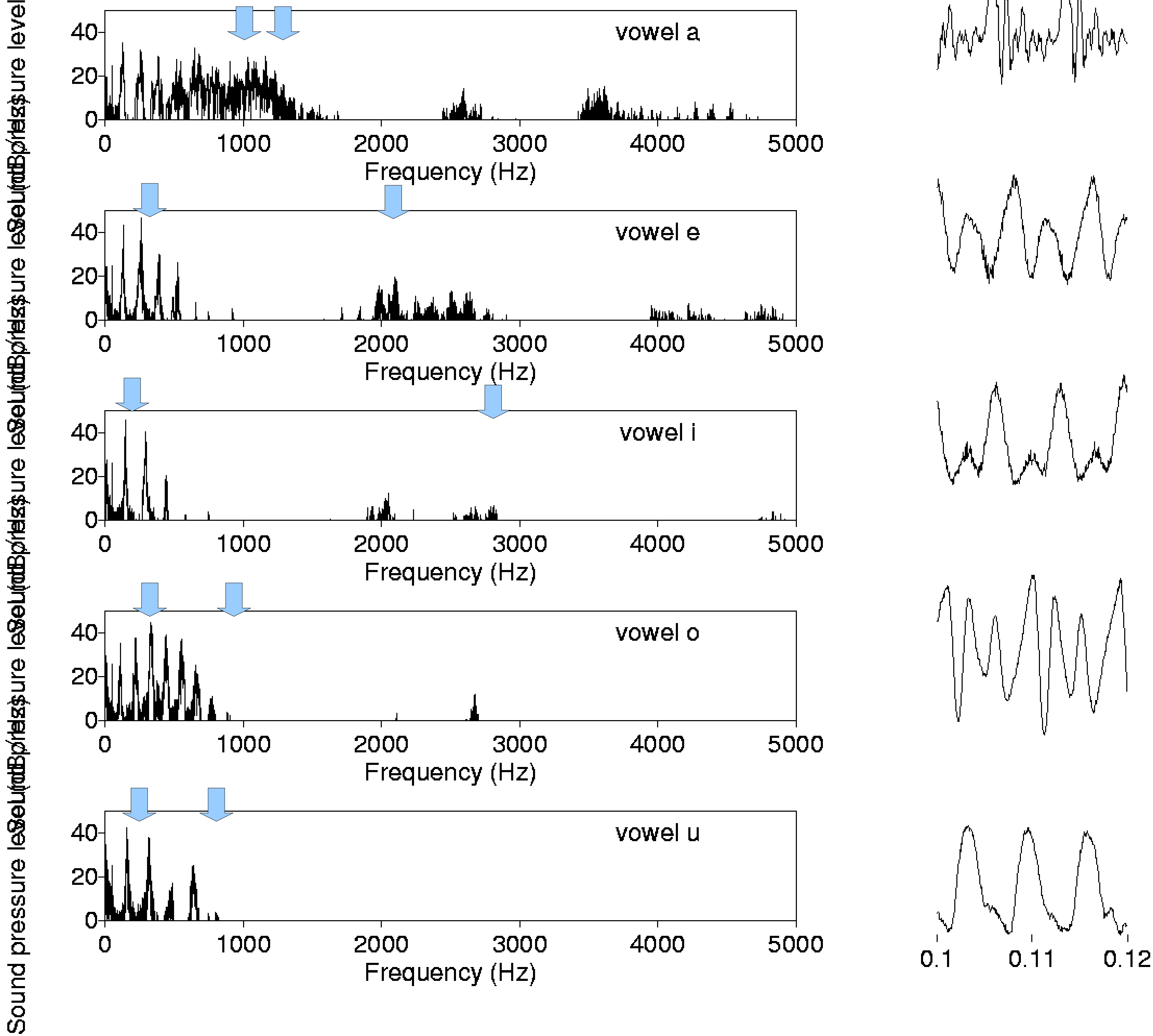
$$\tilde{p}_\gamma(\nu) = \Gamma(\gamma+1) \left( \frac{1}{(b(\nu_0)+i\,(\nu+\nu_0))^\gamma} + \frac{1}{(b(\nu_0)+i\,(\nu-\nu_0))^\gamma} \right)$$




signal and spectrum of gamma-tone with
t=4
b = 150 Hz
$\nu_0$ =1000 Hz

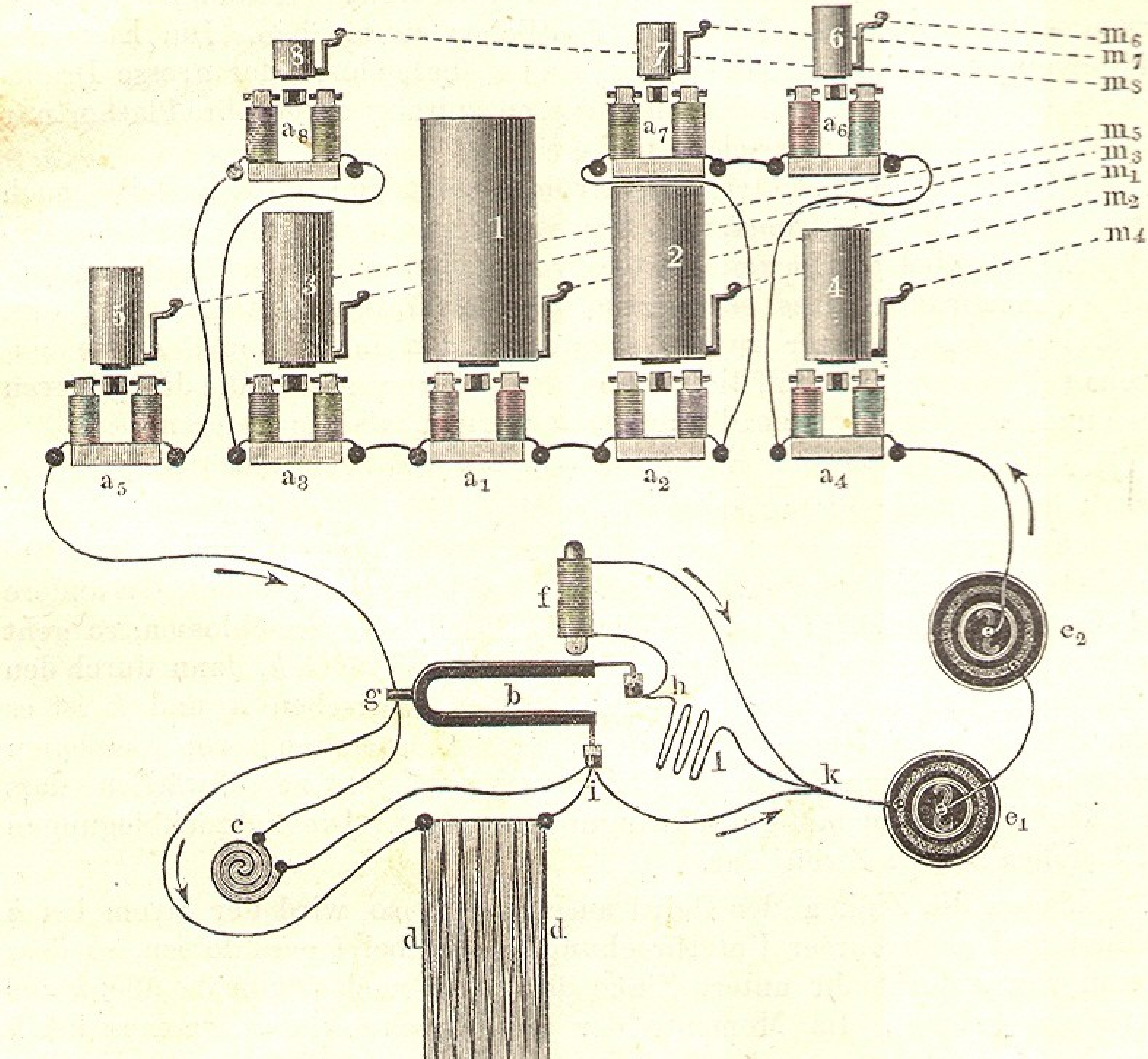
# Vowels, spectra and signals



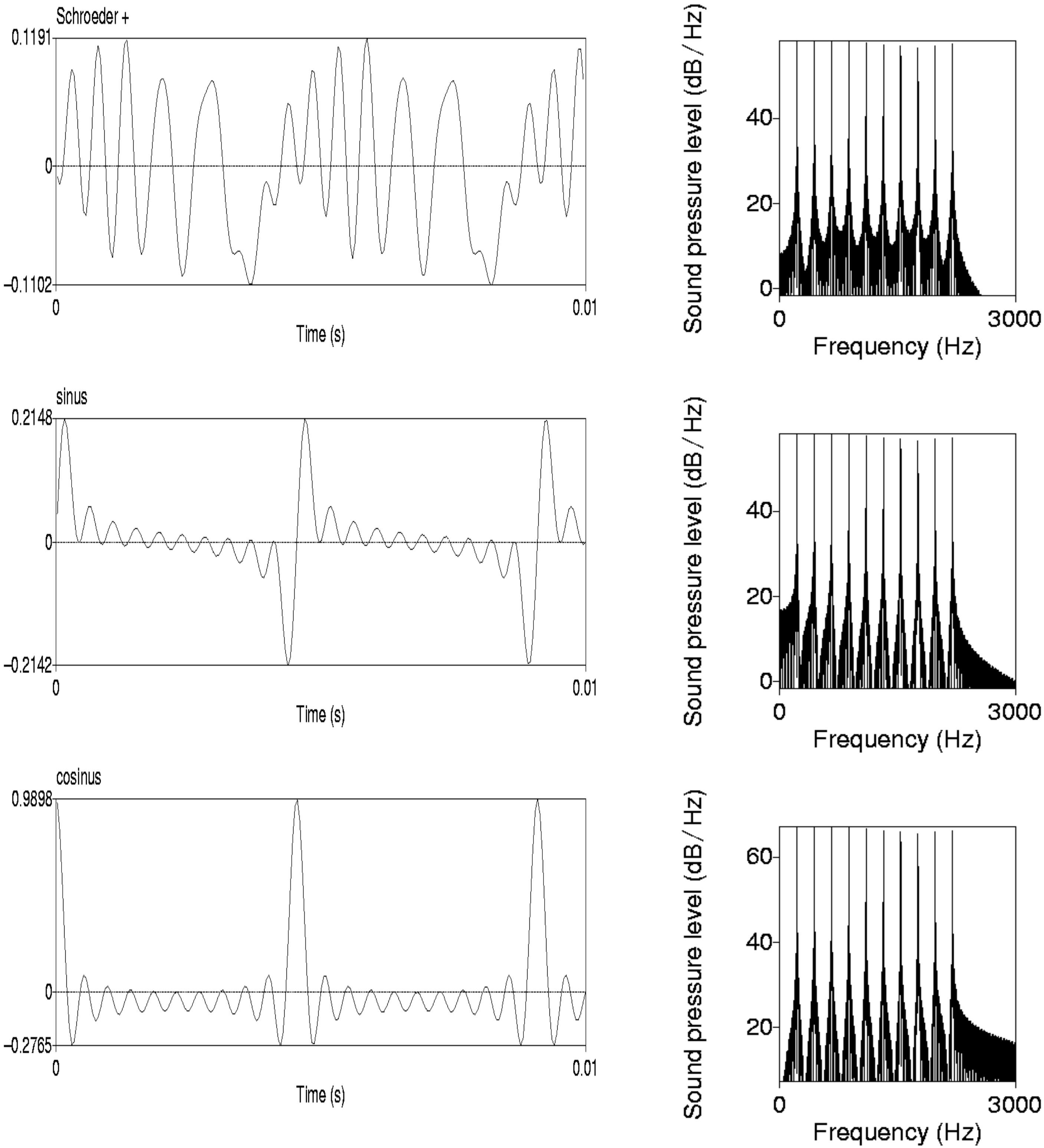

102praat
vokale-hgd
rauschen fuer
rauschvokale

| | | |
|---|---|---|
| a | **1000** | 1400 |
| e | 500 | **2300** |
| i | 320 | **3200** |
| o | **500** | 1000 |
| u | **320** | 800 |

Fig. 64.




