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Acoustics I: room acoustics

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introduction

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statistical room acoustics
geometrical room acoustics
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tools
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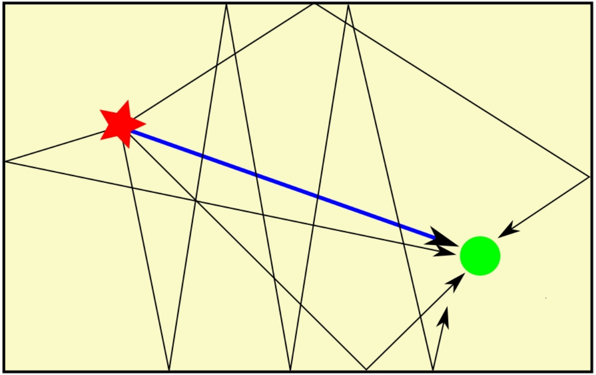
introduction

sound propagation in rooms



introduction

approaches and indicators in room acoustics:

statistical	assumption: sound field is composed of direct sound and *diffuse field*. Indicators: reverberation time, direct/diffuse energy ratio.
geometrical	assumption: propagation along straight rays (high frequency approximation). Indicators: reverberation time, additional room acoustical parameters.
wave based	solutions of the wave equation, analytical solutions for simple geometries only, numerical methods for the general case.

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introduction

applicability of the approaches:

	small rooms	large rooms
low frequencies	W	(W),G,S
high frequencies	(W),G,S	G,S

- S: statistical
- G: geometrical
- W: wave based

statistical room acoustics

diffuse sound field

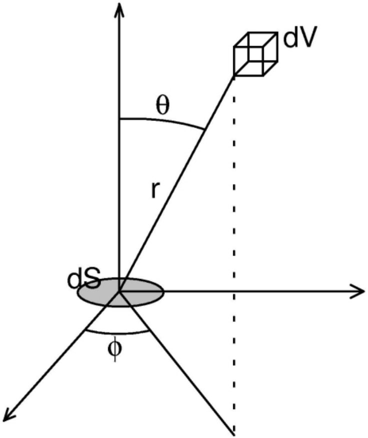
- statistical approach ignoring specific position of features
- fundamental assumption: direct + diffuse sound field
- properties of a diffuse sound field:
  - constant sound energy density
  - no dominant sound incidence direction
- conditions for a diffuse sound field in practice:
  - only little total absorption
  - homogeneous distribution of the absorption

sound energy density and intensity on a surface

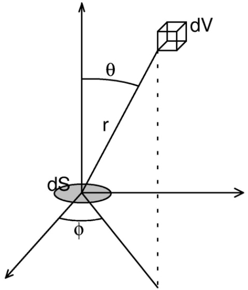
energy density and intensity

- situation: room with a diffuse sound field of energy density w
- wanted: normal component of sound intensity on the surfaces
- solution:
  - formulation of the relation between a small volume element and a surface element
  - integration over the volume

energy density and intensity



energy density and intensity



energy E captured by $\mathrm{d}S$, stemming from $\mathrm{d}V$:

$$E = \mathrm{d}S \cos\theta \frac{w \cdot \mathrm{d}V}{4\pi r^2}$$

in spherical coordinates: $\mathrm{d}V = r^2 \cdot \mathrm{d}r \cdot \mathrm{d}\theta \cdot \sin(\theta) \cdot \mathrm{d}\phi$

energy density and intensity

- power W captured by $\mathrm{d}S$ corresponds to the energy collected in 1 second
- → energy incident from a half-sphere with radius $R = c \cdot 1$ sec

$$W = \frac{w\mathrm{d}S}{4\pi} \int_0^{c\cdot 1sec} \int_0^{2\pi} \int_0^{\pi/2} \cos(\theta)\sin(\theta)\mathrm{d}\phi\mathrm{d}\theta\mathrm{d}r = \frac{wc}{4}\mathrm{d}S = I\mathrm{d}S$$

and for the intensity:

$$I_{\text{wall}} = \frac{w \cdot c}{4}$$

power balance in the diffuse field

power balance in the diffuse field

- situation: sound source emits power W_{source} in a room, assuming a diffuse field
- wanted: sound pressure in steady state
- solution:
  - interpret diffuse field as superposition of plane waves
  - balance condition for $W_{\text{source}} = W_{\text{absor}}$

power balance in the diffuse field

absorbed power:

$$W_{\text{absor}} = I_{\text{wall}} A = \frac{wc}{4} A$$

where:

$$A = \sum_i \alpha_i \cdot S_i$$

from $W_{\text{source}} = W_{\text{absor}}$ follows:

$$w = \frac{4 W_{\text{source}}}{Ac}$$

power balance in the diffuse field

for a plane wave in a cylindrical tube of cross sectional area 1 m^2 and height $= c \cdot 1$ sec:

$$I = \frac{p^2}{\rho c} = wc$$

and finally:

$$p^2_{\text{diffuse}} = \frac{4 W_{\text{source}} \rho c}{A}$$

distance dependency in the sound field

distance dependency of p in the sound field

- distance dependency of p in the sound field for an omnidirectional point source:
  - superposition of p^2 of direct and diffuse sound

direct sound:

$$p^2_{\text{direct}} = \frac{W_{\text{source}}\rho c}{4\pi r^2}$$

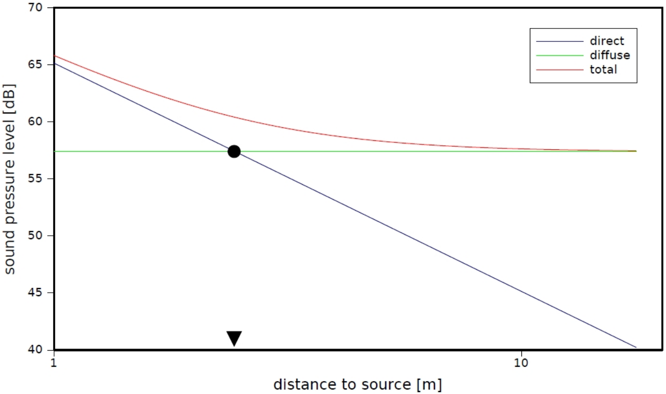
diffuse sound:

$$p^2_{\text{diffuse}} = \frac{4W_{\text{source}}\rho c}{A}$$

distance dependency in the sound field

summation:

$$p^2 = p^2_{\text{direct}} + p^2_{\text{diffuse}} = W_{\text{source}}\rho c \left(\frac{1}{4\pi r^2} + \frac{4}{A} \right)$$



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distance dependency in the sound field

- critical distance r_c where $p^2_{\text{direct}} = p^2_{\text{diffuse}}$:

$$\text{from} \quad \frac{1}{4\pi r_c^2} = \frac{4}{A} \quad \text{follows} \quad r_c = \sqrt{\frac{A}{16\pi}}$$

reverberation, reverberation time

reverberation, reverberation time

- observation of the non-stationary process after muting the source:
  - power balance:

$$0 = W_{\mathrm{absor}}(t) + V \frac{\mathrm{d}w(t)}{\mathrm{d}t}$$

with

W_{absor}: absorbed power by the room surfaces

V: room volume

w: energy density

reverberation, reverberation time

with $W_{\text{absor}} = wcA/4 \rightarrow$ differential equation for $w(t)$:

$$0 = \frac{w(t)c}{4}A + V\frac{\mathrm{d}w(t)}{\mathrm{d}t}$$

hypothesis for the solution:

$$w(t) = w_0 e^{bt}$$

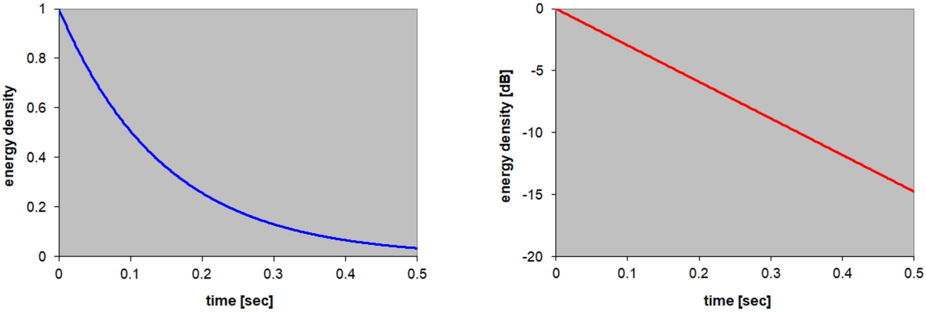
comparison of coefficients yields: $b = -\frac{cA}{4V}$

reverberation, reverberation time

time dependency of $w(t) \rightarrow$ reverberation :

lin

log



reverberation, reverberation time

- reverberation time T:
  - time span for a drop of w to 10^{-6} of its initial value
  - corresponds to -60 dB

from:

$$e^{-\frac{cA}{4V}T} = 10^{-6}$$

follows (Sabine formula):

$$T = \frac{-\ln(10^{-6})4V}{cA} = \frac{0.16V}{A}$$

reverberation time according to Eyring

Eyring's reverberation time

- model for sound propagation process:
  - sound energy particles propagate along straight lines
  - after a hit at a room surface:
    - specular reflection
    - $\text{energy}_{\text{new}} = \text{energy}_{\text{old}} \cdot (1 - \alpha)$
    - α: average absorption coefficient
  - distance between two reflections: mean free path length ℓ
  - for rectangular rooms: $\ell = \frac{4V}{S}$
    - V: room volume
    - S: room surface

Eyring's reverberation time

energy E of a particle after N reflections:

$$E(N) = E_0(1-\alpha)^N$$

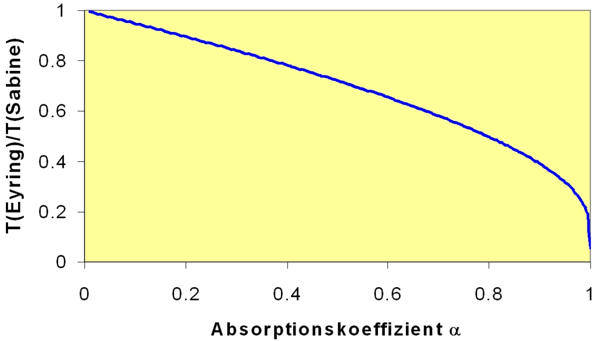
E drops to 10^{-6} after M reflections with

$$M = \frac{\ln(10^{-6})}{\ln(1-\alpha)} = \frac{-13.8}{\ln(1-\alpha)}$$

M reflections correspond to a path length $L = M \cdot \ell$ corresponding to a time T (reverberation time):

$$T = \frac{M\ell}{c} = \frac{-13.8 \cdot 4V}{\ln(1-\alpha)cS} = \frac{0.16V}{-\ln(1-\alpha)S}$$

comparison of Eyring and Sabine



- always: $T_{\text{Eyring}} < T_{\text{Sabine}}$
- for $\alpha \to 0$: $T_{\text{Eyring}} = T_{\text{Sabine}}$
- for $\alpha \to 1$: $T_{\text{Eyring}} \to 0,\ T_{\text{Sabine}} > 0$

example: reverberation time calculation

Sabine reverberation time calculation

- rectangular room 10m x 6m x 4m with
  - front and rear wall: plaster
  - one side wall: windows
  - one side wall: wooden boxes
  - floor: carpet
  - ceiling: plaster

absorption coefficients α [.]:

