Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Acoustics I: absorption-reflection-transmission

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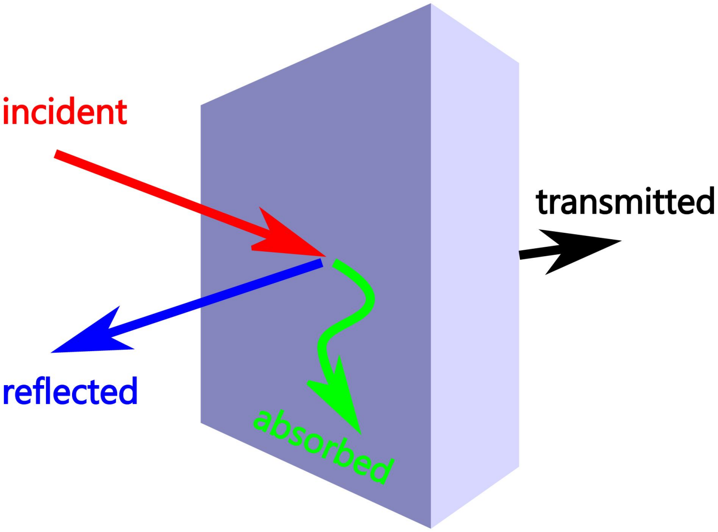
2022-12-12

introduction

introduction



absorption

characterization of absorption and reflection

characterization of absorption and reflection

- absorption property $\rightarrow$ absorption coefficient (real, $0 < \alpha < 1$)

$$\alpha = \frac{\text{absorbed energy}}{\text{incident energy}}$$

characterization of absorption and reflection

- reflection property $\rightarrow$ reflection factor (complex, $0 < |R| < 1$)

$$R = \frac{\text{sound pressure reflected wave}}{\text{sound pressure incident wave}}$$

characterization of absorption and reflection

- relation between α and R

$$\alpha = 1 - |R|^2$$

absorber types

porous absorbers

porous absorbers

- materials:
  - glass fibers
  - organic fibers (e.g. wood)
  - open foams
- absorption mechanism:
  - sound particle velocity corresponds to oscillating air in the pores
  - $\rightarrow$ friction losses
- optimal placement:
  - at location where sound particle velocity is high

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resonance absorber: type Helmholtz

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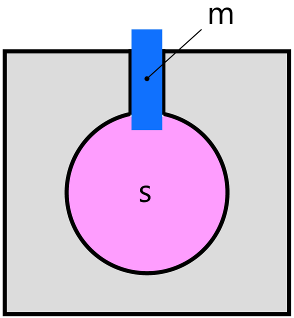
- configuration:
  - damped spring-mass system
    - spring = enclosed air volume
    - mass = oscillating air column
    - damping = lossy element
- absorption mechanism:
  - maximal absorption due to high velocity friction losses at resonance

resonance frequency f_{res} for stiffness s and mass m:

$$f_{\mathrm{res}} = \frac{\sqrt{\frac{s}{m}}}{2\pi}$$

resonance absorber: type Helmholtz



- mass $m = ?$
- stiffness of the spring $s = ?$

resonance absorber: type Helmholtz

mass m:

- mass of the oscillating air column:
  - mass of cylinder of length l + end correction l_{corr}
  - $l_{corr} \approx 0.8R$ (radius of cylinder)
  - with S: cross sectional area of cylinder follows:

$$m = \rho_0(l + l_{corr})S$$

resonance absorber: type Helmholtz

stiffness s of the spring:

- piston acting on air volume
- virtual experiment
  - air cavity of volume V
  - piston of area S
  - external force F makes piston to sink in by Δl

resonance absorber: type Helmholtz

force F leads to a pressure change ΔP with

$$\Delta P = \frac{F}{S}$$

penetration depth Δl corresponds to ΔV with

$$\Delta V = -\Delta l \cdot S$$

resonance absorber: type Helmholtz

adiabatic state change (linearized):

$$\frac{\Delta P}{P_0} = -\kappa \frac{\Delta V}{V}$$

inserted:

$$\frac{F}{\Delta l} = \kappa \frac{P_0 S^2}{V}$$

with

$$c = \sqrt{\kappa \frac{P_0}{\rho_0}}$$

follows

$$\frac{F}{\Delta l} = s = c^2 \rho_0 \frac{S^2}{V}$$

resonance absorber: type Helmholtz

resonance frequency:

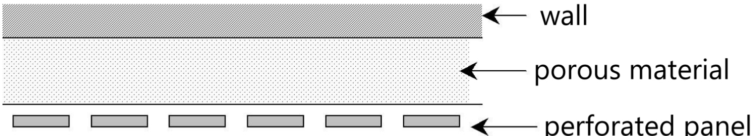
$$f_{res} = \frac{c}{2\pi}\sqrt{\frac{S}{V(l + l_{corr})}}$$

- for practical applications: installation of porous damping in the resonator neck (max. velocity)
  - energy loss
  - lowering of the resonator quality factor
  - extension of absorbing effect over a wider frequency range

resonance absorber: panels with holes or slits (Helmholtz)

panel with holes

- perforated panel in front of an air cavity (with damping material)

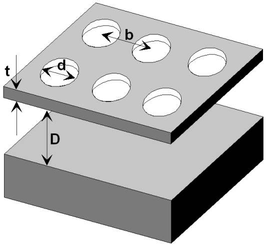


- spring-mass resonator with:
  - spring: air cavity
  - mass: mass of the oscillating air columns in the holes (end correction!)
  - damping: porous absorber in the cavity

resonance absorber: micro-perforated absorber (Helmholtz)

micro-perforated absorber

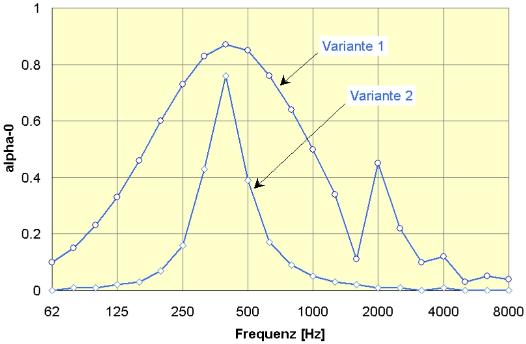
- panel with very small holes in front of an air cavity



- spring-mass resonator where:
  - spring: air cavity
  - mass: mass of the oscillating air columns (end correction!)
  - damping: friction losses in the tiny holes
- analytical description available

micro-perforated absorber

	variant 1	variant 2
plate thickness	3 mm	3 mm
holes diameter	0.4 mm	2 mm
holes spacing	2 mm	15 mm
distance to wall	100 mm	50 mm



micro-perforated absorber

- transparent solutions are possible!

resonance absorber: membrane absorber

resonance absorber: membrane absorber

- configuration:
  - damped spring-mass system
    - spring = enclosed air
    - mass = vibrating plate or membrane
    - damping = porous material and plate
- absorption mechanism:
  - maximal absorption at resonance due to losses in the plate and in air

resonance frequency f_{res} for stiffness s'' per unit area and mass m'' per unit area:

$$f_{res} = \frac{\sqrt{\frac{s''}{m''}}}{2\pi}$$

resonance absorber: membrane absorber

stiffness s'' of air cavity per unit area:

$$s'' = \frac{\rho_0 c^2}{l_w}$$

with

l_w: distance to wall (thickness of air cavity)

and consequently:

$$f_{\text{res}} = \frac{c\sqrt{\frac{\rho_0}{m'' l_w}}}{2\pi}$$

resonance absorber: membrane absorber

- field of application: low frequency absorbtion
- design rules:
  - plate area > 0.4 m^2
  - plate dimensions > 0.5 m
  - air cavity has to be filled with porous material
- typical absorption $\alpha \approx 0.6$ over 1...2 octaves
- sandwich combinations with porous absorber possible
- optimal placement:
  - where sound pressure is maximal