App. of Helmholtz to produce artificially vowels sponsored by Ludwig II von Bayern



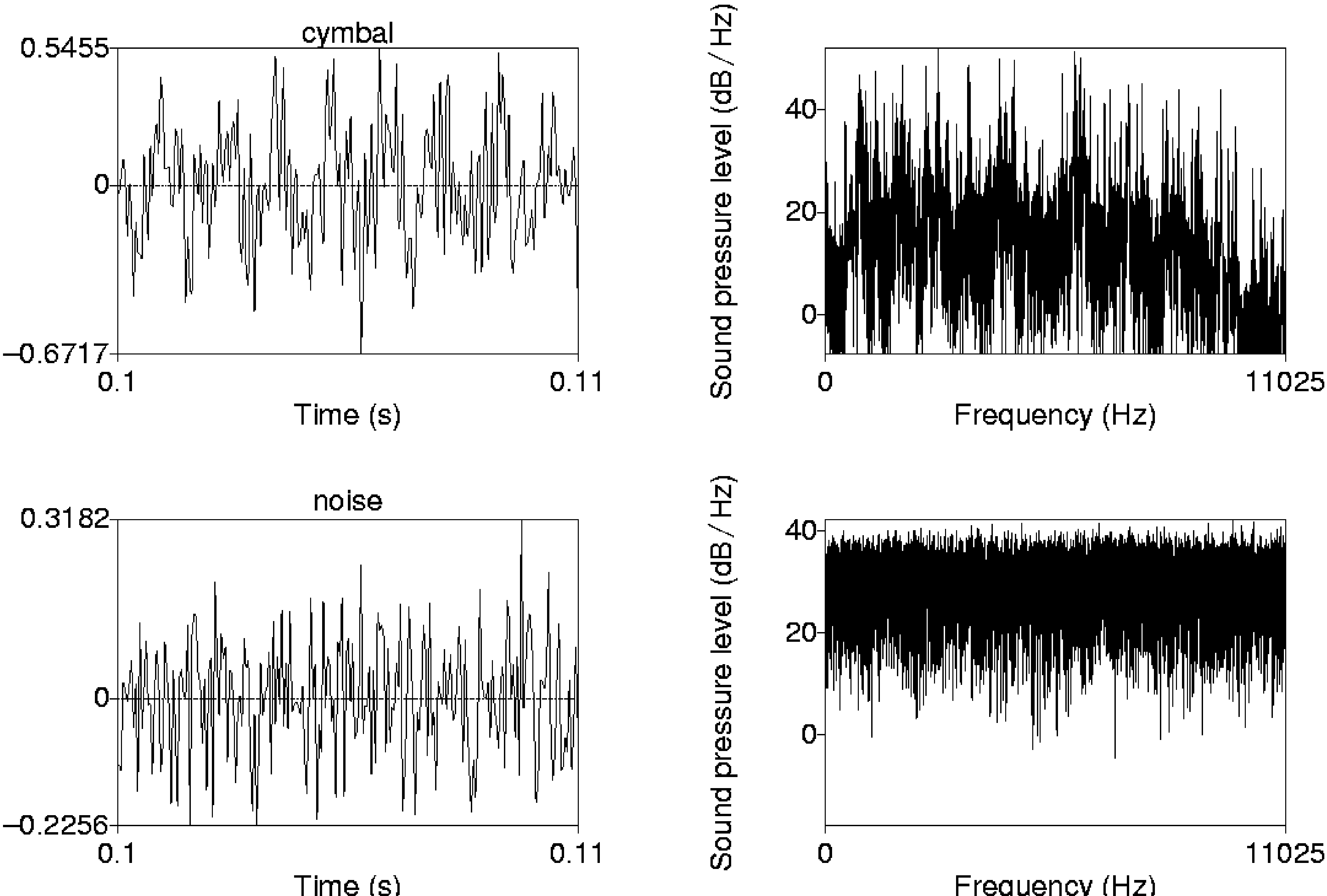

The sound pressure curves look different, but the sounds are practically indistinguishable

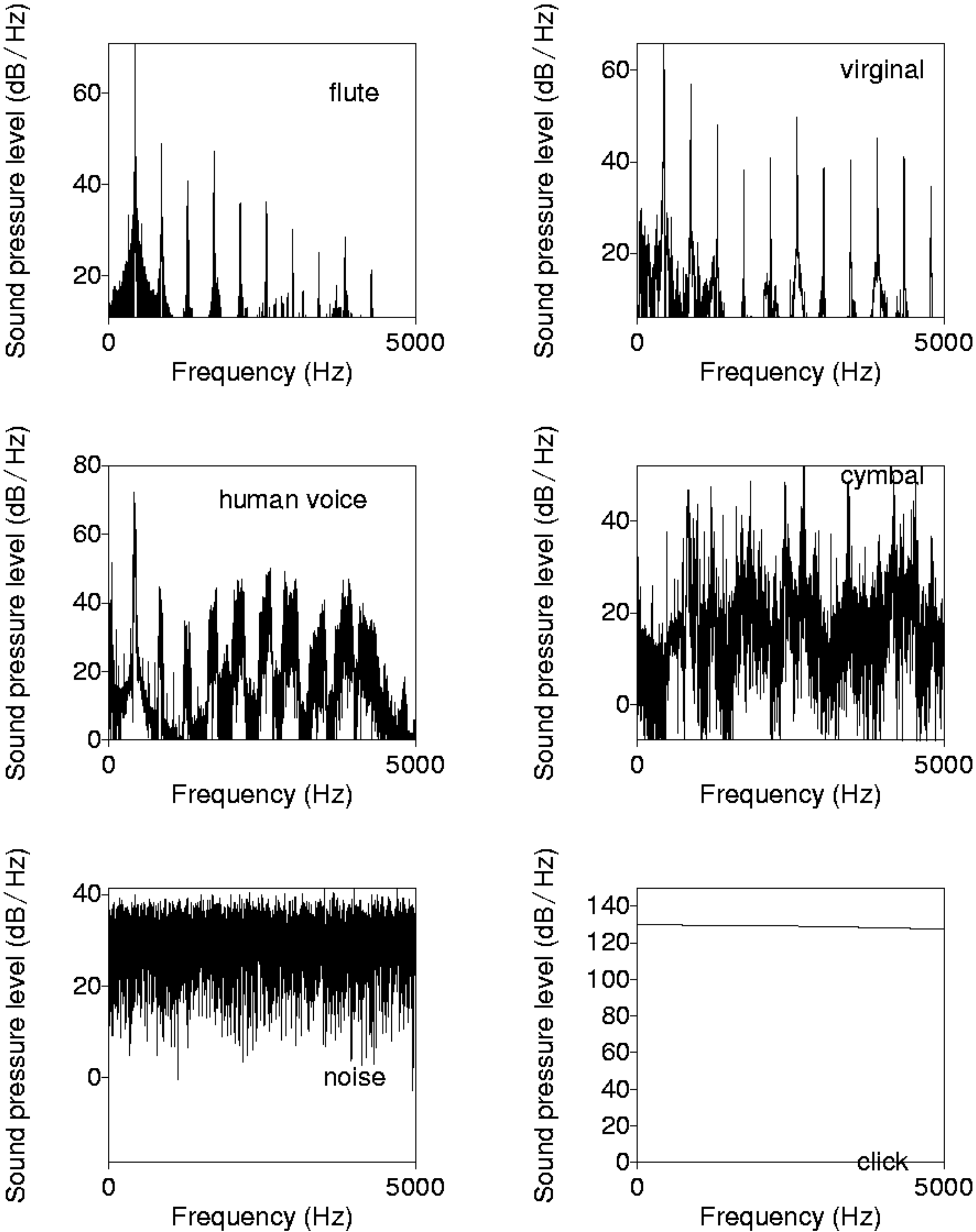
but the power spectra are up to a scale identical

First refinement:

102praat  cymbal.wav, noise.wav

Timbre  determined by the **power spectrum**






Few spectral lines (few harmonics) soft tone many harmonics sharp tone

102praat
flute.wav spinett.wav
i-reg.wav cymbal.wav
noise.wav click.wav

# Ohm's Law of Acoustics:

Ohm  1841, Helmholtz 1863

1) Ear performs a (windowed) Fourier analysis

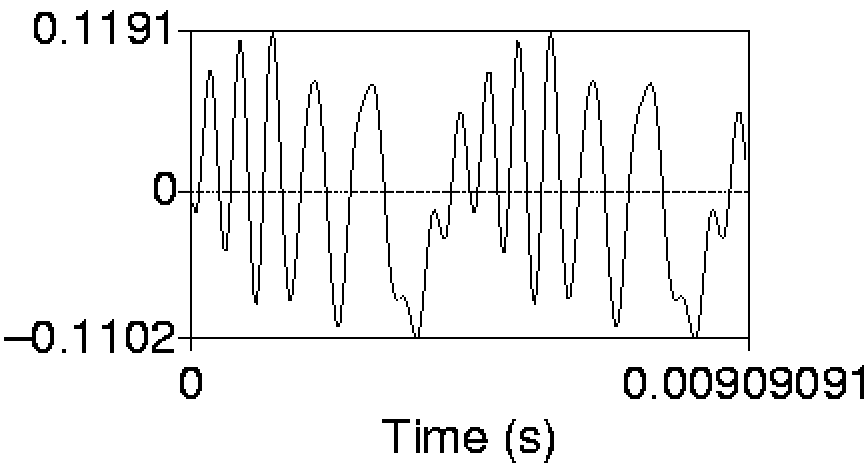
2)  Phases play no role.