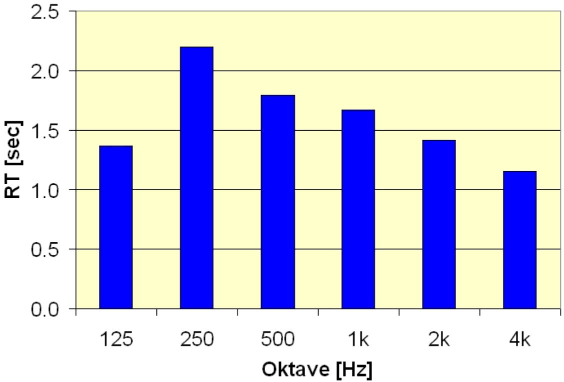
	125	250	500	1k	2k	4k
plaster	0.01	0.01	0.02	0.02	0.03	0.04
window	0.1	0.04	0.03	0.02	0.02	0.02
wooden boxes	0.5	0.25	0.15	0.05	0.05	0.1
carpet	0.05	0.08	0.2	0.3	0.35	0.4

Sabine reverberation time calculation

absorption $A = \alpha_i \cdot S_i$ [m^2] for each surface:

	125	250	500	1k	2k	4k
front/rear wall	0.5	0.5	1.0	1.0	1.4	1.9
side wall 1	4.0	1.6	1.2	0.8	0.8	0.8
side wall 2	20.0	10.0	6.0	2.0	2.0	4.0
floor	3.0	4.8	12.0	18.0	21.0	24.0
ceiling	0.6	0.6	1.2	1.2	1.8	2.4
TOTAL	28.1	17.5	21.4	23.0	27.0	33.1

Sabine reverberation time calculation: result



	125	250	500	1k	2k	4k
RT [s]	1.37	2.20	1.80	1.67	1.42	1.16

reverberation times in practice

reverberation times in practice

- reasons for deviations between measured and calculated reverberation times:
    - additional air absorption
        - effect can be included by more subtle formulas
    - non-diffuse sound fields
        - inhomogeneous absorber distribution
        - coupled rooms

reverberation times in practice

- inhomogeneous absorber distribution:
  - high absorption concentrated at one surface
  - sound energy may oscillate between parallel surfaces with low absorption
  - → effect: longer reverberation times than predicted by Sabine/Eyring
- examples of inhomogeneous absorption:
  - rooms with exclusive absorption by audience
  - gyms with absorbing ceilings

reverberation times in practice

- coupled rooms:
    - rooms with different damping, connected to each other by a small common opening
    - source and receiver in the room with higher damping
    - $\rightarrow$ sagging reverberation curves
- examples of coupled rooms:
    - churches with attached chapels
    - auditorium and foyer (coupling by open doors)
    - coupled reverberation chambers (KKL)

geometrical room acoustics

geometrical room acoustics

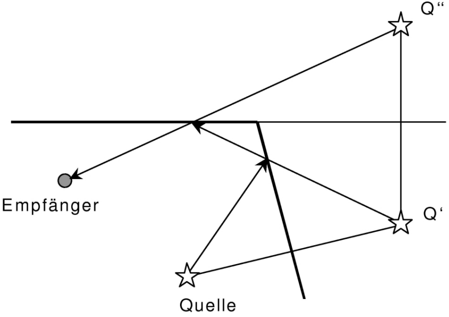
- model of sound propagation:
  - sound propagation in form of energy droplets that travel along straight lines (rays)
  - $\rightarrow$ high frequency approximation ($\approx$ light)
- consequences:
  - consideration of energies only $\rightarrow$ wave phenomena are ignored:
    - no diffraction
    - no interference
    - no resonances

geometrical room acoustics

- consideration of absorption in air and at room surfaces
- reflection at surfaces:
  - specular reflection
    - at smooth surfaces
  - diffuse reflection (Lambert's law)
    - at depth structured (compared to λ) surfaces

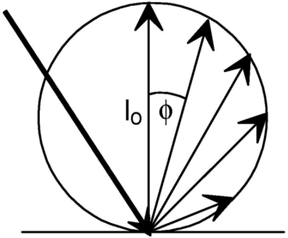
geometrical room acoustics

- specular reflection:
  - angle of incident ray = angle of reflected ray



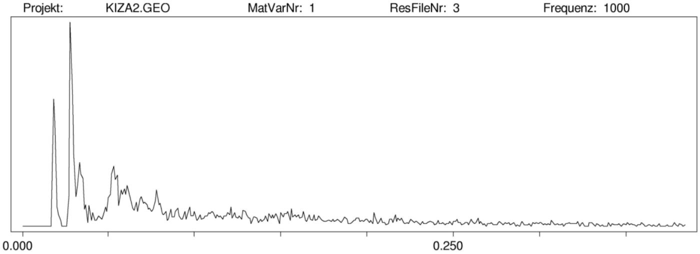
geometrical room acoustics

- diffuse reflection:
  - Lambert's law: $I(\phi) \sim \cos(\phi)$



geometrical room acoustics

- result of an analysis with geometrical acoustics:
    - energy impulse response
    - energy as a function of time of arrival (impulse excitation)



objective room acoustical criteria

objective room acoustical criteria

- energy impulse response allows for evaluation of a wide variety of room acoustical criteria such as:
    - reverberation time T
    - Early Decay Time EDT
    - clarity C80
    - Deutlichkeit D50
    - center time TS
    - strength G
    - lateral energy fraction LF

objective room acoustical criteria

- reverberation time T [s]
    - *global* descriptor
    - just audible difference: 5%
    - evaluation: inverse integration of the energy impulse response, $T = 2 \cdot T'$ with T': time for drop from -5...-35 dB

objective room acoustical criteria

- Early Decay Time EDT [s]
  - subjectively more relevant than T
  - just audible difference: 5%
  - evaluation: inverse integration of the energy impulse response, $EDT = 6 \cdot T'$ with T': time for drop from 0. . .-10 dB

objective room acoustical criteria

- clarity $C80$ [dB]
    - just audible difference: 0.5 dB
    - typical value for music rooms: 0 dB
    - evaluation:

$$C80 = 10 \log \left(\frac{\int_{0}^{80ms} h^2(t)\mathrm{d}t}{\int_{80ms}^{\infty} h^2(t)\mathrm{d}t} \right)$$

objective room acoustical criteria

- Deutlichkeit $D50$ [%]
  - just audible difference: 5%
  - e.g. $D50 = 40\% \rightarrow 87\%$ intelligibility of syllables
  - evaluation:

$$D50 = \frac{\int_0^{50ms} h^2(t)\mathrm{d}t}{\int_0^{\infty} h^2(t)\mathrm{d}t} \times 100\%$$

objective room acoustical criteria

- center time TS [ms]
  - just audible difference: 10 ms
  - evaluation:

$$TS = \frac{\int\limits_0^\infty t \cdot h^2(t)\mathrm{d}t}{\int\limits_0^\infty h^2(t)\mathrm{d}t}$$

objective room acoustical criteria

- strength G [dB]
    - just audible difference: 1 dB
    - evaluation:

$$G = 10 \log \left(\frac{\int\limits_0^\infty h^2(t)\mathrm{d}t}{\int\limits_0^\infty h_{f,10m}^2(t)\mathrm{d}t} \right)$$

where

$h_{f,10m}$: energy impulse response in 10 m under free field conditions.

objective room acoustical criteria

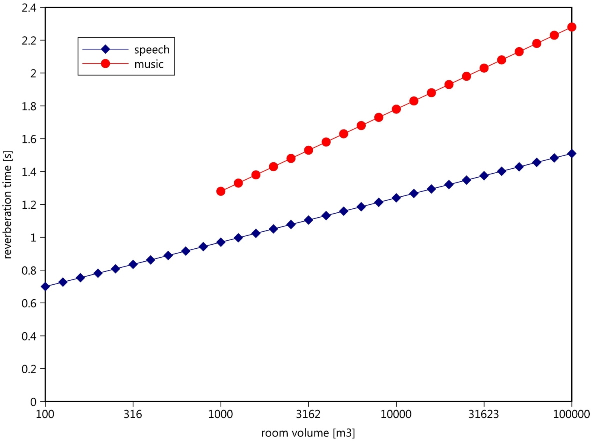
- lateral energy fraction LF [%]
    - just audible difference: 5%
    - evaluation:

$$LF = \frac{\int\limits_{0}^{80ms} h_{\infty}^{2}(t)\mathrm{d}t}{\int\limits_{0}^{80ms} h^{2}(t)\mathrm{d}t} \times 100\%$$

where
h_{∞}: energy impulse response with a figure-of-eight microphone (lateral sensitivity).

objective room acoustical criteria

optimal reverberation times:



objective room acoustical criteria

optimal values for large music rooms:

criterium	optimal range
EDT	1.8. . .2.2 s
C80	-2. . .+2 dB
G	> 0 dB
LF	10% . . . 35%

objective room acoustical criteria

- listening examples
  - general: $T = 2$ s
  - varying values of other criteria

guitar ABCD

- evaluation of transparency of examples A to D

objective room acoustical criteria

values of the criteria:

guitar 2128

Nr.	C80	TS	EDT	T
1	-4.6	200	2.43	2.0
2	0.7	121	2.25	2.0
8	5.3	69	1.75	2.0

room acoustical design criteria for large rooms

design criteria for large rooms

- quietness
  - no audible noise
    - sufficient sound insulation to outside sources
    - sufficient sound insulation to adjacent rooms
    - sufficient low level of technical noise (ventilation, ...)
- direct sound
  - provide sufficient early energy to audience area
    - early energy: up to 50..80 ms after direct sound arrival
- reverberation
  - appropriate reverberation time in dependency of usage, room volume and room type

design criteria for large rooms

- lateral reflections
    - feeling of spaciousness is created by signal differences at the two ears
        - low interaural cross correlation
        - need for strong lateral reflections
- diffusivity
    - temporally smeared reflections are beneficial
    - avoid discrete echoes, no focusing effects

design criteria for large rooms

- balance
  - homogeneous signal strength distribution of all instruments in the audience area
- audibility on stage
  - musicians should hear each other reasonably well

tools for the acoustical design of rooms

tools for the acoustical design of rooms

- statistical room acoustics:
  - calculation of reverberation times
- geometrical room acoustics:
  - construction of sound rays by hand
  - computer based ray tracing
  - computer based mirror source construction
- wave theoretical room acoustics:
  - calculation of room modes
  - numerical simulation (FDTD, BE, FE)
- experimental investigations:
  - in real rooms
  - is physical scale models
- auralisation:
  - listen to a source in a virtual room

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statistical room acoustics: reverberation time calculations

Statistical room acoustics: reverberation time calculations

- formulas of Sabine or Eyring
    - required data:
        - room volume V
        - area S and absorption coefficient α of the materials present in the room
- approximations for situations with dominating audience absorption (area S_a) :

$$T \approx \frac{0.15V}{S_a}$$

geometrical room acoustics: exemplary sound rays

geometrical room acoustics: exemplary sound rays

- evaluation of basic forms
    - shape of ceiling
    - primary form of ground plan
    - focusing elements
- orientation of reflector elements

computer-assisted geometrical room acoustics: ray tracing

geometrical room acoustics: ray tracing

- strategy:
  - source point emits energy particles
  - propagation along straight lines under consideration of specular or diffuse reflection and absorption
  - collection of rays that pass a sphere around each receiver
  - collection → energy impulse response
- advantages:
  - diffuse reflections can be handled
  - computational effort $\sim N_{\text{sources}}$
- disadvantages:
  - radius of receiver spheres $> 0 \rightarrow$ fuzzyness in time and space
  - no explicit truncation criterion

