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Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

Acoustics I: measurements

Kurt Heutschi 2022-12-12

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- emission measurements (passive)
 - description of a sound source
 - ightharpoonup ightharpoonup sound radiation of a lawn mover
- measurements at a receiver position (passive)
 - description of the strength of a source including the propagation to the receiver
 - ightharpoonup
 ightharpoonup o road traffic noise measurement in the living room of a resident
- measurements of a transmission system (often active)
 - description of a transmission system
 - ightharpoonup
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 - ightharpoonup
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emission measurements (passive)

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typical measurement tasks

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- emission measurements (passive)
 - description of a sound source
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 - description of a transmission system
 - ightharpoonup ightharpoonup measurement of the frequency response of a loudspeaker
 - ightharpoonup measurement of the impulse response in a concert hall

typical measurement tasks

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- frequency weighting filte bandpass filters
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- intensity measureme
- impulse respons
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- time bandwin

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- complete description of a sound field requires:
 - sound pressure at all positions for each moment in time
 - sound particle velocity at all positions for each moment in time
 - however: $grad(p) = -\rho \frac{\partial \vec{v}}{\partial t}$ may be used
 - nost important quantity: sound pressure
 - ear is sensitive to sound pressure
 - excellent transducers are available

typical measurement tasks

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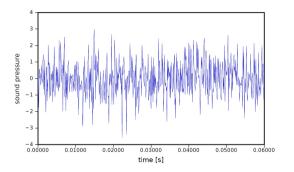
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example of a typical sound pressure time history:



attributes that can be evaluated?

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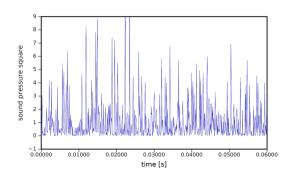
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► first step:

calculate signal square





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- peak value
- integral quantities
 - lacktriangle infinite time window with exponential weighting o moving average
 - $hildsymbol{ riangle}$ finite time window ightarrow average value
- statistical quantities, e.g. the fraction of the signal duration with sound pressure exceeding a certain threshold



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- peak value
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momentary sound pressure level L(t)

$$L(t) = 10 \log \left(\frac{1}{RC} \int_{-\infty}^{t} \frac{p^2(\tau)}{p_0^2} e^{\frac{\tau - t}{RC}} d\tau \right)$$
 [dB]

where

RC: time constant, SLOW = 1 s, FAST = 0.125 s

 $p(\tau)$: instantaneous sound pressure

 p_0 : reference sound pressure = 2×10^{-5} Pa

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Equivalent continuous sound pressure level *Leq*

$$\textit{Leq} = 10 \log \left(rac{1}{T} \int\limits_0^T rac{
ho^2(au)}{
ho_0^2} \mathrm{d} au
ight) \qquad ext{[dB]}$$

where

T: measurement time interval

 $p(\tau)$: instantaneous sound pressure

 p_0 : reference sound pressure = 2×10^{-5} Pa

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Sound exposure level L_E (SEL former designation)

$$L_E = 10 \log \left(\frac{1}{1 \sec} \int_0^{\tau} \frac{p^2(\tau)}{p_0^2} d\tau \right)$$
 [dB]

where

T: measurement time interval

 $p(\tau)$: instantaneous sound pressure

 p_0 : reference sound pressure = 2×10^{-5} Pa

signal attributes: applications

signal attributes

momentary sound pressure level L(t):

- maximum level with time constant FAST: Lmax, $Fast \rightarrow descriptor$ for shooting noise or the pass-by of road vehicles
- minimum level: $Lmin \rightarrow \text{estimation of a stationary signal with}$ occurrence of transient disturbing noise

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equivalent continuous sound pressure level Leq:

characterization of non-stationary sources and signals

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sound exposure level L_E , SEL:

measurement of single events such as e.g. train pass-bys

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 \rightarrow software sound level meter (Delphi) demo

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filters

filters

filters

- frequency weighting filters (to mimick frequency response of the ear)
 - A-filter
 - C-filter
- bandpass filters for frequency analysis
 - constant relative bandwidth (perception related)
 - third-octave band filters
 - octave hand filters
 - constant absolute bandwidth (technical analysis)
 - narrow band filters (e.g. 1 Hz, 3 Hz, 10 Hz)
 - ► FFT