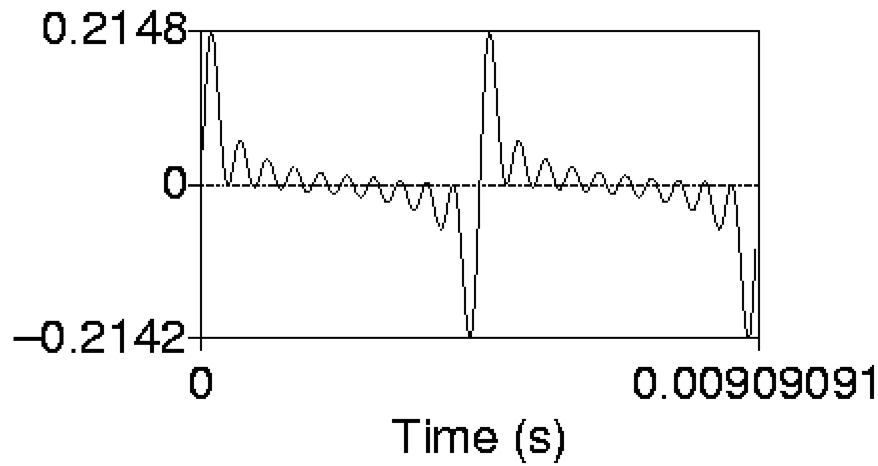
3) The different Harmonics of a periodic tone are fused

4) Pitch of a sound determined by lowest harmonic,

roughly:
long time scales (>0.1 s) processed as temporal properties,
short time scales ( < 0.1 s) as power spectral properties

Independence of phases:




$$p(t) = \sum_{n=1}^{10} \sin(2\pi\,(n\,220\,t + \tfrac{n^2}{10})$$

$$p(t) = \sum_{n=1}^{10} \sin(2\pi\,n\,220\,t)$$

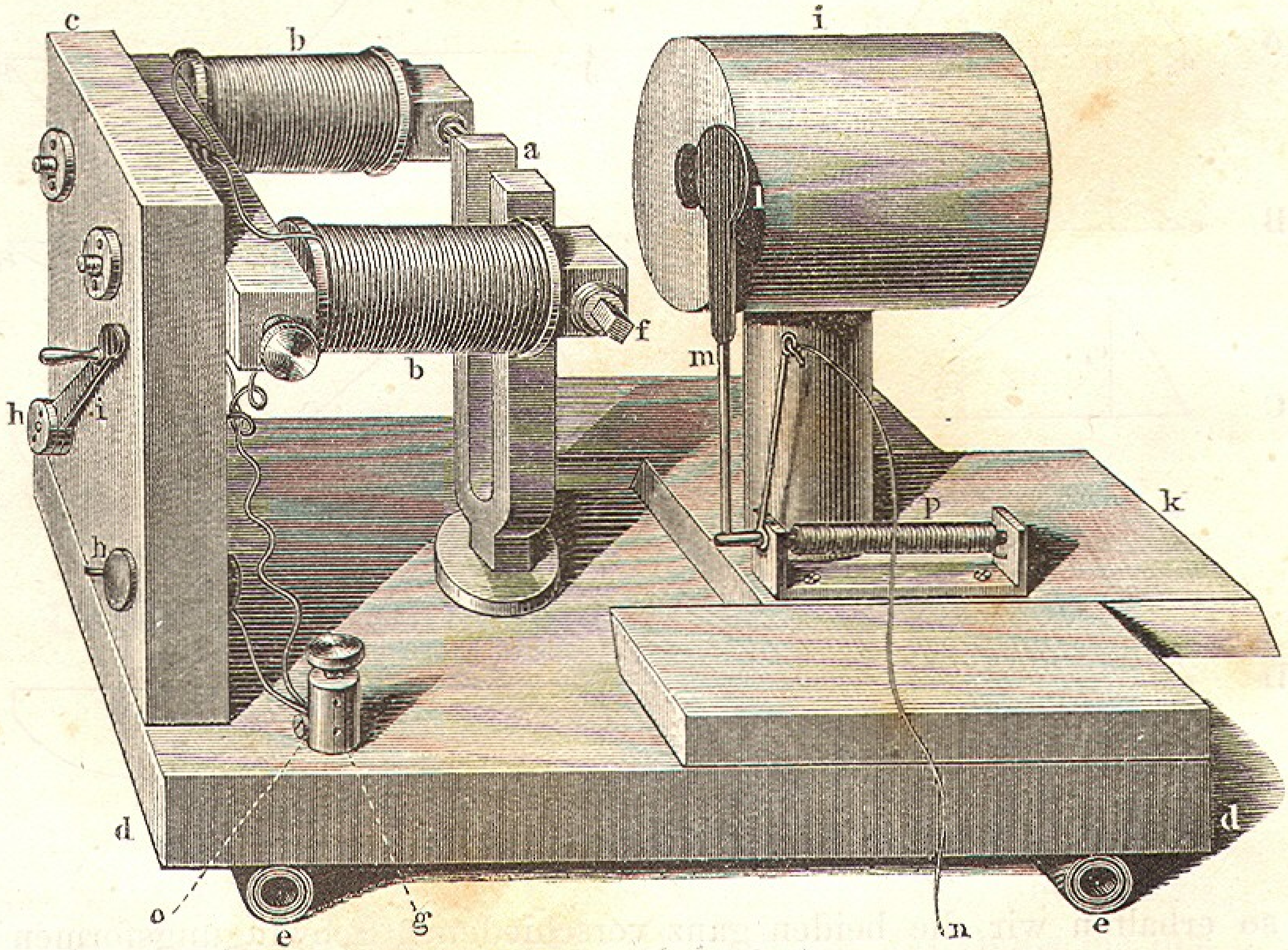
$$\tilde{p}(2\pi\nu) = \sum_{n=1}^{10} i\delta(\nu - n\,220)e^{i\,2\pi n^2/10}$$

$$\tilde{p}(2\pi\nu) = \sum_{n=1}^{10} i\delta(\nu - n\,220)$$

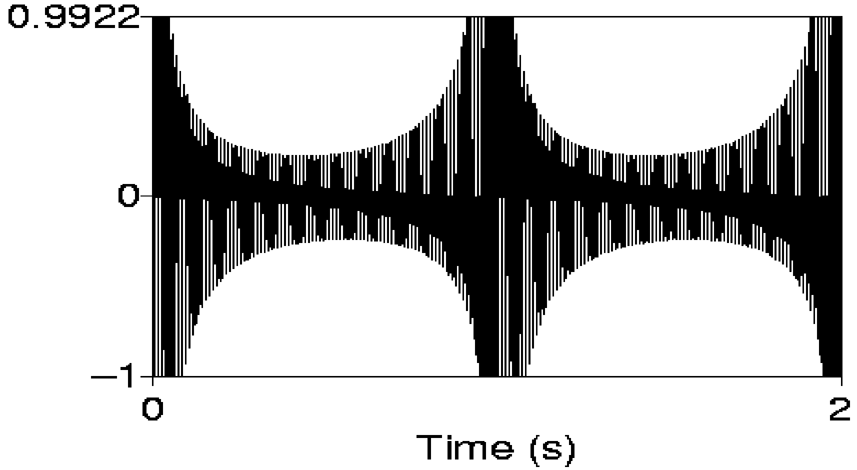
schroederplus10, sin10

Apparatus of helmholtz to test the independence on phases (Tonempf.)

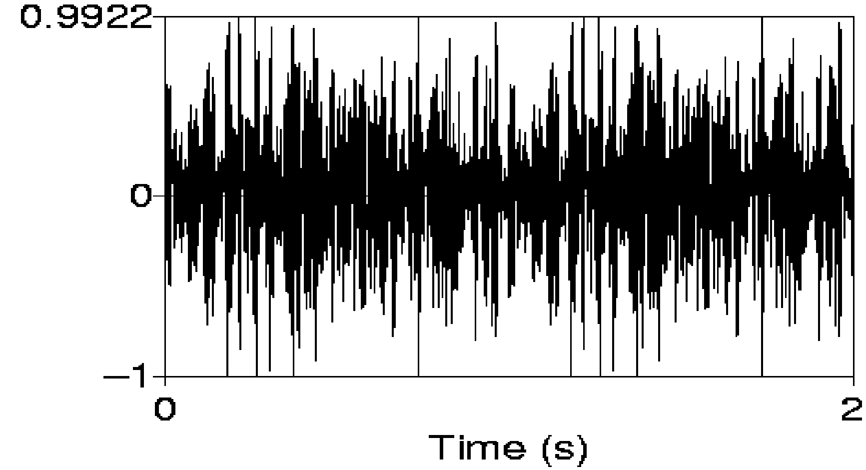
Fig. 32.



$p(t) = \sum_{n=1}^{100} \sin(2\pi\,(100+n)\,t)$ $\quad$ $p(t) = \sum_{n=1}^{100} \sin(2\pi\,(100+n)\,t + 2\pi\,r[n])$

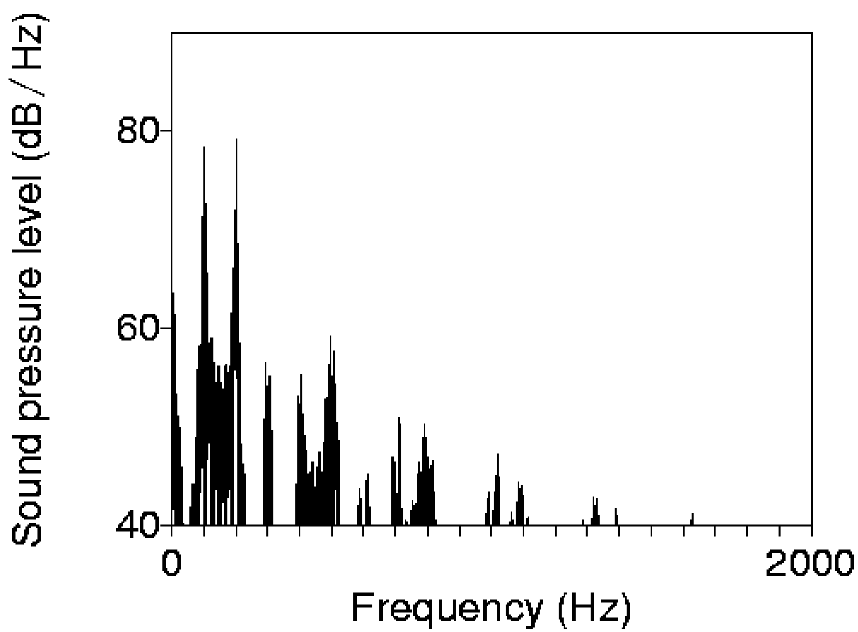


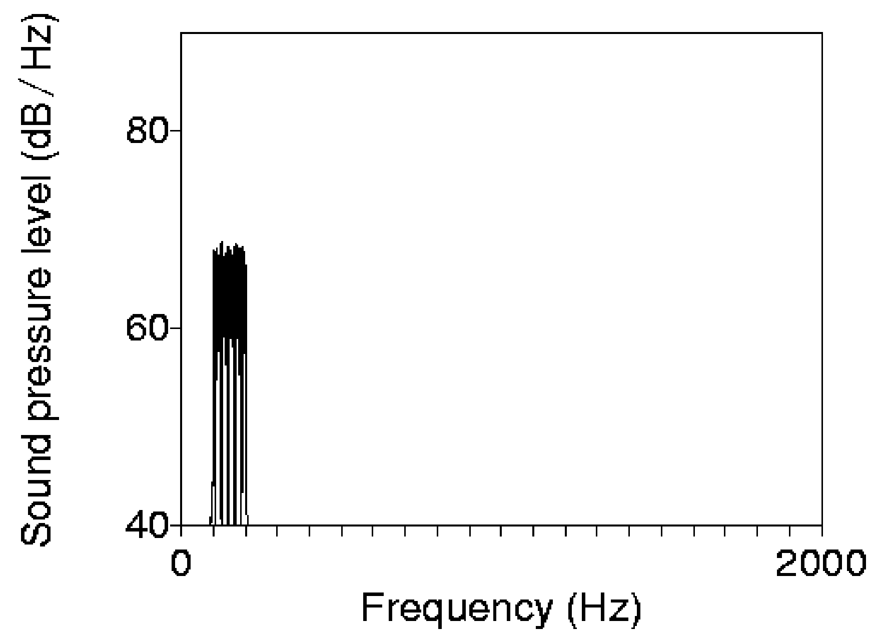

102praat: sin-coherent.wav




sin-random,wav

Fourier transform should only differ in phase, i.e. identical power spectrum
but: spectra over finite time interval look also different



Our ear performs a windowed Fourier analysis, since we can perceive directly time variations of ca 0.1 s, this should be the maximal width of the window.