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resonance absorber: membrane absorber

measurement methods

measurement of absorption

- methods:
  - Kundt's tube
  - Impedance tube
  - Reverberation chamber
  - Impulse response in situ

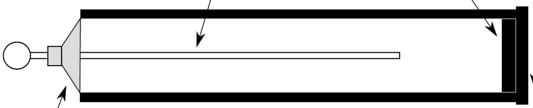
measurement of absorption

properties of the methods

	sound field	incidence	phase	frequency
Kundt's tube	plane	normal	(no)	discrete
Impedance tube	plane	normal	yes	spectrum
Reverberation chamber	diffuse	diffuse	no	third octaves
Impulse response	spherical	arbitrary	yes	spectrum

Kundt's tube

Kundt's tube



- tube diameter $\ll \lambda$ (typ. 10 cm or 2 cm)
- incident and reflected sinusoidal plane wave form an interference pattern (standing wave)
- based on ratio $\frac{p_{max}}{p_{min}}$, absorption coefficient α can be calculated

Kundt's tube

p_e: sound pressure amplitude of incident wave
p_r: sound pressure amplitude of reflected wave

$$\frac{p_r}{p_e} = \sqrt{1-\alpha}$$

sound pressure maxima: constructive interference:

$$p_{\max} = p_e + p_r = p_e(1+\sqrt{1-\alpha})$$

sound pressure minima: destructive interference:

$$p_{\min} = p_e - p_r = p_e(1-\sqrt{1-\alpha})$$

Kundt's tube

from:

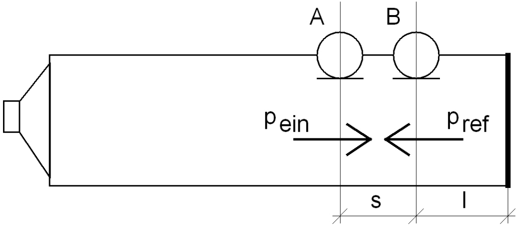
$$n = \frac{p_{\mathrm{max}}}{p_{\mathrm{min}}}$$

follows for the absorption coefficient:

$$\alpha = 1 - \left(\frac{n-1}{n+1} \right)^2$$

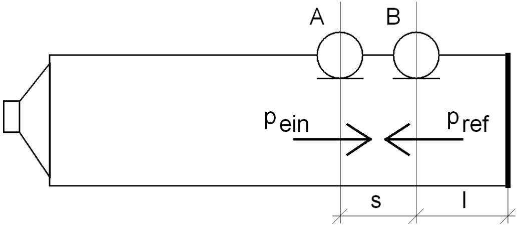
impedance tube

impedance tube



- tube diameter $\ll \lambda$ (typ. 10 cm resp. 2 cm)
- measurement of the transfer function between two fixed microphone positions

impedance tube



with the arbitrary reference $p_{\text{ein}}(A) = 1$ follows

$$H(f) = \frac{p(B)}{p(A)} = \frac{\mathrm{e}^{-\mathrm{j}ks} + R(f) \cdot \mathrm{e}^{-\mathrm{j}k(s+2l)}}{1 + R(f) \cdot \mathrm{e}^{-\mathrm{j}2k(s+l)}}$$

impedance tube

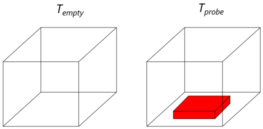
solved for R:

$$R(f) = \frac{\mathrm{e}^{-\mathrm{j}ks} - H(f)}{H(f) - \mathrm{e}^{\mathrm{j}ks}} \mathrm{e}^{\mathrm{j}2k(l+s)}$$

- from R follows α and impedance Z
- measurement details:
  - broadband excitation (white noise, frequency discrimination with help of FFT)
  - high quality microphones necessary, calibration with swapped microphones

reverberation chamber

reverberation chamber



- measurement of the reverberation time T without and with probe material (10. . .12 m^2)
- by usage of empirical relation between α and T, α can be determined
- reverberation time formula derived by Sabine (diffuse field assumption!):