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computer-assisted geometrical room acoustics: mirror source method

geometrical room acoustics: mirror source method

- strategy:
  - construction of all mirror sources up to order *n* for all receivers
  - determine the ”visible” (valid) mirror sources
  - apply weighting of $1/r^2$ and $(1-\alpha)$
  - collection: → energy impulse response
- advantages:
  - any desired temporal resolution possible
  - clearly defined truncation criterion
- disadvantages:
  - diffuse reflections can't be handled
  - computational effort $\sim N_{\text{sources}} \cdot N_{\text{receivers}}$

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scale model experiments

scale model experiments

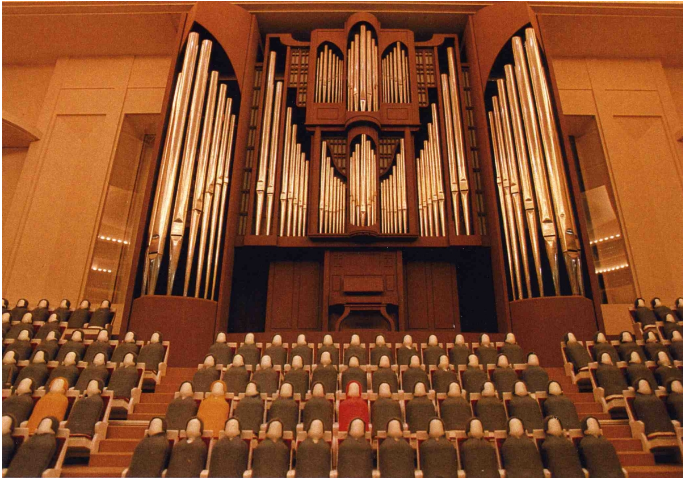
- investigation of sound propagation in physical scale models with help of measurements
- propagation effects scale with wavelength:
  - scaling of geometrical dimensions by $1/s$
  - $\rightarrow$ scaling of frequencies by s
- challenges:
  - identification of model materials with desired absorption properties
  - handling of extremely strong air absorption in the transformed frequency range
- typical scaling factors: 1:10 . . . 1:50

scale model experiments

example: Yokohama Minatomirai Concert Hall

scale model experiments

example: Yokohama Minatomirai Concert Hall



auralisation

auralisation

- auralisation = provide listening impression of the acoustics of a virtual room
- listening impression is ”ultimate” criterion
- very helpful in discussions with non-experts
- audio material: dry recordings with no reverberation
  - example

auralisation with scale models

- auralisation based on physical scale models:
  - frequency up-shift of the signal of interest
  - playback and recording in the model
  - frequency down-shift to create the signal to listen to

auralisation with statistical room acoustics

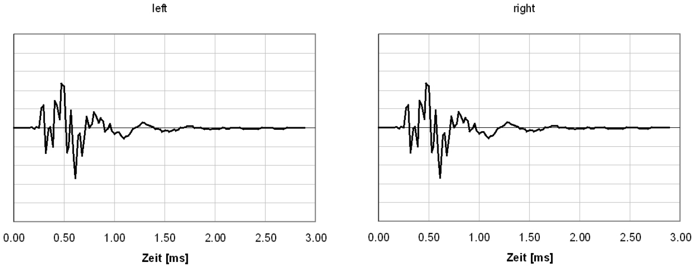
- auralisation based on statistical room acoustics approach:
    - tunable parameters:
        - reverberation time
        - direct sound / diffuse sound ratio
    - reproduction: summation of original signal and output of reverberation engine

auralisation with geometrical room acoustics

- auralisation based on geometrical room acoustics approach:
    - determination of individual energy impulse responses for different incidence directions
    - reproduction
        - by cloud of loudspeakers
        - by headphones after filtering with head related transfer functions

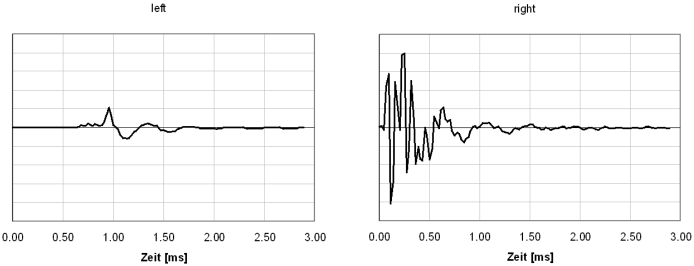
auralisation with geometrical room acoustics

example: time domain representation of HRTF
sound incidence front (elevation $= 0°$, azimuth $= 0°$)



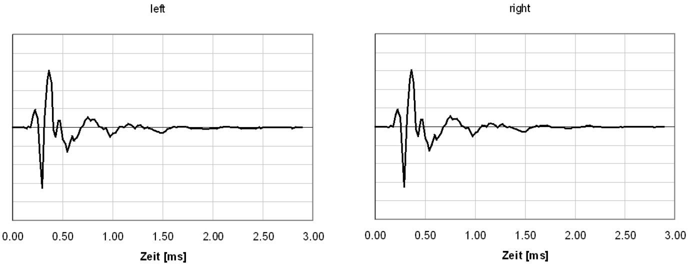
auralisation with geometrical room acoustics

example: time domain representation of HRTF
sound incidence right (elevation = 0°, azimuth = 90°)



auralisation with geometrical room acoustics

example: time domain representation of HRTF
sound incidence front up (elev. = 45°, azi. = 0°)



additional effects usually not considered with statistical and geometrical room acoustics

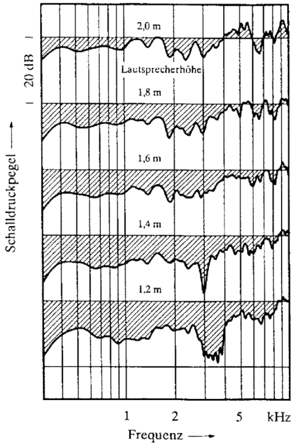
grazing incidence over audience areas

grazing incidence over audience areas

- sound propagation at grazing incidence → strong excess attenuation due to:
  - destructive interference between direct sound and sound scattered at the bodies (heads and shoulders)

grazing incidence over audience areas

example: measured levels at a receiver in the 12th row for a loudspeaker at a height of 1.2 .. 2.0 m

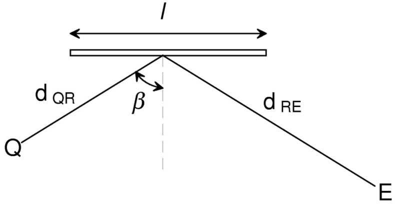


reflection at finite surfaces

reflection at finite surfaces

- geometrical interpretation of a reflection ignores:
  - *wave covers a certain area for full reflection* (frequency dependent)
- quantitative investigation by applying concept of Fresnel zones
- small surfaces → scattering

reflection at finite surfaces



- estimation of the lower limiting frequency f_u for full reflection:

$$f_u = \frac{2c}{(l\cos\beta)^2}\frac{d_{QR}d_{RE}}{(d_{QR}+d_{RE})}$$

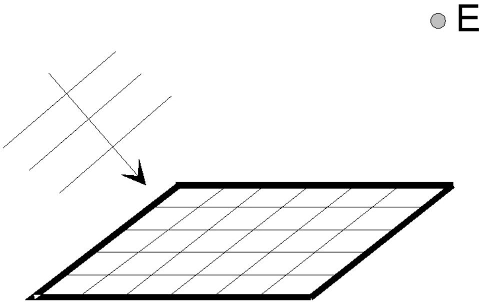
diffusers as design element

design of diffusely reflecting surfaces

how to design a diffuser?

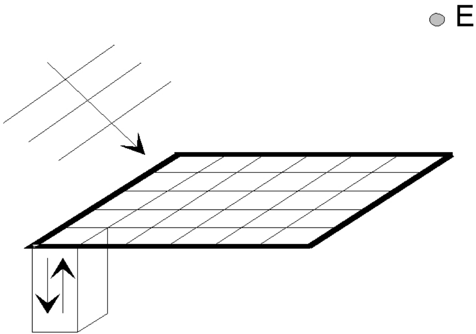
diffusers

- elements with diffuse/scattering reflection characteristics
- necessary condition:
  - introduction of a locally random phase response
    - incoherent superposition of reflection contribution of each surface element of the reflector
    - energetic integration for all directions



diffusers

- random phase response can be realized by
  - varying material properties
  - depth structured surface
    - channels of varying depth



diffusers

- variation of the channel depth according to:
  - white noise
  - sequence s of squared residues (Schroeder Diffuser):
    - $s = m^2 \mathrm{mod} N$ mit $m = 0, 1, 2, \ldots ; N$: prime
    - s will become periodic in N
- frequency range for diffuse reflection:
  - $\lambda_{\mathrm{max}} \approx 2 \cdot \mathrm{max.channel.depth}$
  - $\lambda_{\mathrm{min}} \approx 2 \cdot \mathrm{max.channel.width}$
- caution: significant absorption due to large pressure differences from channel to channel → pressure equalization without radiation

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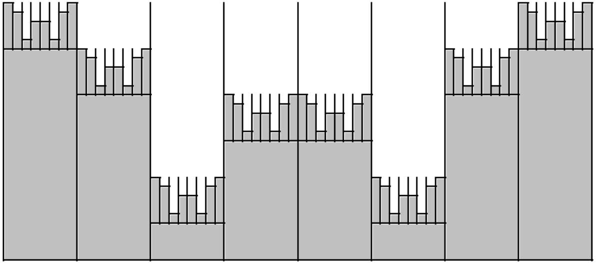
diffusers

- Schroeder diffusor fractal extension:

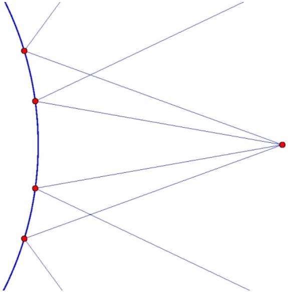


diffusers: practical constructions

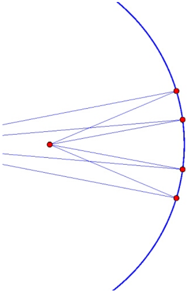
acoustics of round forms

reflection at convex and concave structures

reflection at convex and concave structures



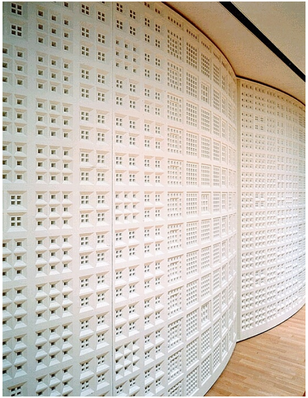
convex → scattering



concave → focusing

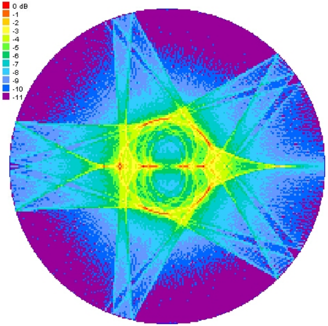
reflection at convex and concave structures

convex structures are often beneficial



example: KKL

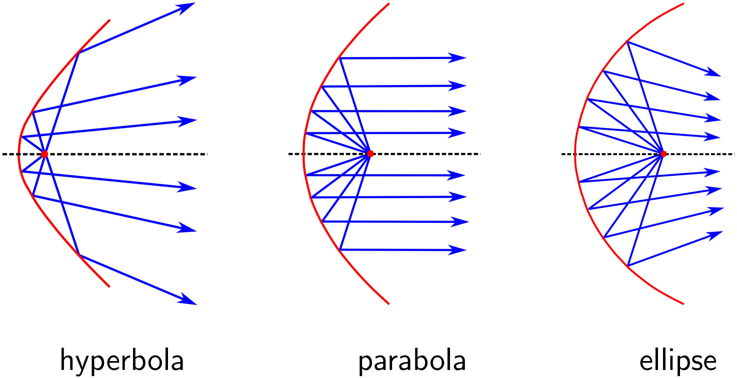
concave structures are often problematic!