Example beats and roughness.

$$e^{i2\pi\,\nu_1\,t} + e^{i2\pi\,\nu_2\,t}$$

$$= e^{i2\pi\,\frac{\nu_1+\nu_2}{2}\,t}(e^{i2\pi\,\frac{\nu_1-\nu_2}{2}\,t} + e^{-i2\pi\,\frac{\nu_1-\nu_2}{2}\,t})$$

$$= 2\cos\left(2\pi\,\frac{\nu_1-\nu_2}{2}\,t\right)e^{i2\pi\,\frac{\nu_1+\nu_2}{2}\,t}$$

We expect: $1/(\nu_1 - \nu_2) \ll 0.1$ s two tones

$1/(\nu_1 - \nu_2) \gg 0.1$ s beats

$\nu_1 = 2000;\ \nu_2 = 2500$

$\nu_1 = 2000;\ \nu_2 = 2010$

$\nu_1 = 2000;\ \nu_2 = 2120$

102praat
beats-third.wav
beats-10.wav
beats-rough.wav

$1/(\nu_1 - \nu_2) >\sim 0.1$ s beats

$\nu_2/\nu_1 >\sim 1.2$ two tones

else rough. maximal roughness at $\nu_2/\nu_1 \sim 1.06 - 1.12$

based on pysiology of the ear

**Theory of harmony Pythagoras - Helmholtz**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | c(530) | 530 | 1060 | 1590 | 2120 | 2650 | 3180 | 3710 | 4240 |
| 9:8 | d(590) | 590 | 1180 | 1770 | 2360 | 2950 | 3540 | 4130 | 4720 |
| 3:2 | g(790) | 790 | | 1580 | | 2370 | 3160 | 3950 | |
| 15:8 | h(1000) | | 1000 | | 2000 | | 3000 | | 4000 |
| 2:1 | c(1060) | | 1060 | | 2120 | | 3180 | | 4240 |

live-music

Calculations of Helmholtz for the degree of roughness for a violin

Fig. 60 A.

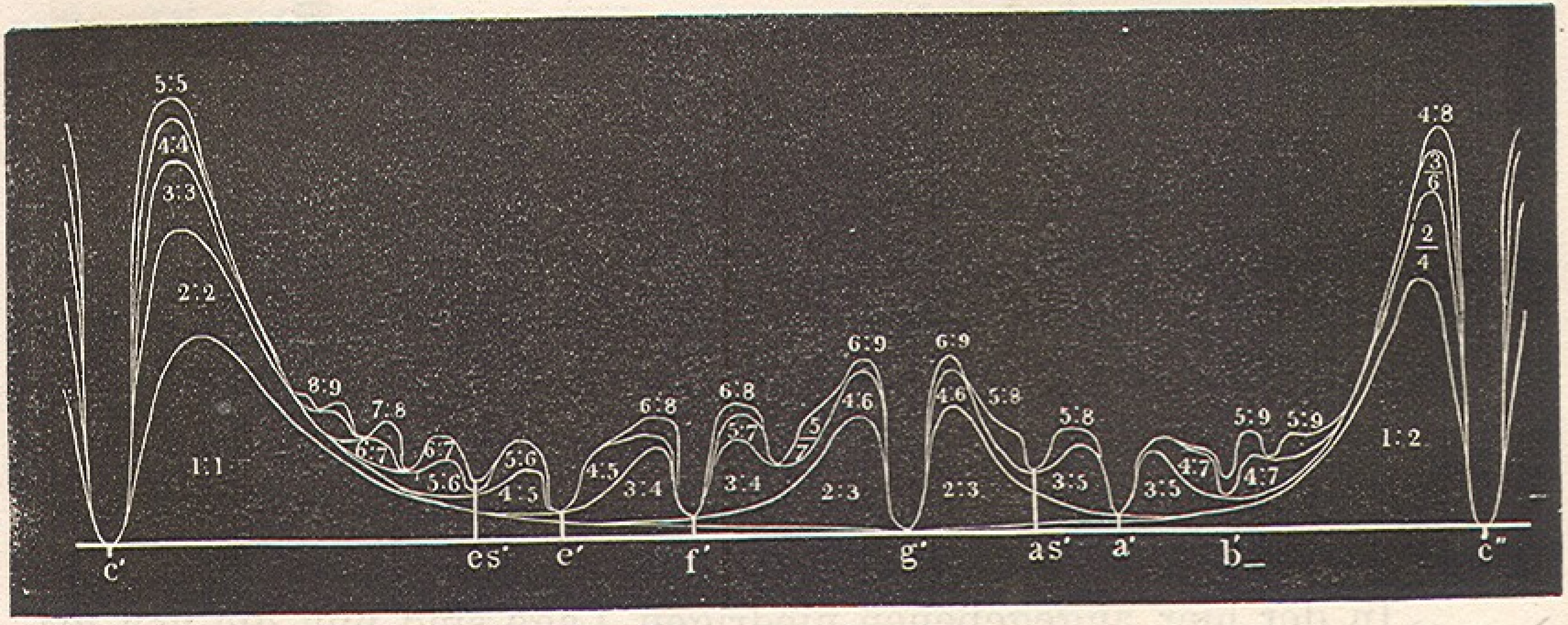
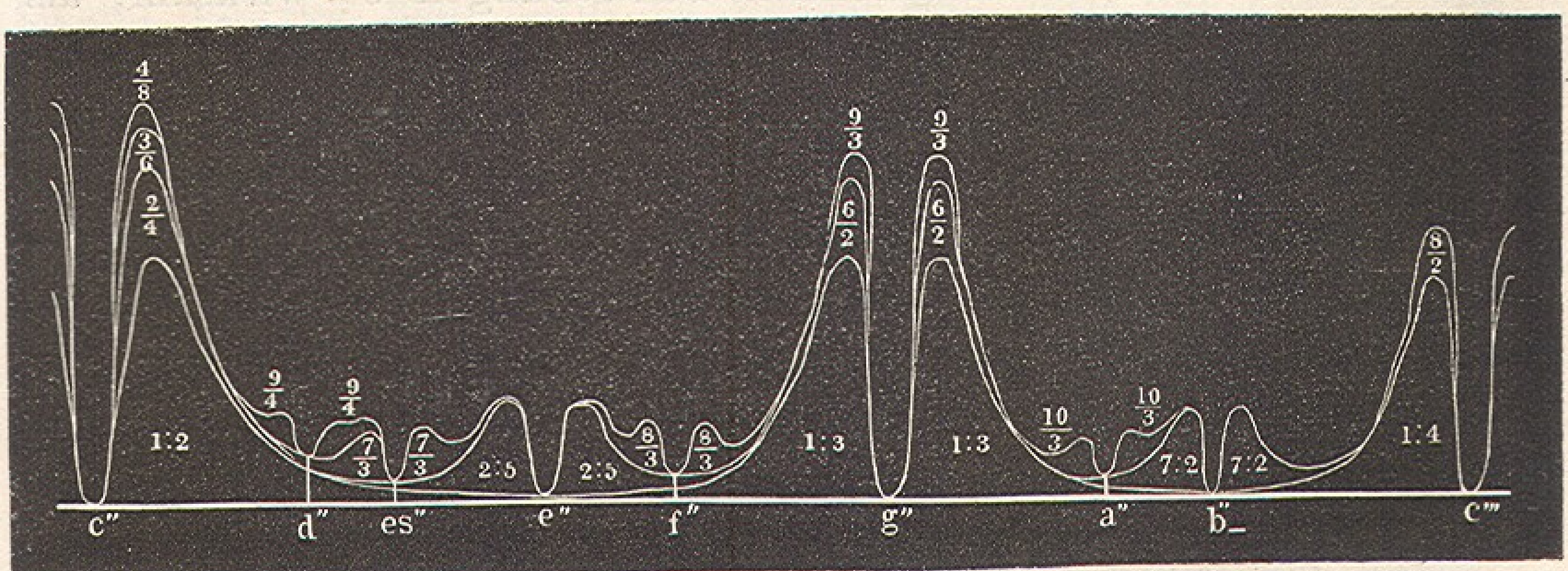
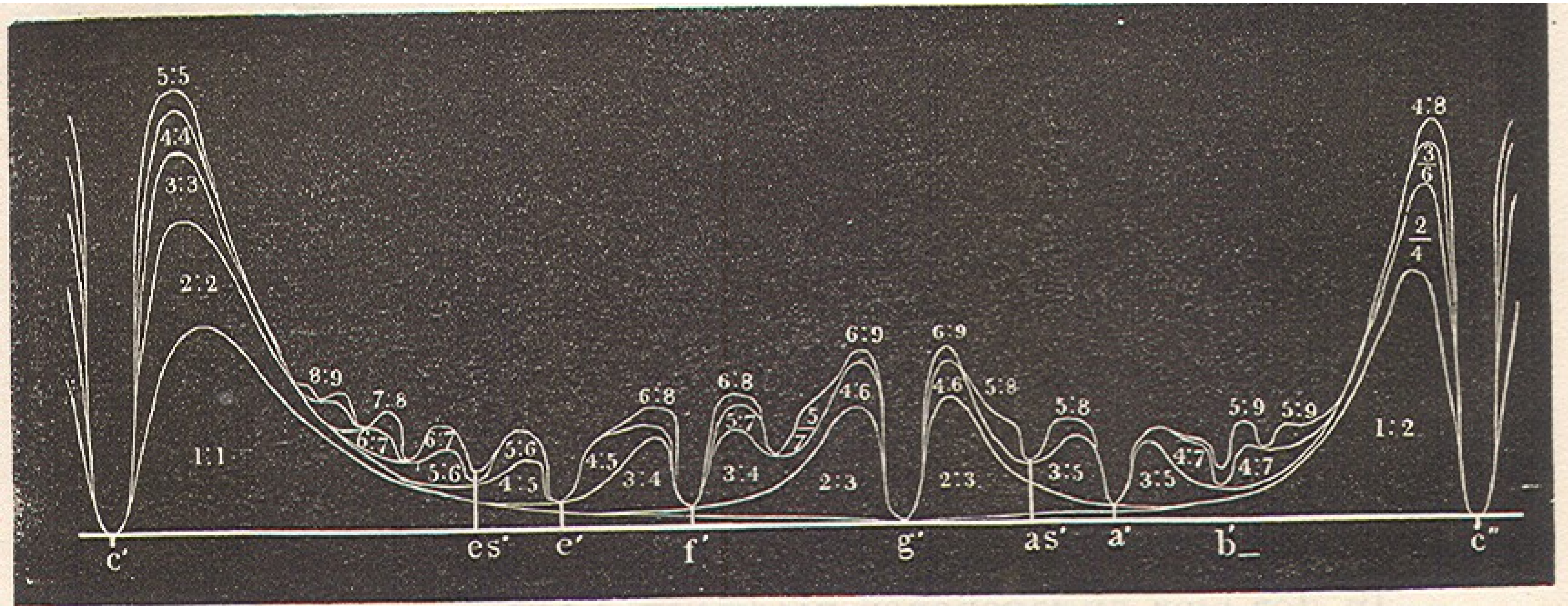