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frequency weighting filters

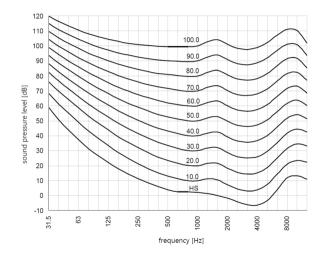
frequency weighting filters

equal loudness contours:



frequency weighting filters





level dependent frequency response \rightarrow A- / C-filter \rightarrow dB(A) / dB(C)

frequency weighting filters

frequency weighting filters

standard C-filter:

$$\mathcal{T}_{\mathsf{C-Filter}}(s) = rac{\mathcal{K}s^2}{(s+\omega_1)^2(s+\omega_2)^2}$$

where

$$\omega_1 = 1.29 imes 10^2 ext{ [rad/sec]}$$

$$\omega_2 = 7.67 \times 10^4 \text{ [rad/sec]}$$

$$\mathit{K}$$
: adjusted for $|\mathit{T}_{\mathsf{C-filter}}| = 1$ at 1 kHz

frequency weighting filters

frequency weighting filters

standard A-filter:

$$\mathcal{T}_{\mathsf{A-Filter}}(s) = rac{\mathcal{K}s^4}{(s+\omega_1)^2(s+\omega_2)^2(s+\omega_3)(s+\omega_4)}$$

where

 $\omega_1 = 1.29 \times 10^2 \, [rad/sec]$

 $\omega_2 = 7.67 \times 10^4$ [rad/sec]

 $\omega_3 = 6.77 \times 10^2$ [rad/sec]

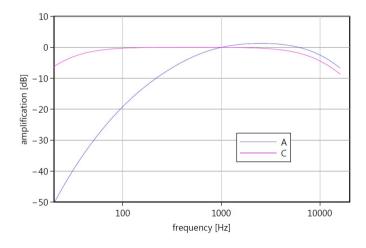
 $\omega_{4} = 4.64 \times 10^{3} \text{ [rad/sec]}$

K: adjusted for $|T_{A-filter}| = 1$ at 1 kHz

frequency weighting filters

frequency weighting filters

frequency response curves:



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bandpass filters: filters for frequency analysis

frequency analysis by third-octave band filters

handnass filters

 \triangleright standard filter series with one center frequency f_m at 1000 Hz

 $f_{m,n} = 1000 \cdot (2^{\frac{1}{3}})^n$ for $n = \cdots - 2, -1, 0, 1, 2, \ldots$

 \triangleright B = 0.23 · f_m . B: bandwidth

 $ightharpoonup f_u = f_m \cdot \frac{1}{2^{\frac{1}{6}}}, f_u$: lower limiting frequency

 $ightharpoonup f_0 = f_m \cdot 2^{\frac{1}{6}}, f_0$: upper limiting frequency

frequency analysis by octave band filters

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 \triangleright standard filter series with one center frequency $f_{\rm m}$ at 1000 Hz

 $f_{m,n} = 1000 \cdot 2^n$ for $n = \dots -2, -1, 0, 1, 2, \dots$

 \triangleright $B = 0.71 \cdot f_m$, B: bandwidth

 $ightharpoonup f_u = f_m \cdot \frac{1}{2^{\frac{1}{2}}}, f_u$: lower limiting frequency

• $f_o = f_m \cdot 2^{\frac{1}{2}}$, f_o : upper limiting frequency

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uncertainty of measurements of random signals

measurement uncertainty of random signals

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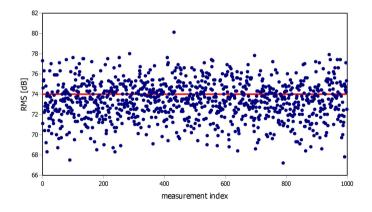
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example: 0.5 sec-Leq analysis of pink noise evaluated in a band of 10 Hz:



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frequency band limited analysis of a random signal is inevitably uncertain for finite observation intervals

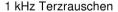
measurement uncertainty of random signals

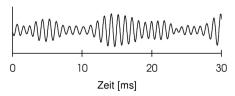
measuring random signals

 \triangleright band limitation \rightarrow subsequent samples are no longer statistically independent

- neighbor sample does not provide completely new information
- ▶ the narrower the analysis bandwidth, the longer the period to wait for a new independent sample

example: 1 kHz third-octave band noise:





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degrees of freedom of a bandlimited random signal:

- random signal
 - bandwidth B
 - ▶ analyzing time *T*
- yields n statistically independent samples

$$n = 2BT$$

▶ n: degrees of freedom

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given a random signal u(t):

- ▶ analysis within the bandwidth *B* during time *T*
- ightharpoonup n = 2BT statistically independent samples u_i

$$rms = \sqrt{\frac{1}{n} \sum_{i=1}^{n} u_i^2}$$

 $\triangleright \sum_{i=1}^n u_i^2$ is χ^2 distributed

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error intervals for selected probabilities p:

n	p = 0.90	p = 0.99
10	$-4.0\cdots+2.6~dB$	$-6.6\cdots+4.0~dB$
100	$-1.1\cdots + 0.9~\mathrm{dB}$	$-1.7\cdots+1.5~dB$
1000	$-0.3\cdots+0.3~\mathrm{dB}$	$-0.5\cdots+0.5~\mathrm{dB}$

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- > standard sensor: electrostatic sound pressure microphone
- directivity:
 - omnidirectional at low frequencies
 - amplification on axis for high frequencies (sound field distortion)
 - corrections:
 - free field microphones
 - pressure response microphones

microphones: directivity

example: sensitivity as a function of θ for a 1/2 inch capsule:

example: sensitivity as a funct



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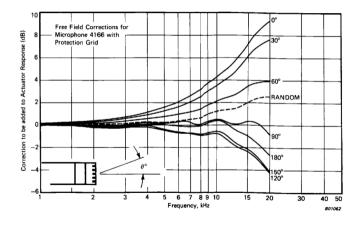
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further specifications:

- upper limiting frequency
 - maximal for small membrane area
 - maximal for high membrane stiffness
- self-noise
 - minimal for large membrane area
 - minimal for low membrane stiffness
- maximal sound pressure
 - maximal for small membrane area
 - maximal for high membrane stiffness

microphones

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examples:

microphone \emptyset	dynamic range	frequency range
inch = 2.5cm	dB(A)	Hz
1	10146	2 18'000
1/2	15146	2 20'000
1/4	29164	2100'000

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calibrators

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microphone calibrators are sound pressure references

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- microphone calibrators are sound pressure references
- **constructions**:
 - pistonphone
 - pressure generation by moving pistons
 - ightharpoonup operation typically at 250 Hz, 124 dB (\pm 0.15 dB
 - correction needed for atmospheric pressure (density of air)
 - acoustical calibrator
 - pressure generation by small loudspeaker
 - ightharpoonup operation typically at 1000 Hz, 94 or 114 dB (\pm 0.30 dB)

calibrators

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sound level meter

sound level meter

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- measurement of sound pressure and evaluation of various signal attributes
 - momentary level, RC = Fast, Slow
 - maximum / minimum level
 - equivalent continuous sound pressure level Leq
 - event level L_E, SEL
 - evaluation in frequency bands or with frequency weighting A/C

sound level meter

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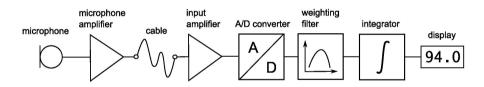
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block diagram:



sound level meter

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sound level meter and wind screen

sound level meter: precision classes

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- ► IEC specifications for sound level meters:
 - class 1: precise instruments for field applications
 - class 2: survey instruments with larger tolerances
- requirements for measurements relating to Swiss noise legislation:
 - ▶ instrument is type approved by *METAS*: Federal Institute of Metrology
 - initial calibration by METAS
 - recalibration every two years