pressure in circular room

reflection at conic section geometries

concave reflection at conic section geometries (source in focal point)



reflection at segments of a circle

reflection at concave segments of a circle

dome structures can often be approximated by

- parts of a sphere (3D)
- parts of circles (2D)

→ Cinderella (Kreis-Reflexionen.cdy)

reflection at concave segments of a circle

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→ Cinderella (Kreis-Reflexionen.cdy)

reflection at concave segments of a circle

segment of a circle appears (depending on source position) as:

- part of a hyperbola
- parabola
- ellipse

reflection at concave segments of a circle

segment of a circle appears (depending on source position) as:

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reflection at concave segments of a circle

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reflection at concave segments of a circle

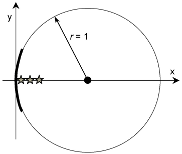
segment of a circle appears (depending on source position) as:

- part of a hyperbola
- parabola
- ellipse

reflection at concave segment of a circle

hyperbolic	parabolic	elliptic	elliptic
$x_Q < 0.5R$	$x_Q = 0.5R$	$x_Q > 0.5R$	$y_Q^2 = x_Q - x_Q^2$
$x_{F2} = \frac{x_Q}{2x_Q - 1}$	$x_{F2} = \infty$	$x_{F2} = \frac{x_Q}{2x_Q - 1}$	$y_{F2} = -y_Q$
divergent	parallel	focusing	focusing

reflection at concave segment of a circle

hyperbolic	parabolic	elliptic	elliptic
			
$x_Q < 0.5R$ $x_{F2} = \frac{x_Q}{2x_Q - 1}$	$x_Q = 0.5R$ $x_{F2} = \infty$	$x_Q > 0.5R$ $x_{F2} = \frac{x_Q}{2x_Q - 1}$	$y_Q^2 = x_Q - x_Q^2$ $y_{F2} = -y_Q$
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reflection at concave segment of a circle

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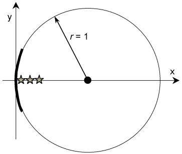	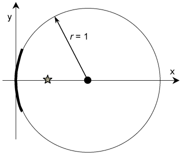		
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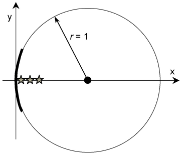	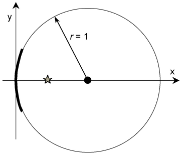	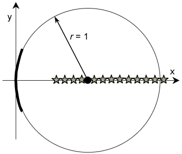	
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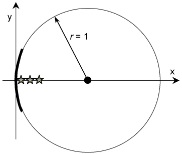
reflection at concave segment of a circle

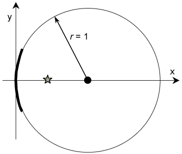
hyperbolic



$$x_Q < 0.5R$$
$$x_{F2} = \frac{x_Q}{2x_Q - 1}$$

divergent

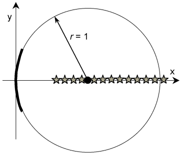
parabolic



$$x_Q = 0.5R$$
$$x_{F2} = \infty$$

parallel

elliptic



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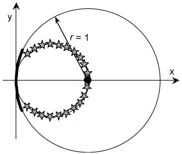
focusing

elliptic

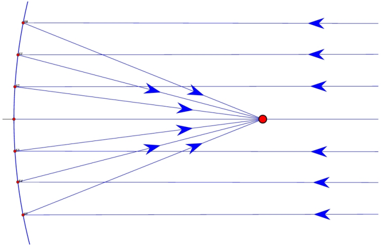


$$y_Q^2 = x_Q - x_Q^2$$
$$y_{F2} = -y_Q$$

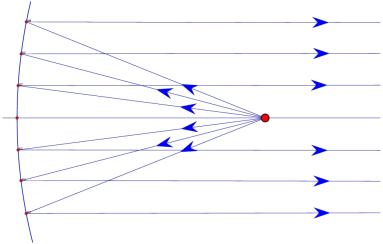
focusing

reflection at concave segments of a circle

study of two arrangements with interesting parabolic behavior:



receiver in focal point



source in focal point

receiver in focal point: sound mirrors

sound mirrors

- large mirrors in form of parts of a sphere for sound amplification and localisation
- erected at the coast of England at the end of world war I
- goal: early detection of foreign airplanes by their acoustical signature
- acoustical aspects:
  - air absorption → only low frequencies detectable in large distances
  - focusing needed for $\lambda > 1$ m
  - → diameter of a mirror structure ≈ several meters
- resulting performance: detection and localisation up to 20 km!

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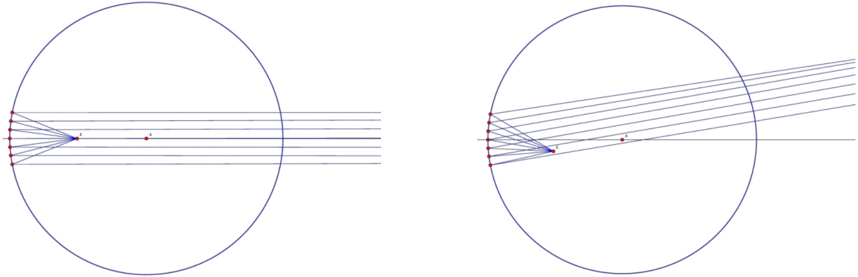
  - air absorption $\rightarrow$ only low frequencies detectable in large distances
  - focusing needed for $\lambda > 1$ m
  - $\rightarrow$ diameter of a mirror structure $\approx$ several meters
- resulting performance: detection and localisation up to 20 km!

sound mirrors

adjustment of focusing direction by moving the listening point in a spherically shaped mirror:



sound mirrors

sound mirrors

sound mirrors

sound mirrors

other localisation methods

binaural localisation:

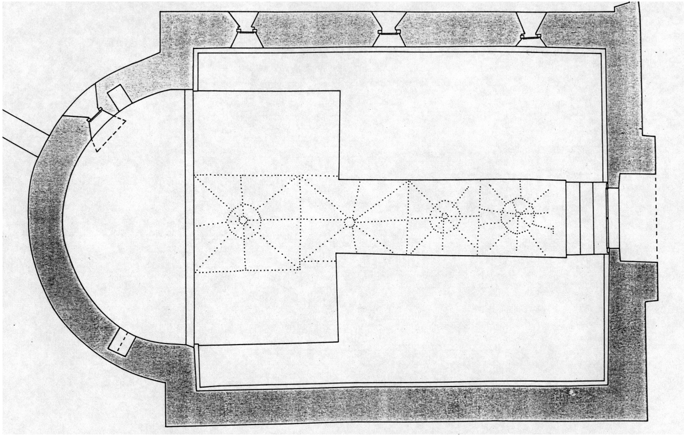
1921: military base near Washington, D.C.

source in focal point:
chapel in Guarda-Giarsun

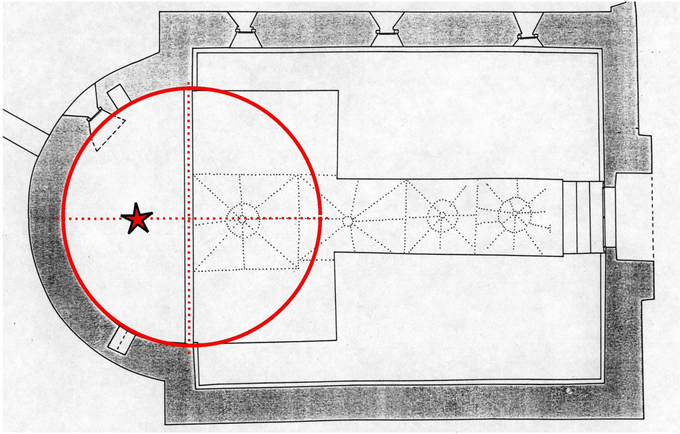
chapel in Guarda-Giarsun

Guarda-Giarsun: interior views

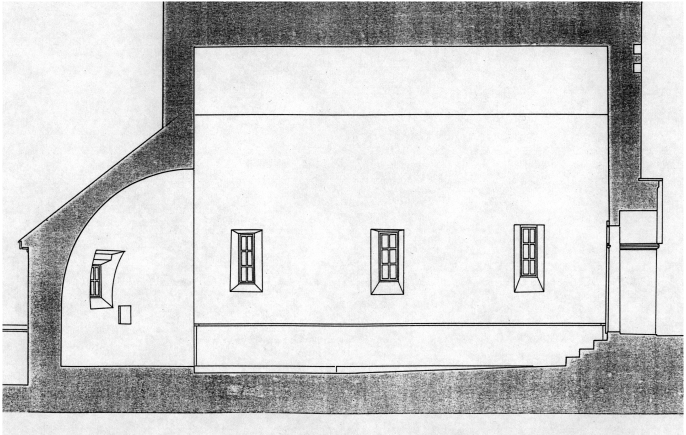
Guarda-Giarsun: ground plan 1(2)



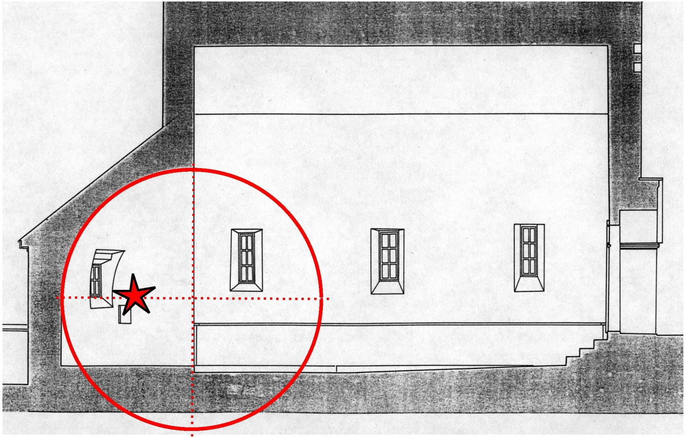
Guarda-Giarsun: ground plan 2(2)



Guarda-Giarsun: longitudinal section 1(2)

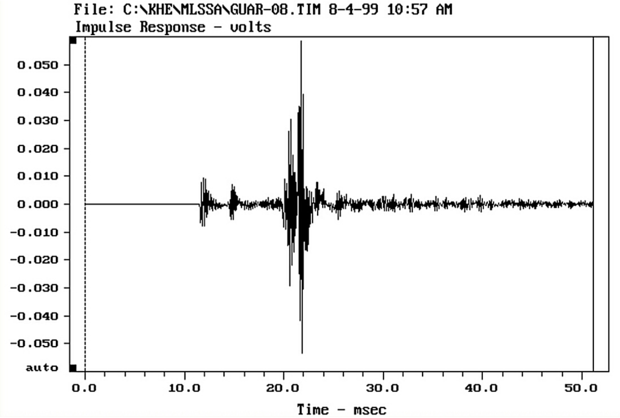


Guarda-Giarsun: longitudinal section 2(2)