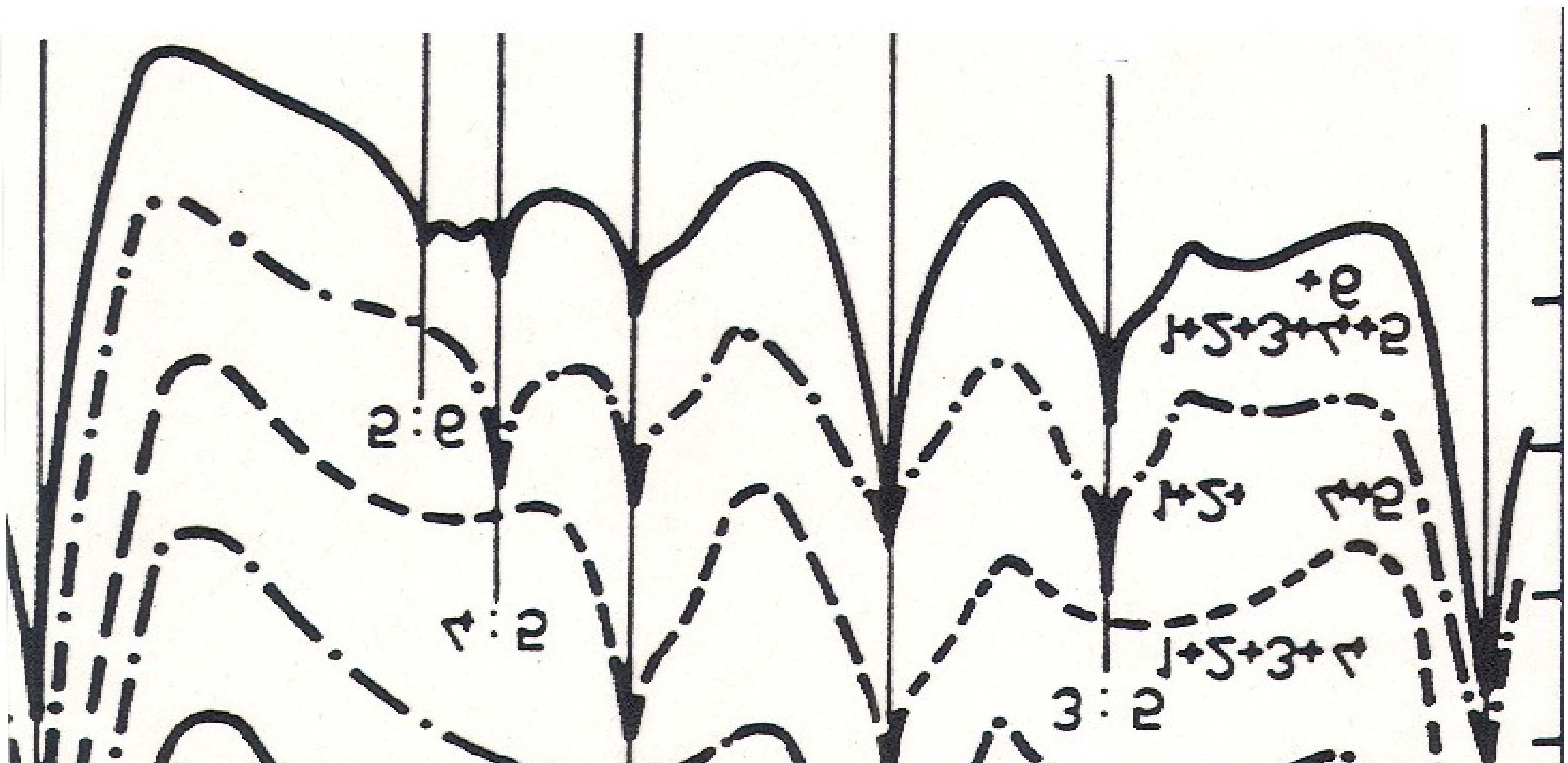

Fig. 60 B.






Helmholtz, 1863

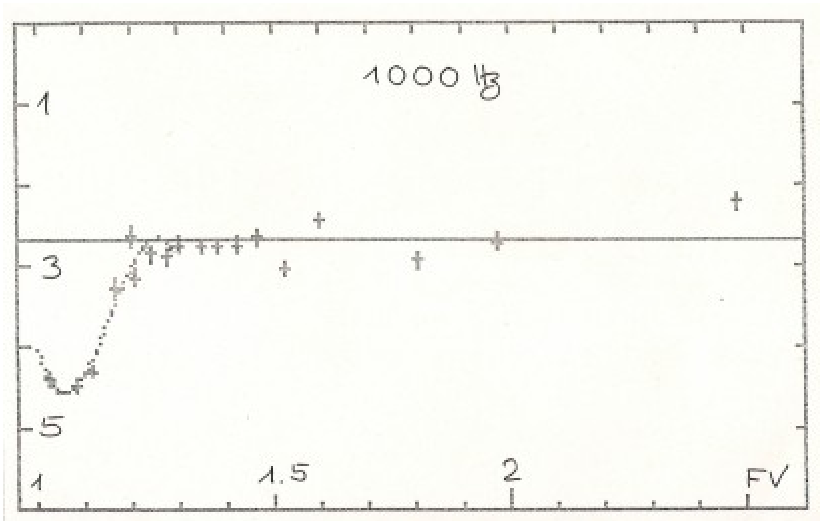
dissonanz

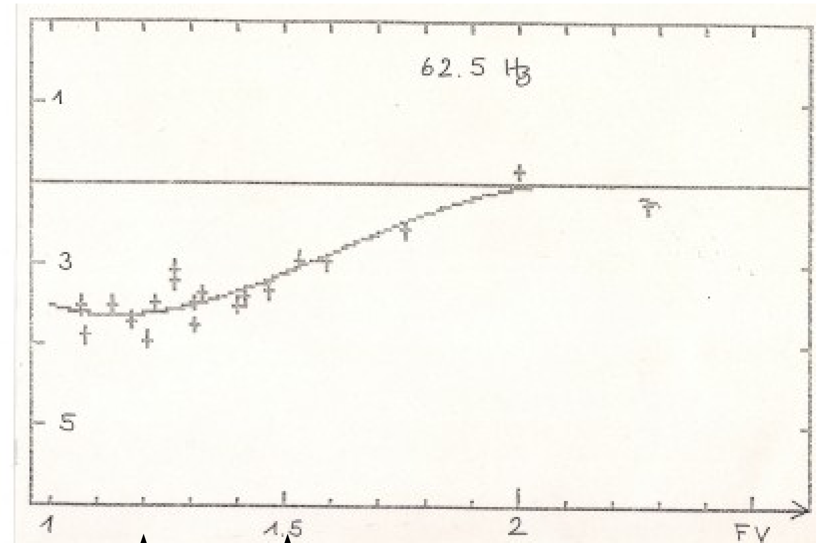


Kameoka, Kuriyagawa, 1969

consonanz

# Interval od roughness larger at low frequencies:




minor third

fifth

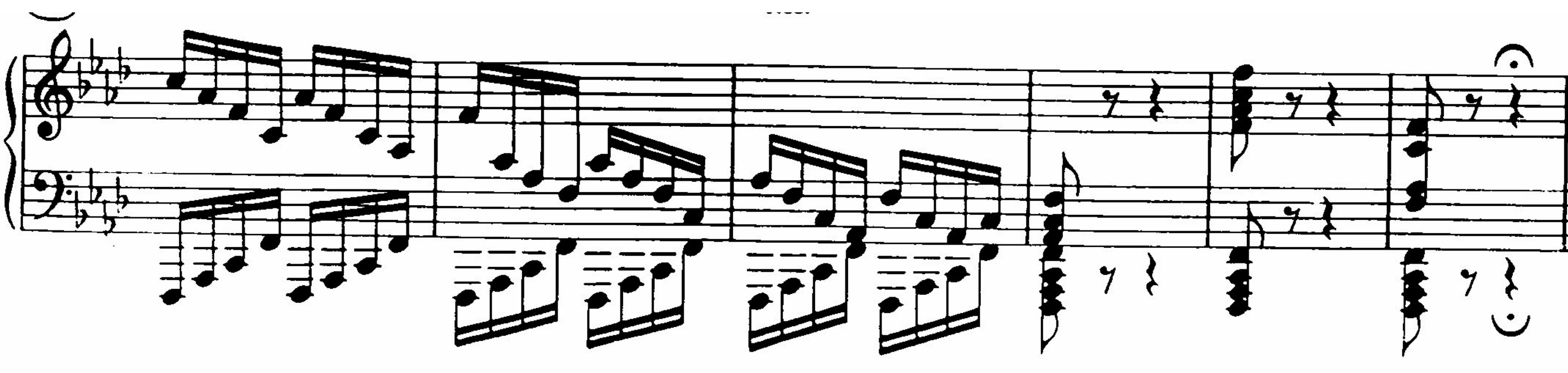
minor third

fifth

Dosch and Specht, 1986
average of 89 subjects

Chopin, Scherzo

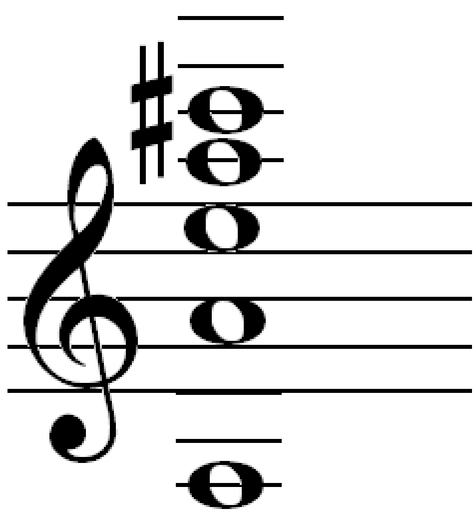

Beetvoven, Appasionata



Example: "pure tone" $p(t) = \sin(2\pi\, 220\, t)$

complex tone $p(t) = \sum_{n=1}^{5} \sin(2\pi\, n\, 220\, t)$

But one can also hear the components, some people better, some worse.