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- registration of the time history of sound pressure level
- instrument specs:
 - ▶ typ. dynamic range 80...120 dB
 - typ. temporal resolution: 1 ms
 - data available for further evaluations

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analyzers for level statistics

analyzers for level statistics

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- evaluation of attributes in level statistics, such as:
 - ► *L*1: level, that is exceeded during 1 % of the measuring time
 - ▶ *L*50: level, that is exceeded during 50 % of the measuring time
- statistical levels play a minor role

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frequency analyzers

frequency analyzers

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- frequency dependent evaluation of the signal attributes
- most widely used: third-octave band analyzers
- todav:
 - handheld
 - operating in realtime: two-channels from 20 Hz...20 kHz

frequency analyzers

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sound recorders

sound recorders

measurement instruments

- recording of the microphone signal for subsequent analysis
- digital recorders:
 - stand-alone hard-disc recorder
 - audio interface with PC.
- ▶ formats with data compression (perceptual coders) do not make sense for measuring purposes

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discussion of uncertainties in the following measurement task:

- determination of the yearly average sound pressure level on a building facade due to road traffic
 - how to do that?
 - sources of uncertainty?

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uncertainties checklist:

- is the source under investigation in a representative condition?
- ▶ is the propagation medium in a representative condition?
- ▶ is the microphone surrounding representative for the location of interest?
 - local reflections?
 - local screening effects?
- errors due to the calibration and tolerances of the instrument
- errors due to possible unwanted noise
- ▶ fundamental uncertainty in the evaluation of random signals

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declaration of results:

- e.g. $63.2 \text{ dB}(A) \pm 0.9 \text{ dB}(A)$
 - number of decimals of a level result should reflect its uncertainty
 - ▶ standard uncertainty represents the range for a 66 % probability

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- **>** sound intensity is a vector quantity where $|\vec{l}| = \overline{p(t) |\vec{v}(t)|}$:
 - ightharpoonup sound pressure ightharpoonup no problem
 - sound particle velocity
 - pressure gradient method
 - hot-wire anemometer

intensity measurement: pressure gradient method

intensity measurement

fundamental relation between sound particle velocity and sound pressure:

$$\rho_0 \frac{\partial v_x}{\partial t} = -\frac{\partial p}{\partial x}$$

or:

$$v_{x} = -\frac{1}{\rho_{0}} \int \frac{\partial p}{\partial x} \mathrm{d}t$$

> sound particle velocity can be estimated from pressure gradient

intensity measurement: pressure gradient method

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approximation of pressure gradient by the pressure difference at two positions in close neighborhood:

$$\frac{\partial p}{\partial x} pprox \frac{p(x) - p(x + \Delta x)}{\Delta x}$$

- ightharpoonup optimal choice of Δx ?
- practical limitations?

intensity measurement: pressure gradient method: probe

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intensity measurement

intensity measurement: pressure gradient method: residual intensity

typical values for the **residual intensity** $(L_p - L_l)$ for a plane wave under 90° re. probe axis:

	residual intensity
8.5 mm	$>$ 15 dB for 250 Hz \scriptstyle 6.3 kHz
12 mm	$>$ 17 dB for 250 Hz $_{\cdot\cdot}$ 5 kHz
50 mm	> 15 dB for 250 Hz 6.3 kHz > 17 dB for 250 Hz 5 kHz > 23 dB for 250 Hz 1.25 kHz

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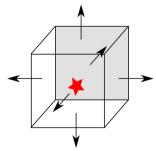
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intensity probe

applications:

- ightharpoonup sensor with accurate cosine(ϕ) directivity
- measurement of sound power with suppression of the contribution of unwanted sources

$$W = \int_{S} \vec{I} d\vec{S}$$
 [W



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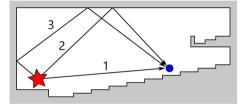
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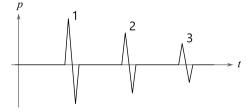
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motivation

impulse response between a source and a receiver resolves different propagation paths:





difficulty

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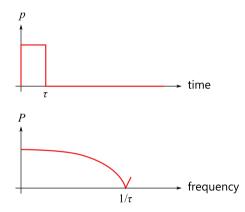
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excitation impulse has to be short:



challenge:

how to excite the system with sufficient energy?