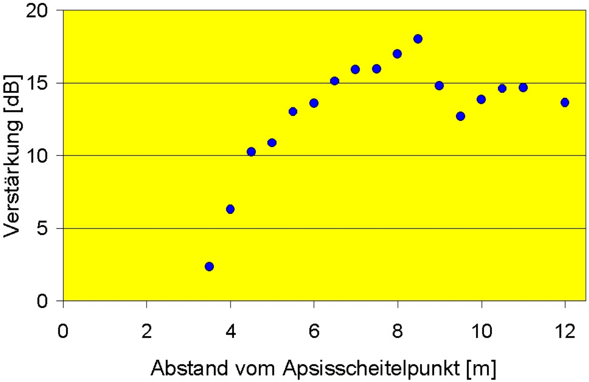
Guarda-Giarsun: impulse response measurement

source located in focal point, receiver distance 4 m

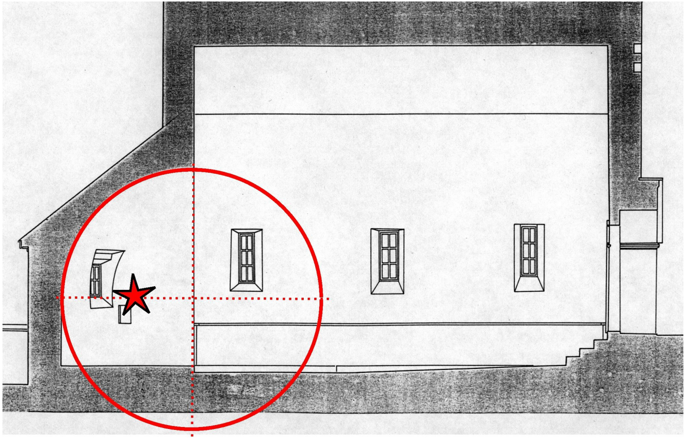


Guarda-Giarsun: amplification

source located in focal point, amplification as function of distance



Guarda-Giarsun: longitudinal section 2(2)

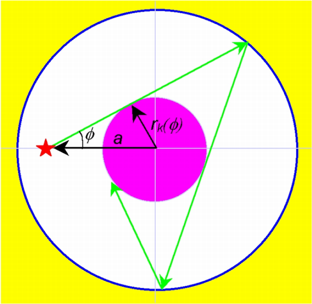


sound field in a circle

energy distribution in a circle 1(2)

→ Kreis-Strahlen.exe

energy distribution in a circle 2(2)



ray(ϕ) → energy concentration on a circle with radius $r_k(\phi) = a\sin(\phi)$

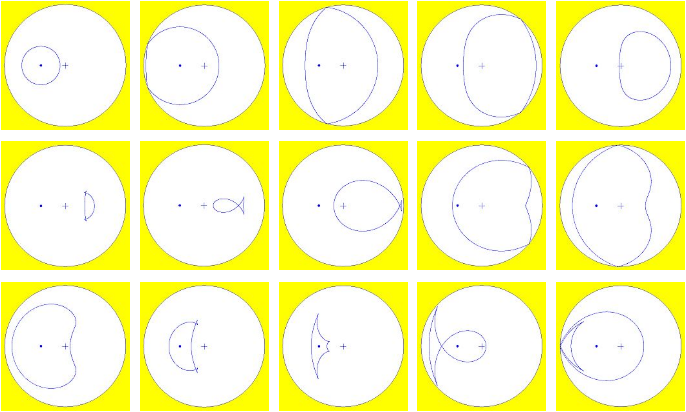
→ density: $\frac{1}{\frac{\partial r_k}{\partial \phi}} = \frac{1}{a\cos(\phi)}$ max. for $\phi = 90 \rightarrow r_k = a$

wave fronts in circular rooms

development of wave fronts in a circular room:

movie: wave fronts in a circle

wave fronts in circular rooms

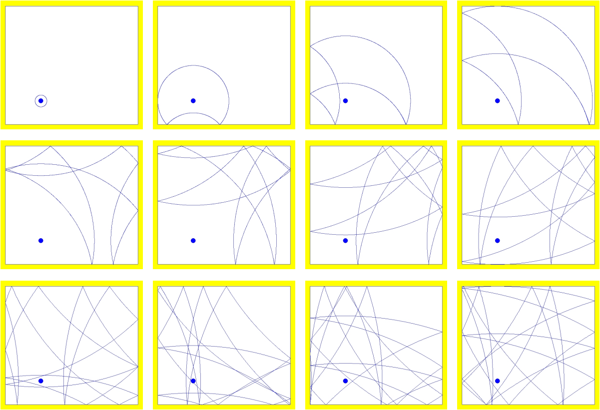


wave fronts in rectangular rooms

development of wave fronts in a rectangular room:

movie: wave front in a rectangular room

wave fronts in rectangular rooms

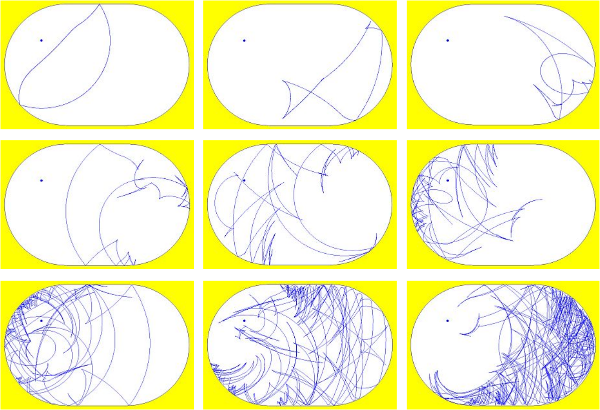


chaotic behavior in stadium rooms

development of wave fronts in a stadium room:

movie: wave front in a stadium room

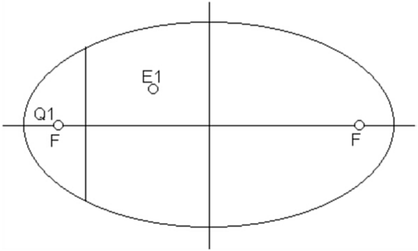
chaotic behavior in stadium rooms



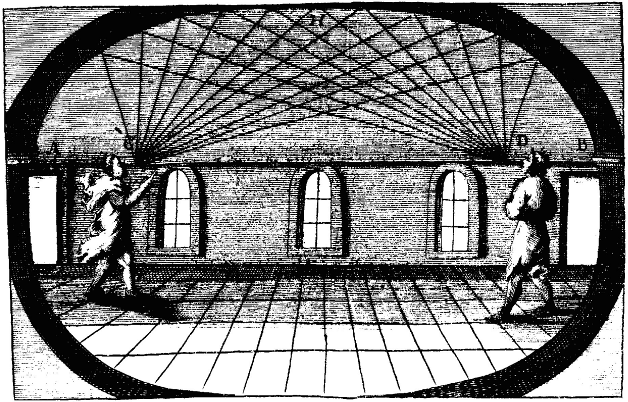
examples of buildings with round structures

KIZA, church in Thun-Allmendingen

KIZA Thun-Allmendingen: elliptic ground plan



KIZA Thun-Allmendingen: focusing effects in ellipses



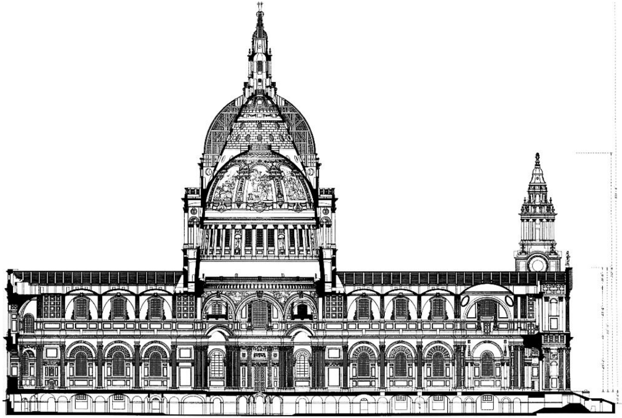
Athanasius Kircher, 1684

KIZA Thun-Allmendingen: intervention by a shield

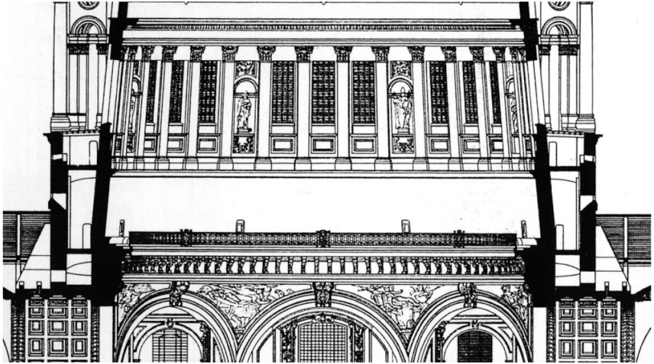
St. Pauls Cathedral, London

St. Pauls Cathedral, London (1:3)

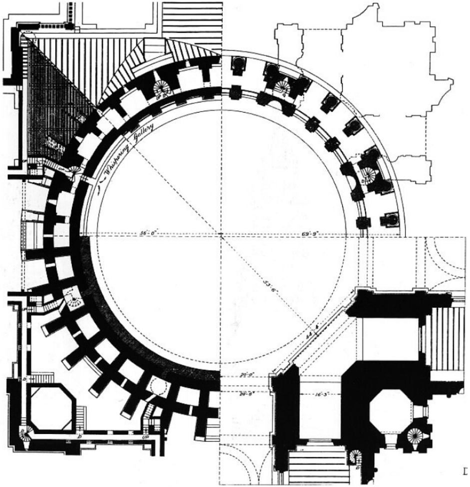
accessible gallery below the dome allows for communication by whispering over large distances.



St. Pauls Cathedral, London (2:3)



St. Pauls Cathedral, London (3:3)



Pantheon Rome
27 BC, Agrippa
118-128, Hadrian

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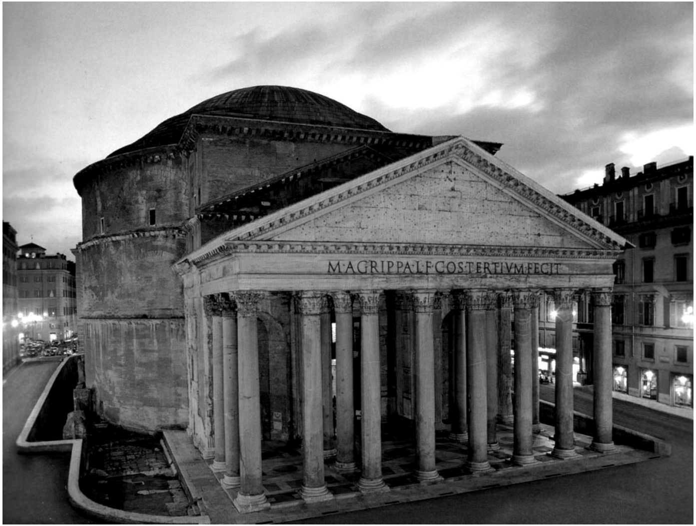
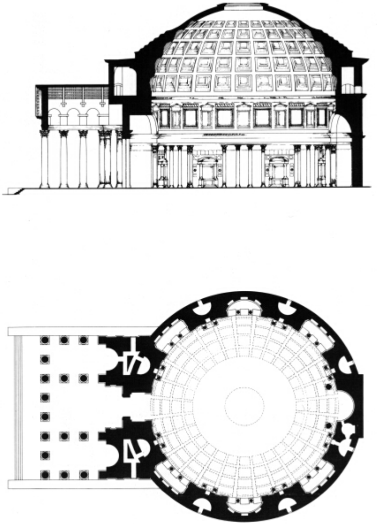
Pantheon Rome