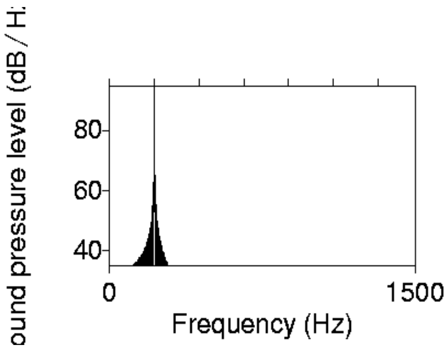


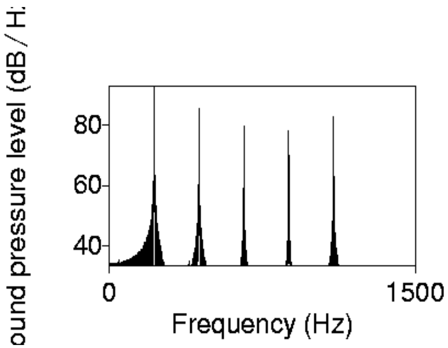
102praat
sin-1, sin-5,

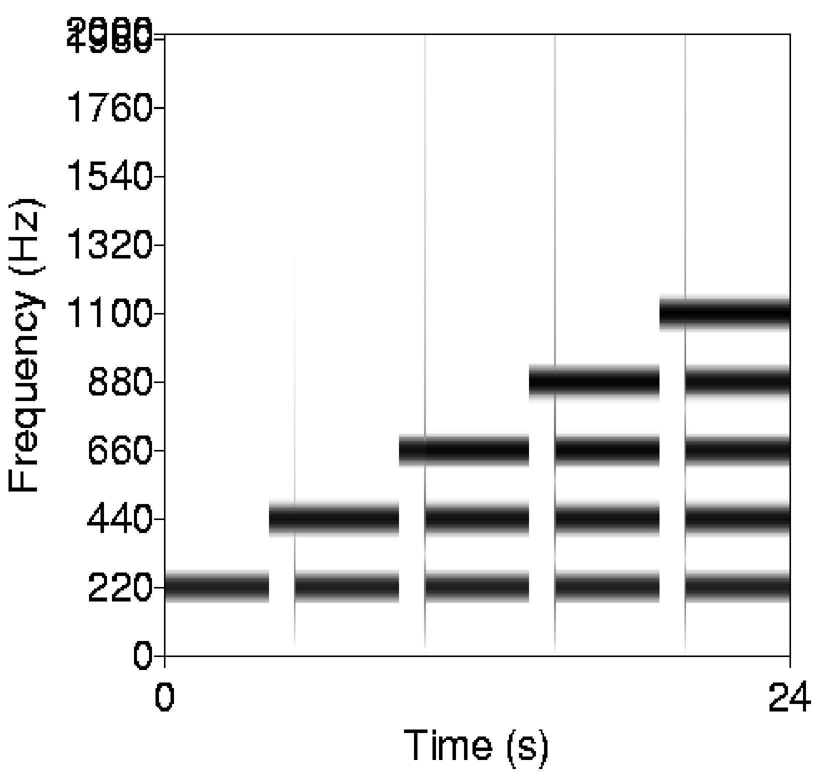
Fusion of tones

A tone with several harmonics: is it a single tone or a collection of tones?

both:
Helmholtz:
we perceive synthetically (perzipieren) the whole tone
we can perceive analytically (apperzipieren) the components of the tone.



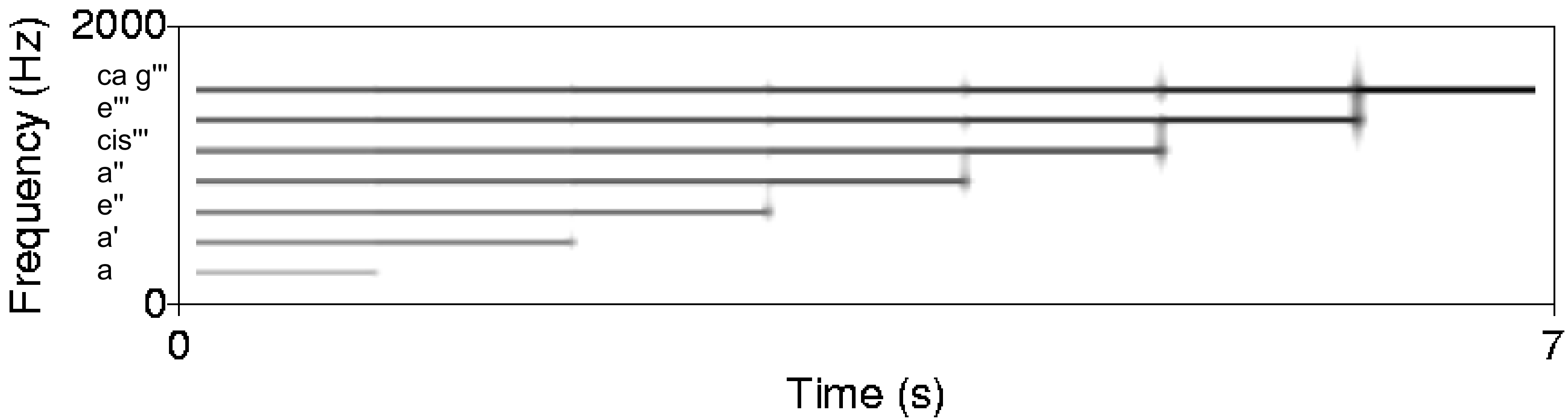




102praat
sin-1.wav
sin-5.wav
chain-harmonic-insert.wav

The missing fundamental
We now take off components from below

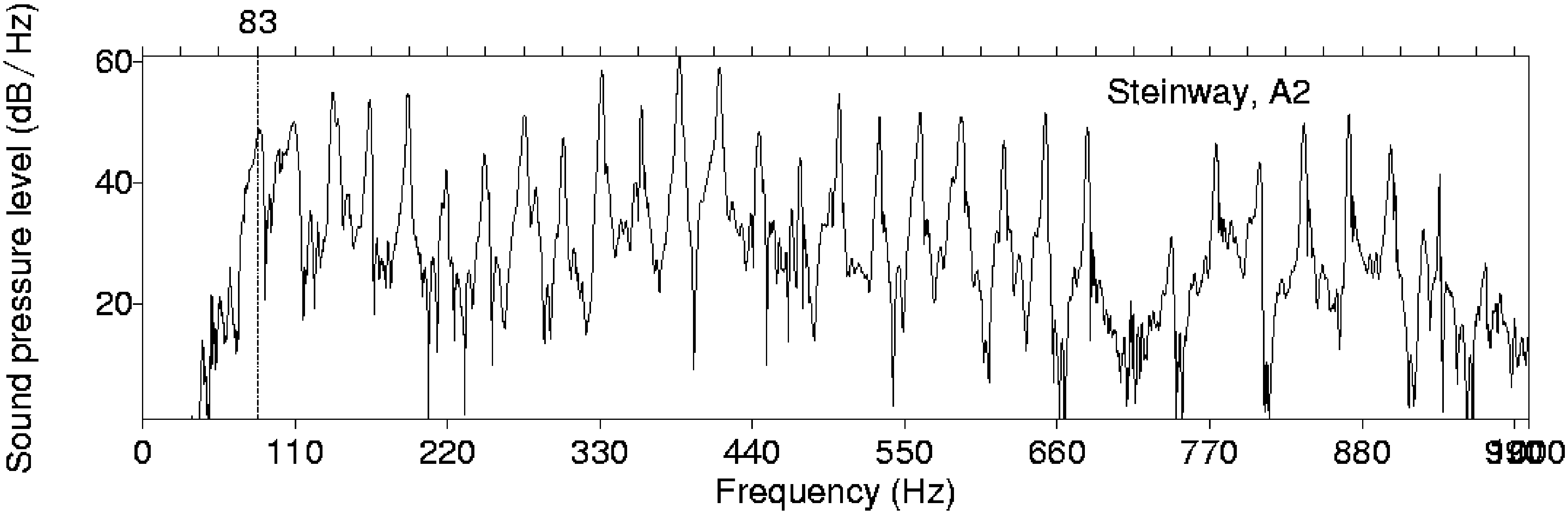
102praat chain-fundamental-tracking.collection