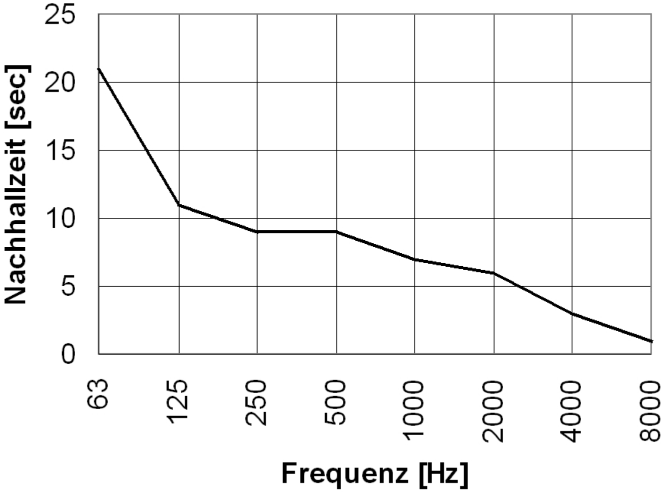
$$T = \frac{0.16V}{\sum(\alpha_i \cdot S_i)}$$

reverberation chamber

- high accuracy for large differences *with* and *without* material probe
  - $\rightarrow$ test chamber with minimal absorption (reverberation chamber)
- result: α_S in third octaves or octaves
- investigation in diffuse sound field corresponds to averaging over all incidence directions
- $\alpha_S > 1$ is possible!
  - sound field with concentrated absorber violates diffuse field assumption
  - edge effects (diffraction along the border of the probe)

reverberation chamber at Empa

reverberation chamber Empa: Tempty



in situ impulse response measurement

in situ impulse response measurement

- in situ determination of absorption coefficients for:
  - already installed surfaces (e.g. room acoustical analysis of existing objects)
  - elements that can't be brought to the laboratory
  - investigation for specific angles of incident

in situ impulse response measurement

example: transparent noise barrier

in situ impulse response measurement

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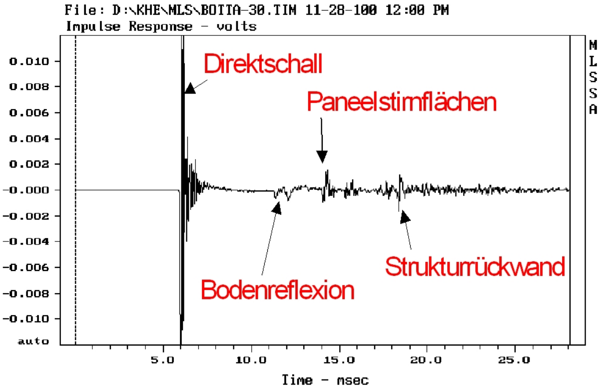


in situ impulse response measurement

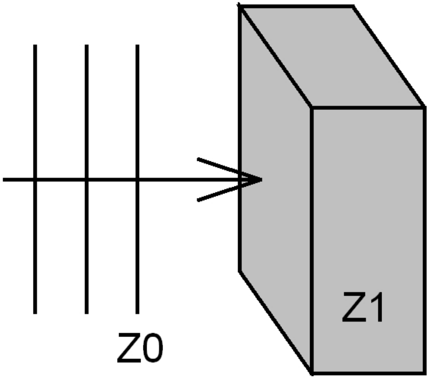
- points to consider:
  - size of the element under test has to be sufficiently large (critical at low frequencies → check with Fresnel zone)
  - measurement geometry should allow for a separation of different contributions (critical at low frequencies)
  - reflection contributions have to be compensated for additional geometrical divergence
  - increased measurement uncertainty for non-flat surfaces (normalisation!)