excitation

impulse response

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possible excitations:

- pistol shots (spectrum?, directivity?)
- bursting balloons (spectrum?, directivity?)
- electrical sparks (spectrum?, directivity?)

preferred choice:

▶ loudspeakers (often poor $S/N \rightarrow trick?$)

averaging process

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possible strategy to overcome poor S/N: averaging

repetition of single impulse measurements (only for time-invariant systems!)

```
increase of wanted signal: +6 dB per doubling increase of noise: +3 dB per doubling 
S/N improvement: +3 dB per doubling
```

averaging process: summation of several measurements

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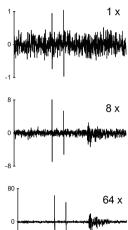
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averaging process

impulse response

- multiple averaging over single impulse measurements is very time consuming
 - wait until system response has dropped to sufficiently low values (in rooms: seconds)
 - \triangleright averaging numbers O(10'000) are needed
- correlation methods implement averaging processes very efficiently

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ightharpoonup system input signal: x(t)

ightharpoonup system output signal: y(t)

auto-correlation function:

$$R_{xx}(\tau) = \frac{1}{2T} \int_{-T}^{+T} x(t-\tau)x(t)dt \qquad (T \to \infty)$$

cross-correlation function:

$$R_{xy}(\tau) = \frac{1}{2T} \int_{-\tau}^{+T} x(t-\tau)y(t)dt \qquad (T \to \infty)$$

Wiener-Hopf-equation

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for a system with impulse response h(t):

$$R_{xy}(\tau) = h(t) * R_{xx}(\tau)$$

if $R_{xx}(au)$ corresponds to a Dirac pulse, the relation simplifies to

$$R_{xy}(au) = h(t)$$

signals with dirac-like ACF?

signals with dirac-like ACF

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signals with dirac-like ACF:

- Dirac pulse
- white noise
- periodically continued maximum length sequences (pseudo random sequences)

maximum length sequences

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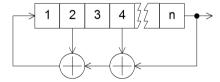
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- ▶ two-valued signal (+1,-1) for lengths $L=2^n-1$ with (n: integer > 1)
- white spectrum
- optimal crest-factor = 1 (= 0 dB)
- ► fast algorithm (Hadamard transformation) for the correlation calculation
- generation with help of shift registers with appropriate feed-back



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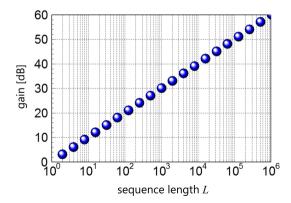
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benefit

- ightharpoonup correlation with sequence of length L corresponds to averaging L times a single impulse measurement
- ▶ gain or S/N improvement = $log_2(L) \cdot 3 dB$



MLS Demo

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to be considered in MLS measurements:

- periodicity of the maximum length sequence
- validity of time-invariance property of the system under test
- ▶ linearity of the system (inclusive excitation, e.g. loudspeaker)

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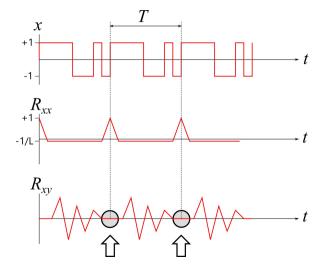
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periodicity of the ML sequence

possible aliasing by the periodic repetition of the maximum length sequence:



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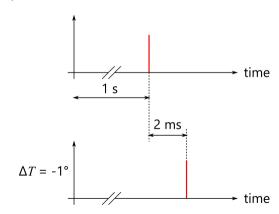
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time-invariance of the system

fundamental requirement for averaging: time-invariance of the system! caution: e.g. temperature dependency of the speed of sound: $\Delta T = -1^\circ \to \Delta c = -0.6 \text{ m/s}$



linearity of the system

impulse response

- ▶ air and boundaries are linear in good approximation
- serious problem: exciting loudspeaker
- correlation process is extremely sensitive to nonlinear distortion
- results in increased background noise in the impulse response
- optimal S/N is obtained for moderate loudspeaker volume