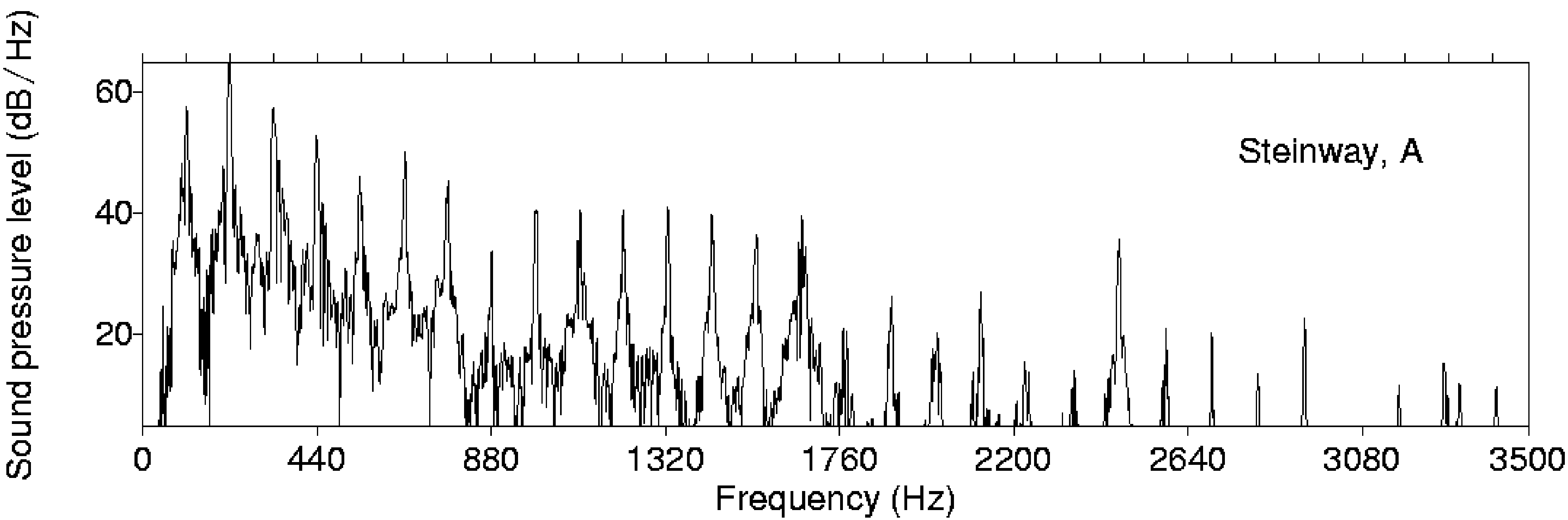



We take subsequently one harmonic tone out of the complex tone

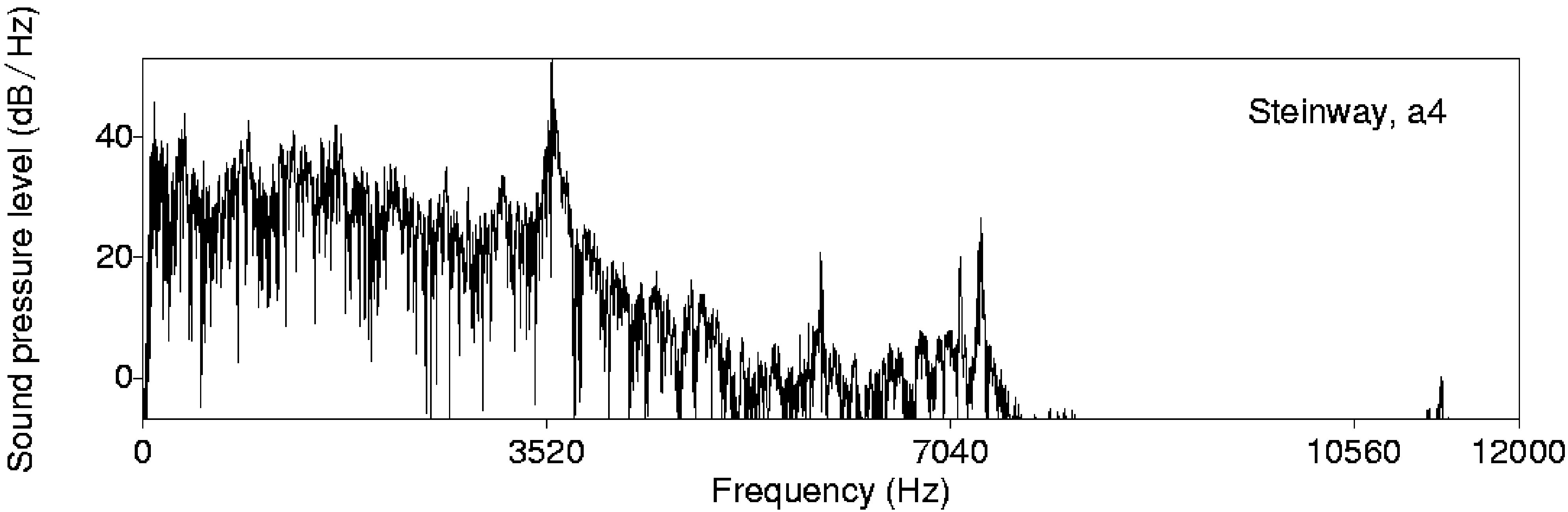
This happens also in musical instruments

103praat 27_5Hz_A2_real_steinway.wav 110Hz-A_real



103praat 3250Hz-a4-real-steinway



Explanation until ca 1940 : Difference tones

If a sound is processed linearly, nothing happens to the spectrum, except linear scaling.

But if the function is not linear, we observe additional spectral lines (partial tones)

$$(2a\cos(\omega_1 t) + 2b\cos(\omega_2 t))^n$$

$$= \left(a(e^{i\omega_1 t} + e^{-i\omega_1 t}) + b(e^{i\omega_2 t} + e^{-i\omega_2 t})\right)^n$$

$$= (a\,b)^n(e^{ni\omega_1 t} + e^{i((n-1)\omega_1+\omega_2)t} + \ldots e^{i((n-1)\omega_1-\omega_2)t} +$$

$$\ldots$$

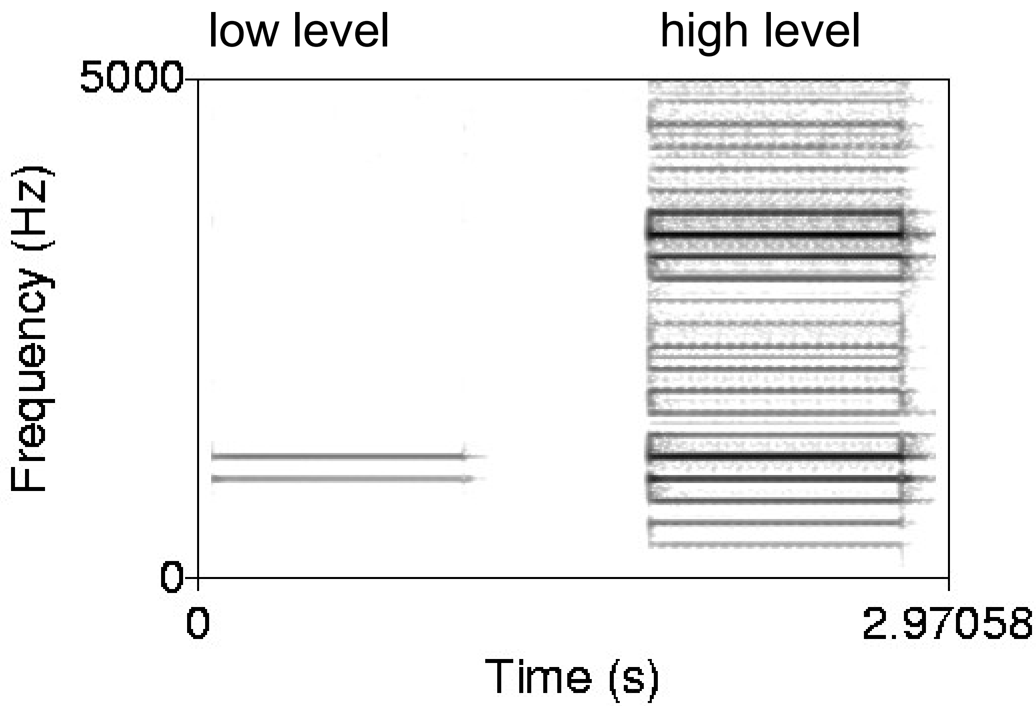
$$n = 2 : \; 2\omega_1, \; \omega_1 + \omega_2, \; \omega_1 - \omega_2, \; 2\omega_2$$

$$n = 3 : 3\omega_1, \; 2\omega_1 - \omega_2, \ldots$$

For a harmonic tone $p(t) = \sum_k^n \cos(2\pi k\nu_0)$

the difference ton $\omega_{k+1} - \omega_k = 2\pi\,(k+1-k)\,\nu_0 = 2\pi\nu_0$ is the fundamental tone

103praat dif-tone-laut, leise 1000,1220 Hz

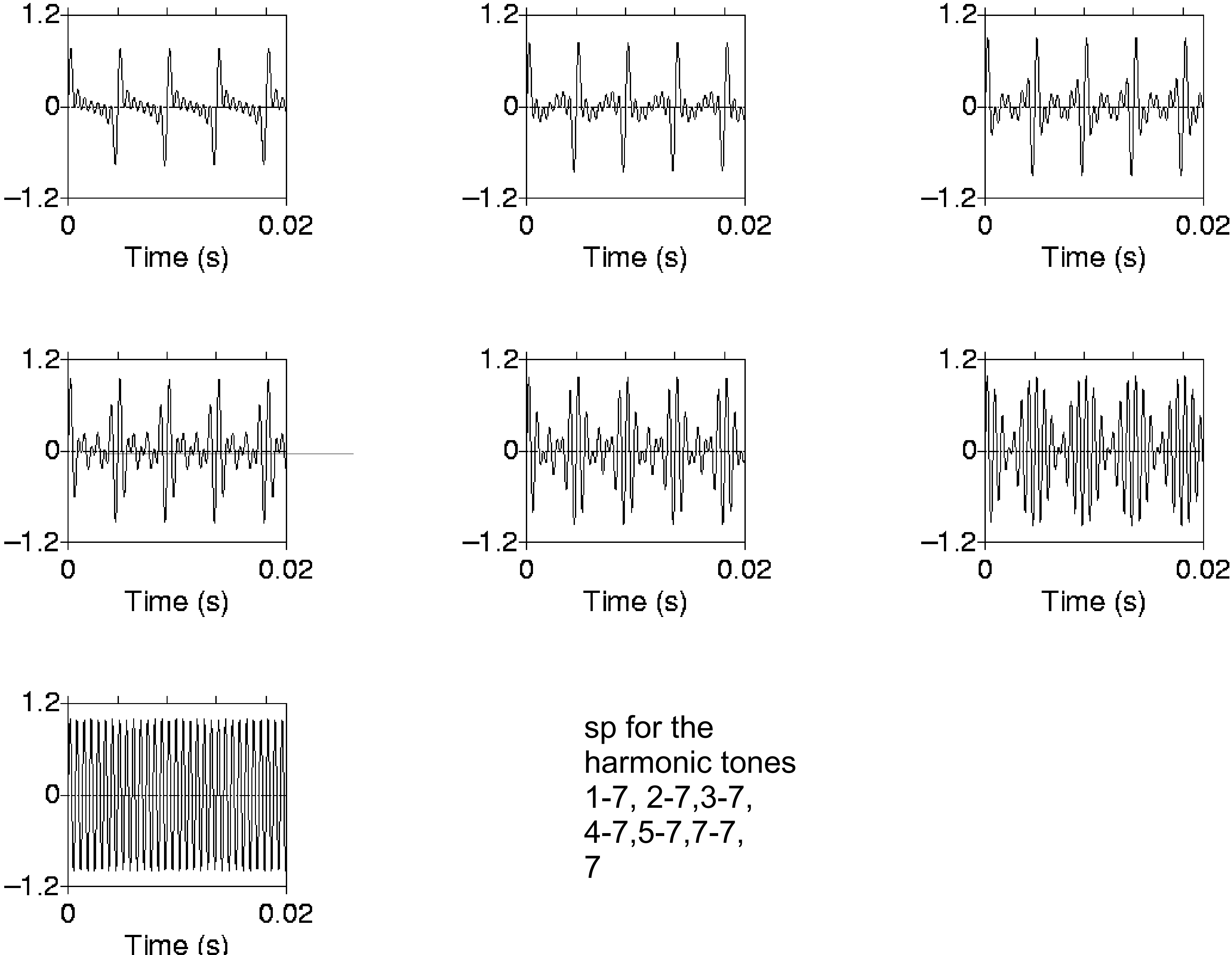



Spectrogram of the rcorded tone, consisting of two components at 1000 and 1220 Hz. At the high level the nonlinear distortions are clearly visible.