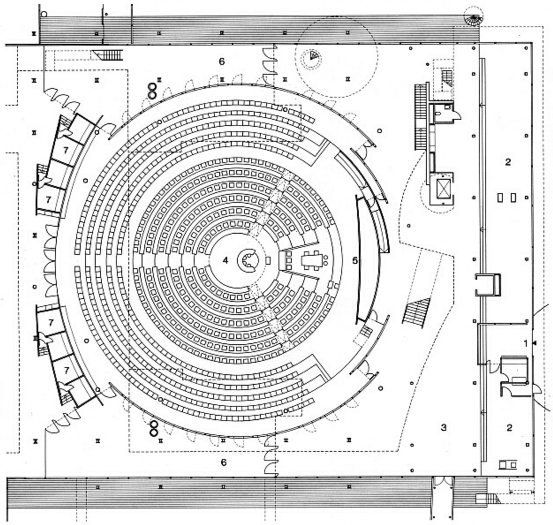
Pantheon Rome



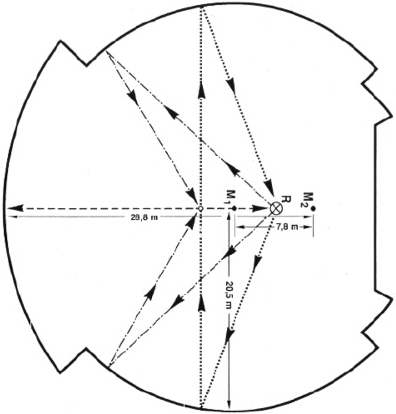
Plenarsaal Bonn

Plenarsaal Bonn 1(6)

Plenarsaal Bonn 2(6)



Plenarsaal Bonn 3(6)

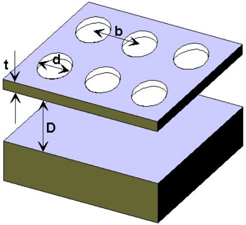


Plenarsaal Bonn 4(6)

- remedial measure 1: all non transparent surfaces were covered with absorbing material
  - highly absorbing eagle wall
  - carpets along the walking zones

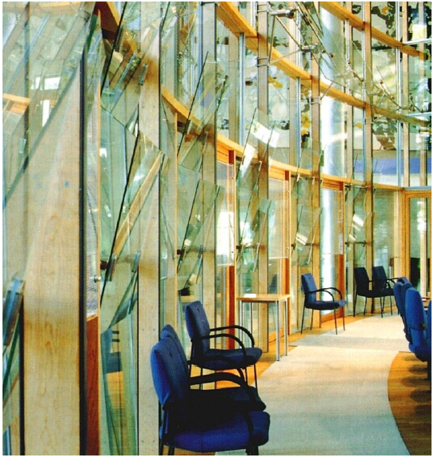
Plenarsaal Bonn 5(6)

- remedial measure 2: installation of transparent micro-perforated glass absorbers



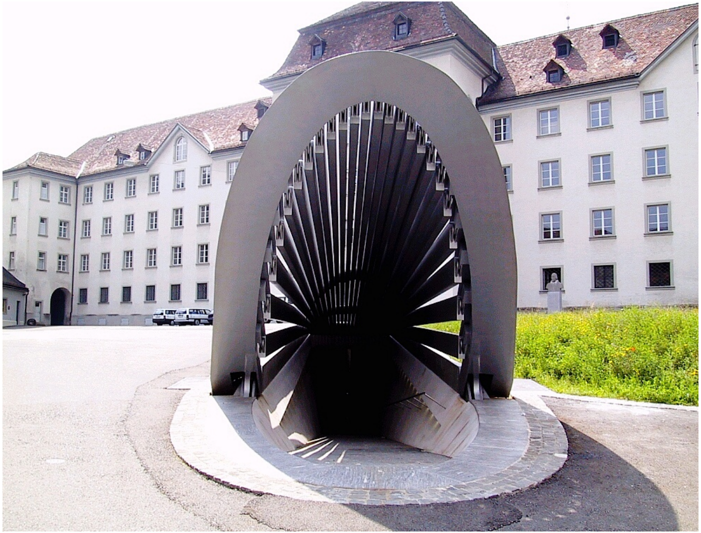
Plenarsaal Bonn 6(6)

- remedial measure 3: guidance of sound reflections by tilted glass areas

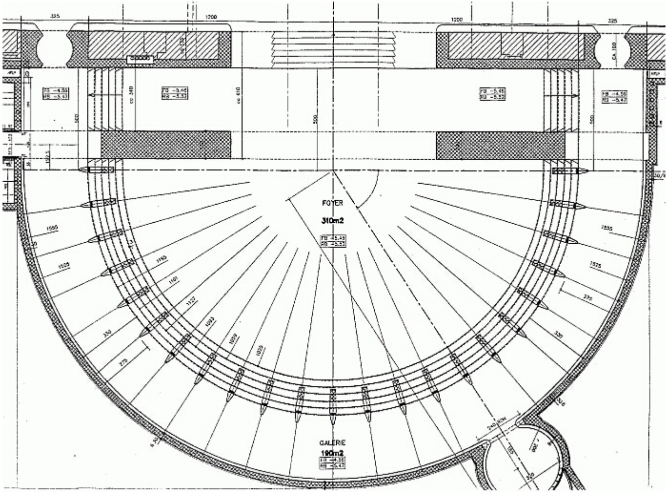


Forum im Pfalzkeller
St. Gallen
1999, Santiago Calatrava

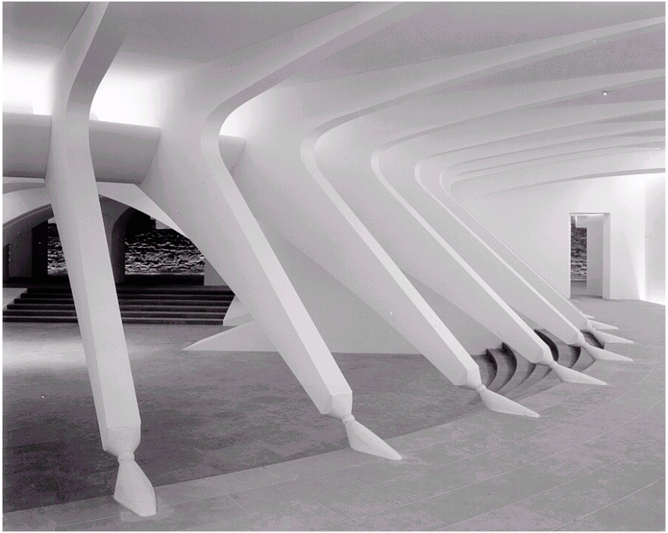
Forum im Pfalzkeller St. Gallen: entrance



Forum im Pfalzkeller St. Gallen: groundplan



Forum im Pfalzkeller St. Gallen: interior view 1

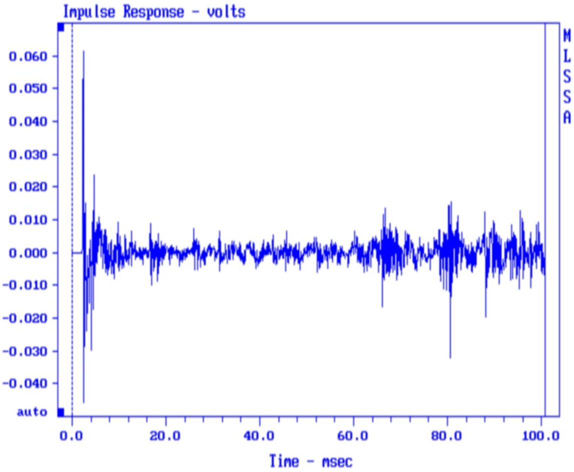


Forum im Pfalzkeller St. Gallen: interior view 2

Forum im Pfalzkeller St. Gallen: interior view 3

Forum im Pfalzkeller St. Gallen: focusing problem

impulse response measurements:



Forum im Pfalzkeller St. Gallen: focusing problems - remedial measures:

- central part of the ceiling was covered with 40 mm absorption
- installation of absorption along the curved rear wall
- installation of furniture with sound absorbing covers

wave theoretical room acoustics

wave theoretical room acoustics

- in rooms with dimensions $\approx$ wavelength of interest:
  - no longer free propagation
  - formation of resonances
  - wave based approach necessary
- strategy: search for the pressure field that fulfills:
  - wave equation
  - boundary conditions

wave theoretical room acoustics

- wave equation (Helmholtz equation):

$$\triangle \check{p} + \frac{\omega^2}{c^2}\check{p} = 0$$

wave theoretical room acoustics

- formulation of the boundary conditions (locally reacting surfaces):

$$\frac{p}{v_n} = Z$$

  - with Newton:

$$\frac{\partial p}{\partial n} = -\rho_0 \frac{\partial v_n}{\partial t}$$

  - follows an impedance relation in pressure only:

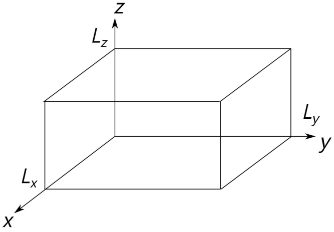
$$\frac{1}{\rho_0}\frac{\partial p}{\partial n} = -\frac{1}{Z}\frac{\partial p}{\partial t}$$

wave theoretical room acoustics

- boundary condition in complex writing for sinusoidal time dependencies:
  - $$\frac{1}{\rho_0}\frac{\partial \check{p}}{\partial n} = -\frac{1}{Z}\check{p}j\omega$$
  - resp.
    $$Z\frac{\partial \check{p}}{\partial n} + j\omega\rho_0\check{p} = 0$$
  - special case: $Z \rightarrow \infty \Rightarrow \frac{\partial \check{p}}{\partial n} = 0$

analytical solution for a rectangular room with rigid boundaries

analytical solution rectangular room



$$\frac{\partial \check{p}}{\partial x} = 0 \qquad \text{for } x = 0, x = L_x$$

$$\frac{\partial \check{p}}{\partial y} = 0 \qquad \text{for } y = 0, y = L_y$$

$$\frac{\partial \check{p}}{\partial z} = 0 \qquad \text{for } z = 0, z = L_z$$

analytical solution rectangular room

- sound field $\check{p}(x, y, z)$ has to fulfill the boundary conditions and the Helmholtz equation
- Helmholtz equation in Cartesian coordinates:

$$\frac{\partial^2 \check{p}}{\partial x^2} + \frac{\partial^2 \check{p}}{\partial y^2} + \frac{\partial^2 \check{p}}{\partial z^2} + k^2 \check{p} = 0$$

analytical solution rectangular room

assumption for sound pressure $\check{p}(x, y, z)$:

$$\check{p}(x, y, z) = C \cos\left(\frac{n_x \pi x}{L_x}\right) \cos\left(\frac{n_y \pi y}{L_y}\right) \cos\left(\frac{n_z \pi z}{L_z}\right)$$

with

n_x, n_y, n_z: positive integers including 0

C: arbitrary constant

- standing wave with nodes and anti-nodes (maxima)

analytical solution rectangular room

$$\check{p}(x, y, z) = C \cos\left(\frac{n_x \pi x}{L_x}\right) \cos\left(\frac{n_y \pi y}{L_y}\right) \cos\left(\frac{n_z \pi z}{L_z}\right)$$

check of fulfillment of boundary conditions (shown for x-coordinate):

$$\frac{\partial \check{p}}{\partial x} = -C \frac{n_x \pi}{L_x} \sin\left(\frac{n_x \pi x}{L_x}\right) \cos\left(\frac{n_y \pi y}{L_y}\right) \cos\left(\frac{n_z \pi z}{L_z}\right)$$

$$\rightarrow \frac{\partial \check{p}}{\partial x} = 0 \text{ at } x = 0, x = L_x \text{ for } n_x \text{ integer}$$

analytical solution rectangular room

check of fulfillment of Helmholtz equation:

→ list of the second order derivatives with respect to space coordinates:

$$\frac{\partial^2 \check{p}}{\partial x^2} = -C\frac{n_x^2\pi^2}{L_x^2}\cos\left(\frac{n_x\pi x}{L_x}\right)\cos\left(\frac{n_y\pi y}{L_y}\right)\cos\left(\frac{n_z\pi z}{L_z}\right)$$

$$\frac{\partial^2 \check{p}}{\partial y^2} = -C\frac{n_y^2\pi^2}{L_y^2}\cos\left(\frac{n_x\pi x}{L_x}\right)\cos\left(\frac{n_y\pi y}{L_y}\right)\cos\left(\frac{n_z\pi z}{L_z}\right)$$

$$\frac{\partial^2 \check{p}}{\partial z^2} = -C\frac{n_z^2\pi^2}{L_z^2}\cos\left(\frac{n_x\pi x}{L_x}\right)\cos\left(\frac{n_y\pi y}{L_y}\right)\cos\left(\frac{n_z\pi z}{L_z}\right)$$

analytical solution rectangular room

→ inserted:

$$\left[-\frac{n_x^2\pi^2}{L_x^2}-\frac{n_y^2\pi^2}{L_y^2}-\frac{n_z^2\pi^2}{L_z^2}\right]\cdot\cos\left(\frac{n_x\pi x}{L_x}\right)\cos\left(\frac{n_y\pi y}{L_y}\right)\cos\left(\frac{n_z\pi z}{L_z}\right)+$$

$$+k^2\cos\left(\frac{n_x\pi x}{L_x}\right)\cos\left(\frac{n_y\pi y}{L_y}\right)\cos\left(\frac{n_z\pi z}{L_z}\right)=0$$

o.k. for

$$k^2=\frac{n_x^2\pi^2}{L_x^2}+\frac{n_y^2\pi^2}{L_y^2}+\frac{n_z^2\pi^2}{L_z^2}$$

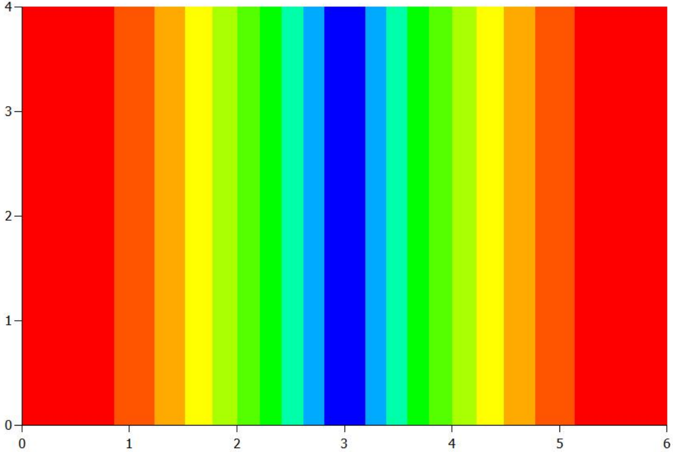
analytical solution rectangular room

- Helmholtz equation in rectangular rooms with rigid boundaries is fulfilled for discrete wave numbers k *only*!
  - each positive (including 0) integer triple n_x, n_y, n_z defines an *eigenvalue* k_{n_x,n_y,n_z}
  - the corresponding sound field $\check{p}(x, y, z)$ is a *mode*
- eigenvalue k can be expressed as frequency f:

$$f = \frac{c}{2}\sqrt{\frac{n_x^2}{L_x^2} + \frac{n_y^2}{L_y^2} + \frac{n_z^2}{L_z^2}}$$

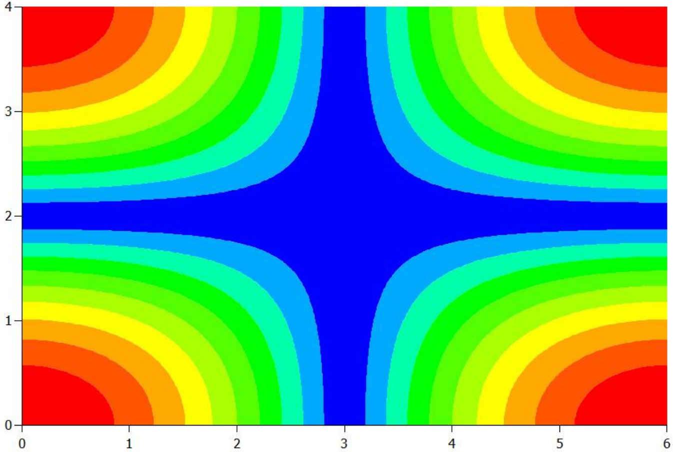
analytical solution rectangular room

exemplary mode $<100>$:



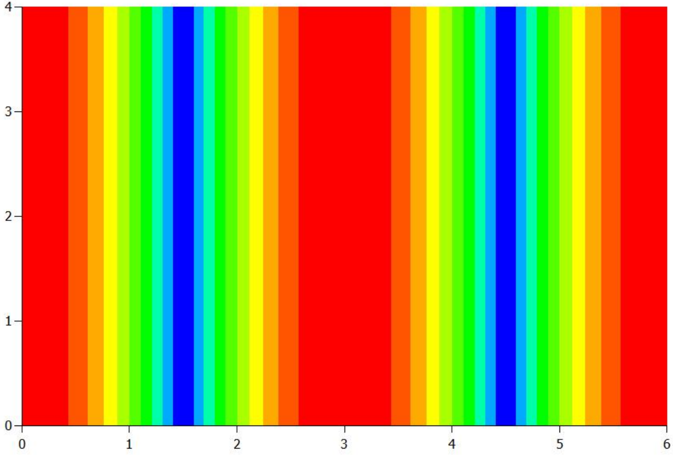
analytical solution rectangular room

exemplary mode $<110>$:



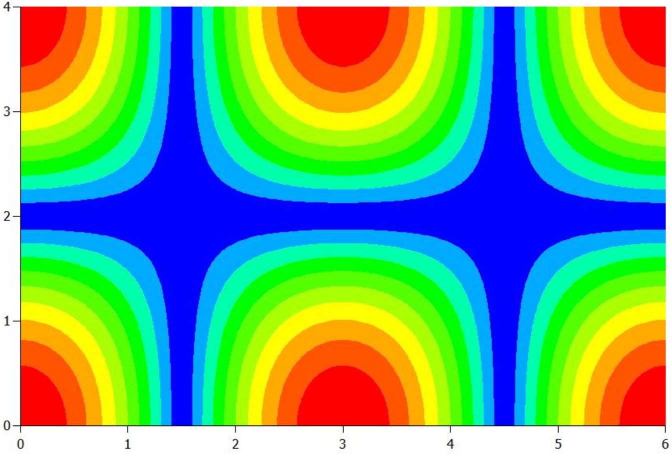
analytical solution rectangular room

exemplary mode <200>:



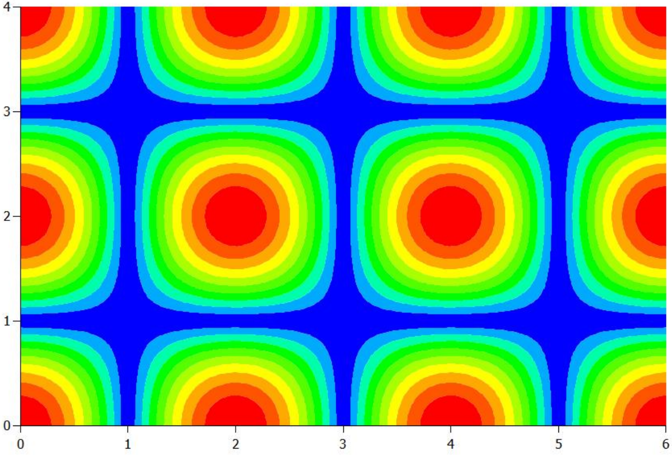
analytical solution rectangular room

exemplary mode <210>:



analytical solution rectangular room

exemplary mode <320>:

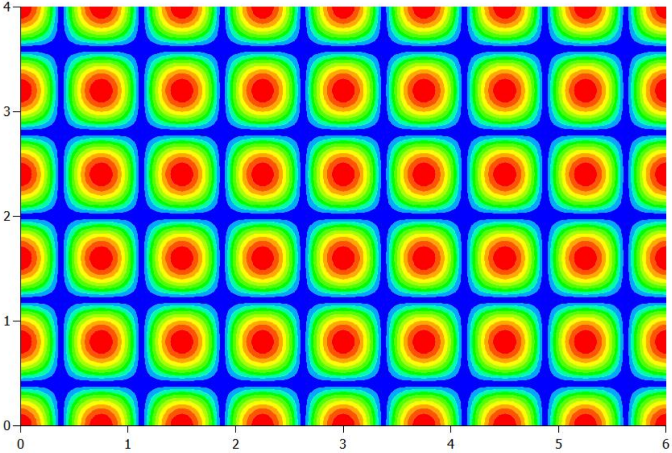


analytical solution rectangular room

mode <850>?

analytical solution rectangular room

exemplary mode <850>:



analytical solution rectangular room

- general findings for the pressure field:
  - all modes: pressure maximum in corners (0-dim)
  - modes with one $n = 0$: pressure maximum at corresponding edges (1-dim)
  - modes with two $n = 0$: pressure maximum at corresponding surfaces (2-dim)
- relevant for the positioning of pressure sensitive absorbers

analytical solution rectangular room

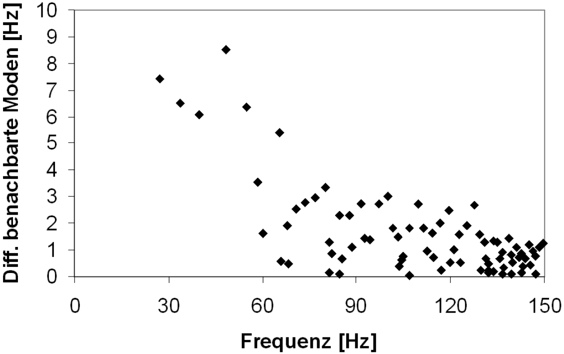
lowest eigenfrequencies for a small studio room of 8.5×6.2×2.6 m (sorted in ascending order):

eigenfrequency [Hz]	n_x	n_y	n_z
20.0	1	0	0
27.4	0	1	0
33.9	1	1	0
40.0	2	0	0
48.5	2	1	0
54.8	0	2	0
58.4	1	2	0
65.4	0	0	1

analytical solution rectangular room

eigenfrequency differences between adjacent modes:

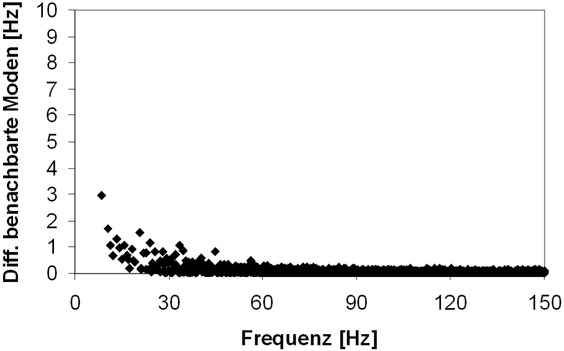
small studio room (8.5m, 6.2m, 2.6m, 137m^3)



analytical solution rectangular room

eigenfrequency differences between adjacent modes:

Tonhalle (29.6m, 19.5m, 14m, 8080m^3)



analytical solution rectangular room

estimate of the number of eigenfrequencies N_f from 0 up to f Hz in a room of volume V:

$$N_f \approx \frac{4\pi}{3} V \left(\frac{f}{c} \right)^3$$

mode density dN_f/df (number of eigenfrequencies per Hz bandwidth):

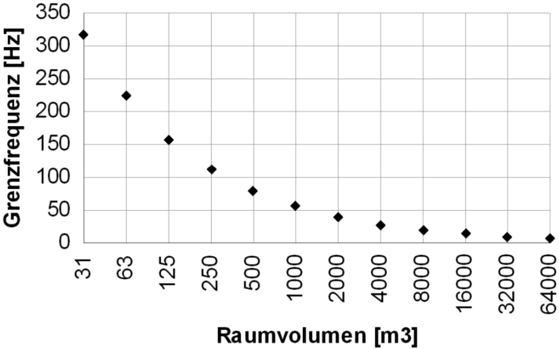
$$\frac{dN_f}{df}(f) \approx 4\pi V \left(\frac{f^2}{c^3} \right)$$

analytical solution rectangular room

- damping in real rooms → finite quality factor of the resonances
  - typical bandwidth: 1 Hz
- consideration of modes is important if they occur as isolated peaks (evaluated at -3dB)
- statistical and geometrical room acoustics applicable if mode peaks overlap
- *"limiting frequency"* = *Schröder frequency* for a mode density $= 1/\mathrm{Hz}$

analytical solution rectangular room

lower limiting frequency for 1 mode per Hz bandwidth:



analytical solution rectangular room

source-receiver transfer function:

- considerations so far: possible sound fields in a room
- open question: can specific modes be excited by a volume source?
- → source-receiver transfer function
  - solution of the wave equation with a source term

analytical solution rectangular room

sound pressure amplitude $\check{p}(E,\omega)$ at receiver E for excitation by volume source at Q:

$$\check{p}(E,\omega) \sim \omega \sum_n \frac{\check{p}_n(E)\check{p}_n(Q)}{(\omega^2 - \omega_n^2)K_n}$$

with
$\sum_n$: sum over all modes
$\check{p}_n(E)$: complex sound pressure amplitude for mode n evaluated at point E
$\check{p}_n(Q)$: complex sound pressure amplitude for mode n evaluated at point Q
ω_n: mode specific eigenfrequency
K_n: mode specific constant

analytical solution rectangular room

$$\check{p}(E,\omega) \sim \omega \sum_n \frac{\check{p}_n(E)\check{p}_n(Q)}{(\omega^2 - \omega_n^2)K_n}$$

- excitation of a mode is possible only if the volume source is located close to a pressure maximum
- excitation of all modes: source position in a corner
- plausibility check:
  - .
  - .

analytical solution rectangular room

$$\check{p}(E,\omega) \sim \omega \sum_n \frac{\check{p}_n(E)\check{p}_n(Q)}{(\omega^2-\omega_n^2)K_n}$$

- excitation of a mode is possible only if the volume source is located close to a mode pressure maximum
- excitation of all modes: position in a corner
- plausibility check:
    - pressure maximum: part. velocity is small $\Rightarrow Z = \frac{p}{v} = Z_{\text{rad}} \rightarrow \infty$
    - pressure minimum: part. velocity is large $\Rightarrow Z = \frac{p}{v} = Z_{\text{rad}} \rightarrow 0$

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room acoustical design of small rooms

room acoustical design of small rooms

- possible problems at *low frequencies*
  - modal density is low, reverberation time is high
    - large pressure variations (in frequency and space)
    - bad transient behavior
  - remedy:
    - damping of low frequencies by installation of resonance absorbers (membrane absorber, Helmholtz absorber, active absorber)

room acoustical design of small rooms

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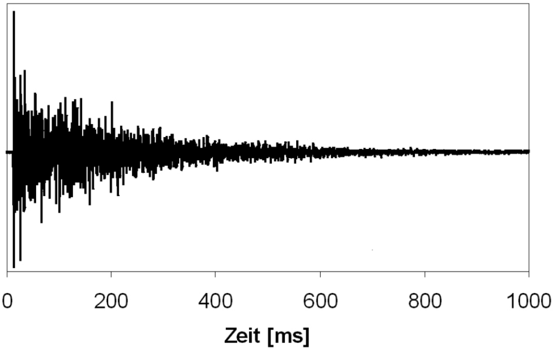
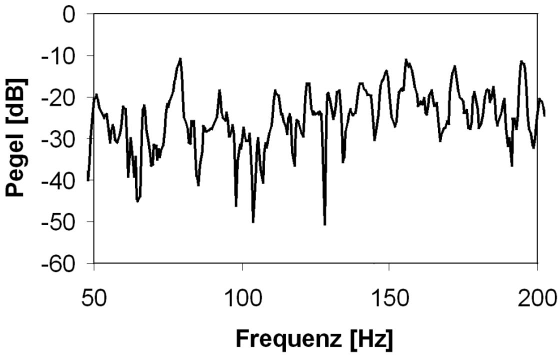
room acoustical design of small rooms

example: listening room in a recording studio before installation of absorbers
→ impulse response from loudspeaker to listener position:



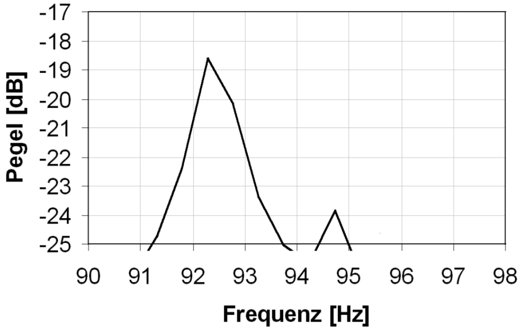
room acoustical design of small rooms

example: listening room in a recording studio before installation of absorbers
→ amplitude response at listener position:



room acoustical design of small rooms

resonance peak width Δf of a mode ↔ reverberation time RT:



$$RT = \frac{2}{\Delta f}$$

Δf: bandwidth at -3 dB points

room acoustical design of small rooms

well conditioned studio room:

$$\Delta f \geq 5\ \text{Hz} \qquad \rightarrow \qquad \text{RT} < 0.4\ \text{s}$$

room acoustical design of small rooms

- possible problems at *mid and high frequencies*
  - too reverberant
    - blurred sound pattern
    - lack of transparency
    - flutter echoes
  - early reflections
    - comb-filter effects, frequency response errors
    - stereo image errors
  - remedy:
    - mid- and high frequency absorption by installation of porous absorbers
    - sound propagation guidance by suitable reflector surfaces
    - diffusely reflecting surfaces

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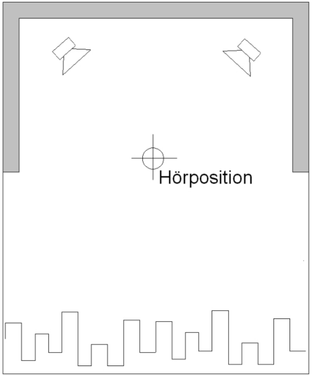
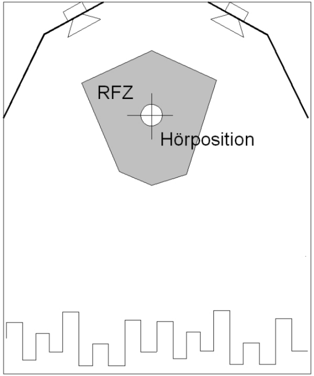
room acoustical design of small rooms

- listening room concept LEDE
  - *L*ive-*E*nd-*D*ead-*E*nd
  - suppression of early reflections by absorption (dead end)



room acoustical design of small rooms

- listening room concept RFZ
  - *R*eflection-*F*ree-*Z*one
  - suppression of early reflections by geometrical means



room acoustical measurements

reverberation time measurements

- reverberation time measurement:
  - global parameter to characterize a room (traditional parameter)
  - averaging over several source and receiver positions
  - measurement procedure:
    - interrupted noise or
    - inverse integration of squared impulse response
  - important: documentation of air humidity and temperature (relevant at high frequencies)
  - evaluation in octave bands
  - decay curve is approximated by straight line (minimal least square deviation)

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impulse response measurement

- impulse response measurement
  - *complete* description of the propagation between source and receiver
  - contains more information → evaluation of additional quantities such as EDT, $C80$, DEU, G, TS, ..., identification of echoes
  - measurement procedures:
    - excitation by impulses (pistols, balloons, ...)
    - excitation by loudspeaker and correlation evaluation (MLS, sinus sweep, ...)
  - sensitive with respect to source directivity

impulse response measurement

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    - excitation by loudspeaker and correlation evaluation (MLS, sinus sweep, ...)
  - sensitive with respect to source directivity

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- general:
  - hints regarding the presence of audience
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  - microphone:
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- measurement geometry of microphone:
  - several positions have to be used (representative for the specific conditions)
  - minimum distance between two positions: 2 m
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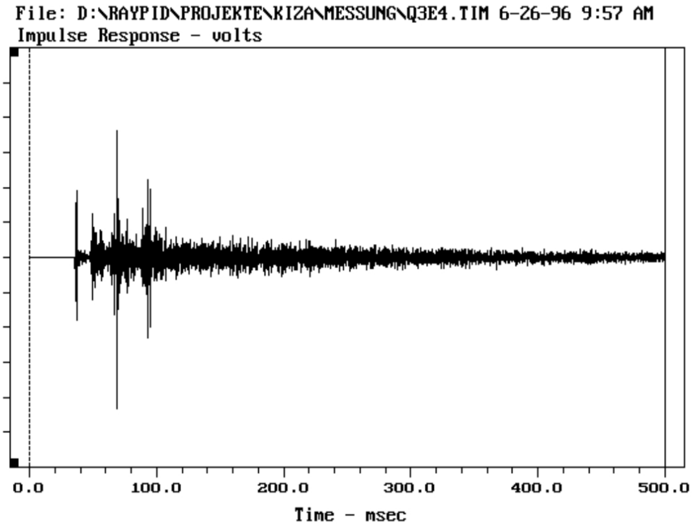
dodecahedron loudspeaker for omnidirectional radiation

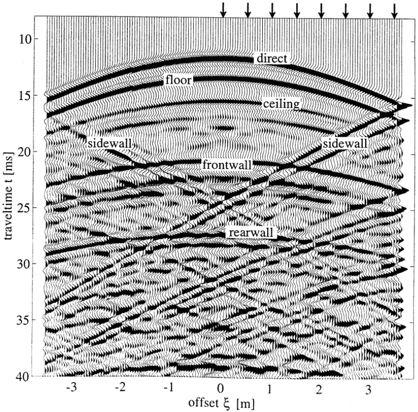
"vase"- type loudspeaker for omnidirectional radiation

example of a measured impulse response



impulse response measurements with linear microphone array

- vertical display of impulse responses
- wave fronts allow for an estimate of propagation direction



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