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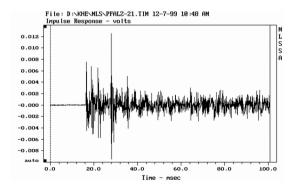
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evaluation of an impulse response measurement

- any disturbing noise shows up homogeneously distributed over the whole impulse response
- ▶ discussion of S/N is possible in a signal-free section: e.g. before the direct sound component



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reverberation time RT: decrease of energy density to 10^{-6} of the initial value after muting the exciting source

- ▶ RT is the most important global indicator for the acoustical characterisation of a room
- standard measurement:
 - pink noise excitation by a loudspeaker
 - recording of the sound pressure decay after muting the source
 - third-octave or octave band filtering
 - typical range for the evaluation: time T' for decay from -5 dB...-35 dB $\rightarrow RT = 2T'$

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reverberation time measurements

reverberation time

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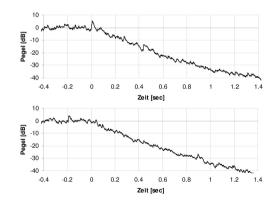
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problem with the standard measurement:

ightharpoonup randomness of the decay process ightharpoonup uncertainty in the evaluation



Schroeder inverse integration

reverberation time

randomness in the decay curve asks for averaging over several measurements $s^2(t)$

derived by Schroeder:

$$\langle s^2(t) \rangle \sim \int\limits_t^\infty r^2(\tau) \mathrm{d} \tau$$

where

 $\langle s^2(t) \rangle$: average of all possible decays of the squared time response $r^{2}(t)$: squared impulse response of the room for the selected source and microphone position

Schroeder inverse integration

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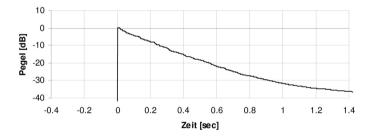
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example Schroeder inverse integration:



reverberation time measurements

reverberation time measurements

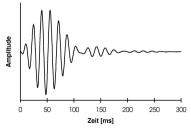
evaluation of short reverberation times with small filter bandwidths:

ightharpoonup narrow bandpass filters (lowest third octaves) ightarrow significant temporal broadening of the impulse

filter decay may be slower than room decay

ightharpoonup necessary condition: $B \cdot T60 > 16$

e.g. impulse response of a 63 Hz third octave band filter:



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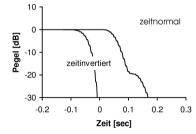
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impulse response of a bandpass filter is asymmetrical

- with respect to decay it is beneficial to invert time axis (frequency behavior is unaltered!):
 - digital filter with inverted time axis or
 - backwards play-back of recorded impulse responses
- ▶ \rightarrow new relaxed condition: $B \cdot T60 > 4$



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b bandpass filtering with bandwidth Δf of an impulse response results in a temporal broadening Δt (-3 dB points) where

$$\Delta t \cdot \Delta f \geq 0.5$$

time - bandwidth uncertainty

time - bandwidth uncertainty

▶ challenge: find 'optimal' filter function for $\Delta t \cdot \Delta f = 0.5$:

$$G(\omega) = 0.5 rac{\sqrt{\pi}}{lpha} \left(e^{-(\omega+\omega_0)^2/4lpha^2} + e^{-(\omega-\omega_0)^2/4lpha^2}
ight)$$

where

 ω_0 : filter center angular frequency in rad/s

$$\alpha = \frac{\Delta\omega}{\sqrt{2\pi}}$$

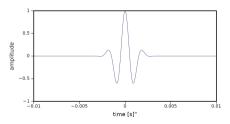
 $\Delta\omega$: filter bandwidth in rad/s

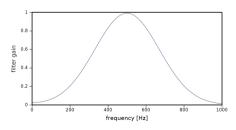
time - bandwidth uncertainty

time - bandwidth uncertainty

impulse response of 'optimal' filter: Gabor pulse

$$g(t) = e^{-lpha^2 t^2} \cos(\omega_0 t)$$





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