Schouten:

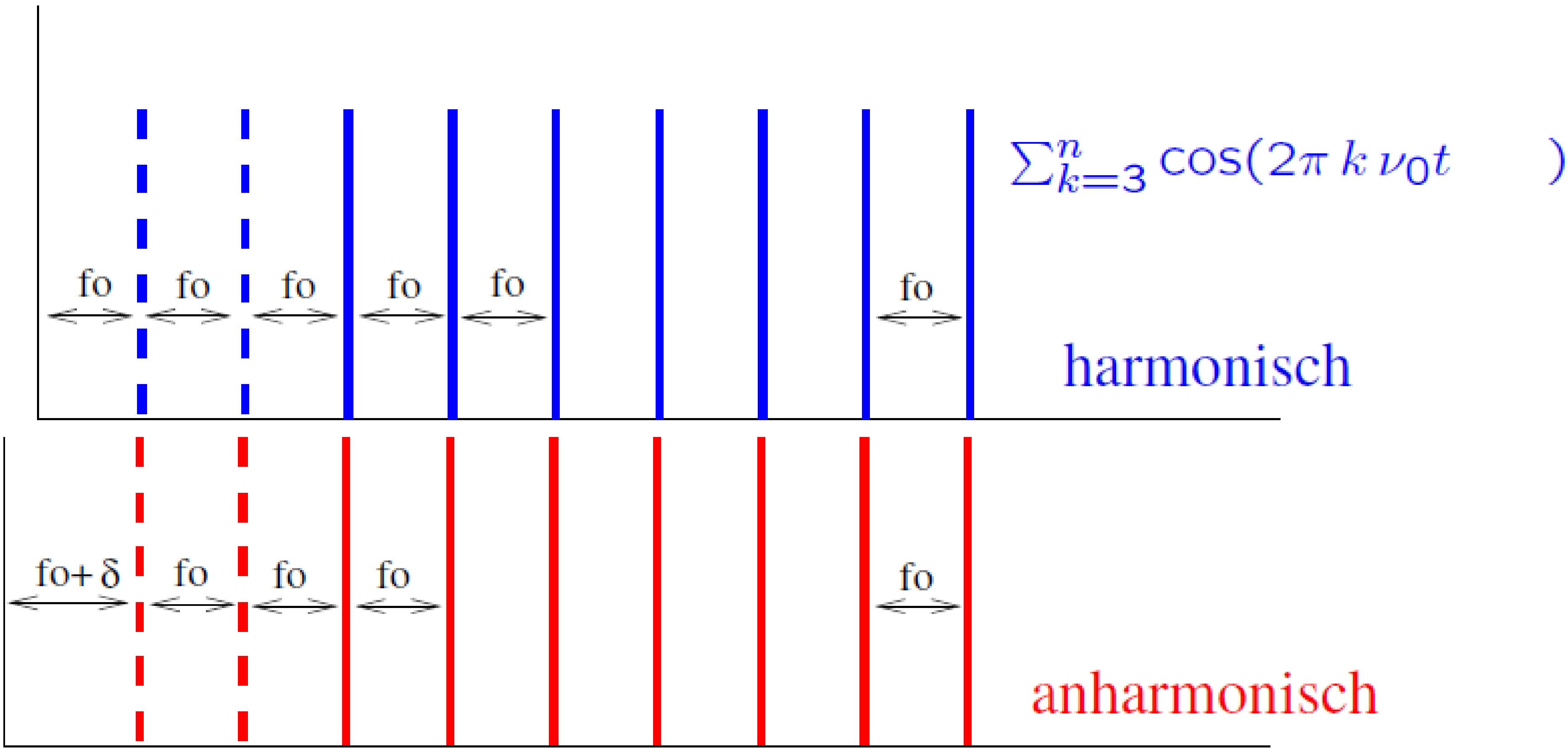
The periodicity of the tone is essential for the pitch of the ``residue'', that is the perceived, but not present fundamental tone.

Indeed sp curves show this periodicity:

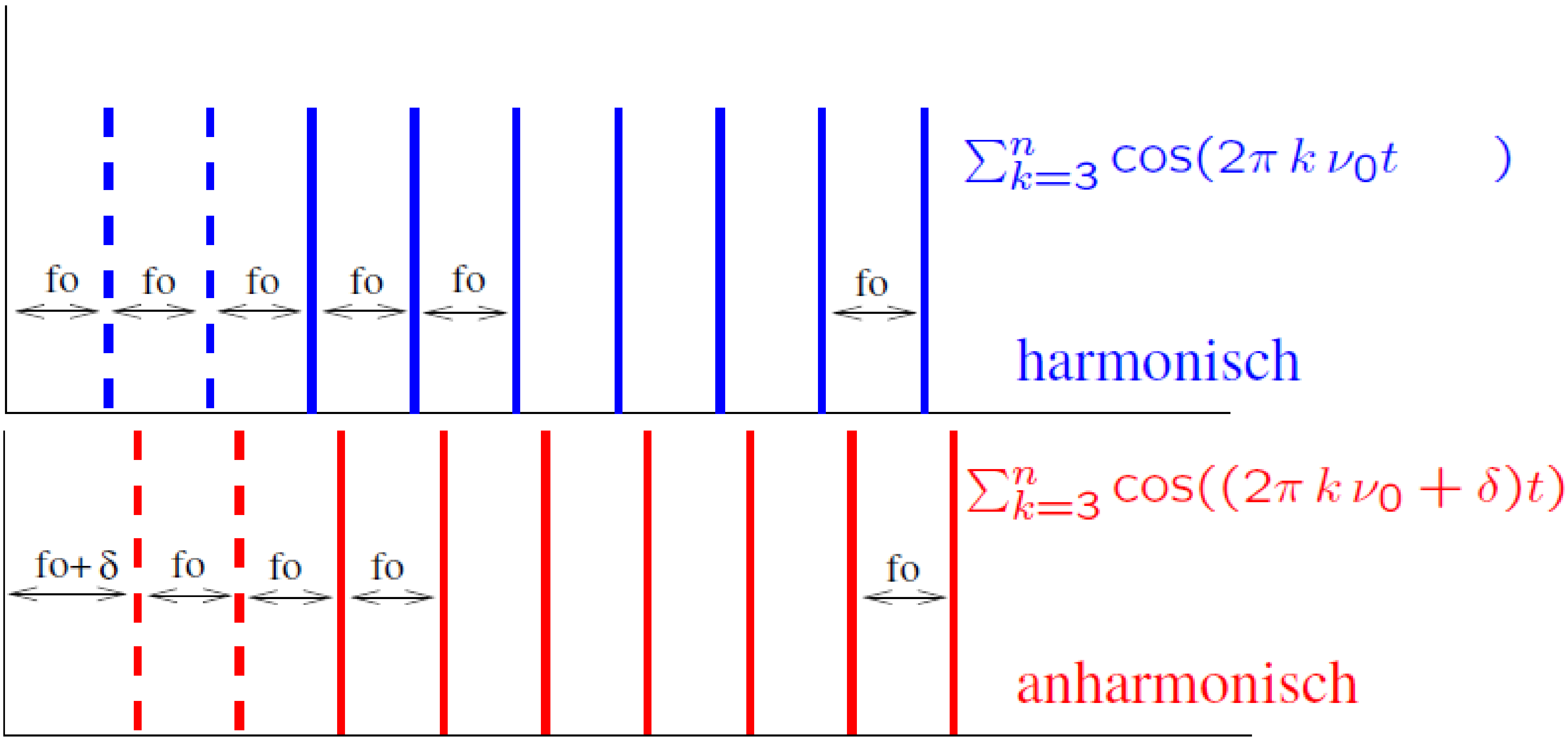



sp for the
harmonic tones
1-7, 2-7,3-7,
4-7,5-7,7-7,
7

The difference tone was excluded by van Schouten by a series of ingenious experiments. A particular simple one is the shifted hamonic tone.



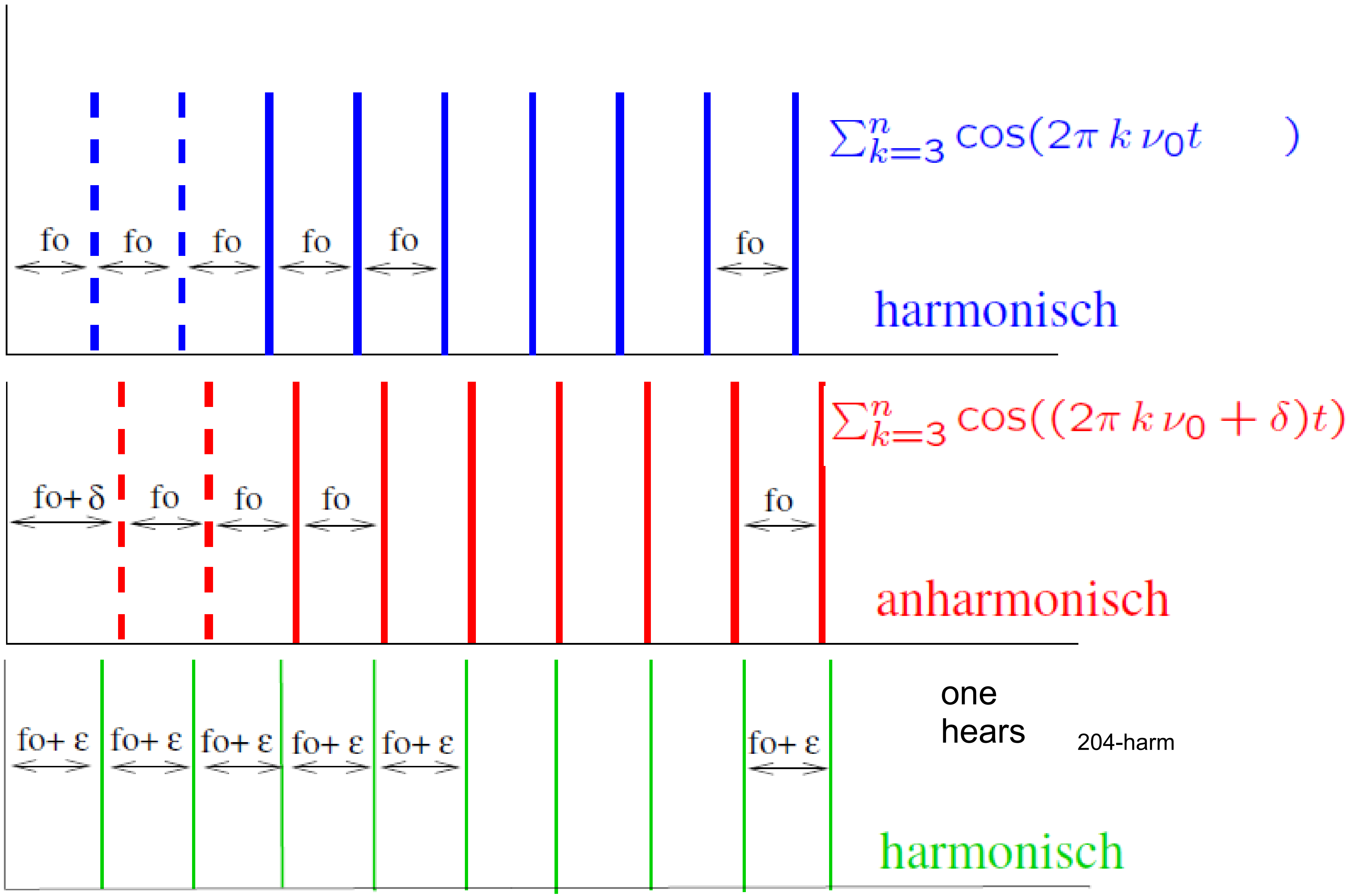
The difference tone was excluded by van Schouten by a series of ingenious experiments. A particular simple one is the shifted hamonic tone.




103praat harm-200 200+40

one hears

The difference tone was excluded by van Schouten by a series of ingenious experiments. A particular simple one is the shifted hamonic tone with missing f




204-harm

The fact that the shifted tone has a ditincly different pitch is a sure sign that the difference tone is not reponsible for fundamental tracking, since the difference tone is unaffected by the shift

The question what determines the pitch of a complex tone is still controversial. We shall come back to it after looking closer into the physics of the ear and the auditory pathway.