relation between absorption and impedance

normal incidence

absorption and impedance: normal incidence

situation: plane wave in medium with impedance Z_0 is incident on a medium with surface impedance Z_1



absorption and impedance: normal incidence

incident wave: p_{I}, v_{I} where

$$\frac{p_{\mathrm{I}}}{v_{\mathrm{I}}} = Z_0$$

reflected wave: p_{II}, v_{II} where

$$\frac{p_{\mathrm{II}}}{v_{\mathrm{II}}} = Z_0$$

superposition at the surface:

$$p = p_{\mathrm{I}} + p_{\mathrm{II}}$$
$$v = v_{\mathrm{I}} - v_{\mathrm{II}}$$

with:

$$\frac{p}{v} = Z_1$$

absorption and impedance: normal incidence

from

$$p_{\mathrm{I}} + p_{\mathrm{II}} = Z_1 \left(\frac{p_{\mathrm{I}}}{Z_0} - \frac{p_{\mathrm{II}}}{Z_0} \right)$$

follows:

$$\frac{p_{\mathrm{II}}}{p_{\mathrm{I}}} = R = \frac{Z_1 - Z_0}{Z_1 + Z_0}$$

- if $Z_1 = Z_0 \rightarrow R = 0,\ \alpha = 1$
- if $Z_1 \gg Z_0 \rightarrow R \rightarrow 1,\ \alpha \rightarrow 0$

absorption and impedance: normal incidence

- porous absorber in front of a rigid wall:
  - hard termination increases resulting impedance $\rightarrow$ reduction of the absorption
  - required thickness of the absorber $> \lambda/4$
  - thin layers should be mounted with distance to the rigid surface

oblique incidence

absorption and impedance: oblique incidence

- locally reacting absorber
  - dominating propagation component perpendicular to the surface (often reasonable assumption due to refraction)
  - impedance is independent of the incident angle
- laterally reacting absorber
  - relevant sound propagation component parallel to the surface

absorption and impedance: oblique incidence

- plane wave reflection for locally reacting absorber:

$$\frac{p_{II}}{p_{I}} = R = \frac{Z_1 - \frac{Z_0}{\cos(\phi)}}{Z_1 + \frac{Z_0}{\cos(\phi)}}$$

with

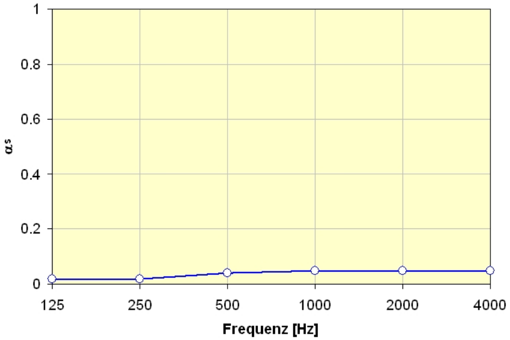
ϕ: angle of sound incidence direction relative to the surface normal direction

- $R = 0$?
- $R \to -1$?

typical absorption coefficients

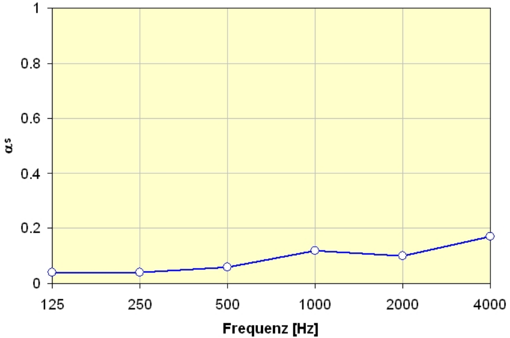
typical absorption coefficients

- stone floor



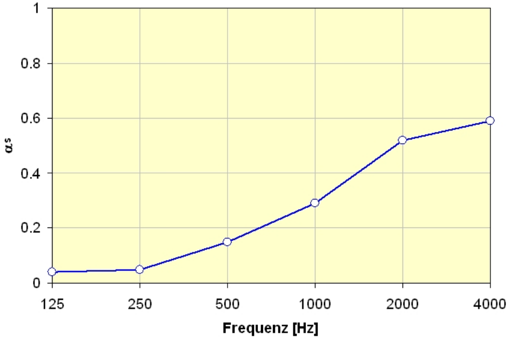
typical absorption coefficients

- parquet floor



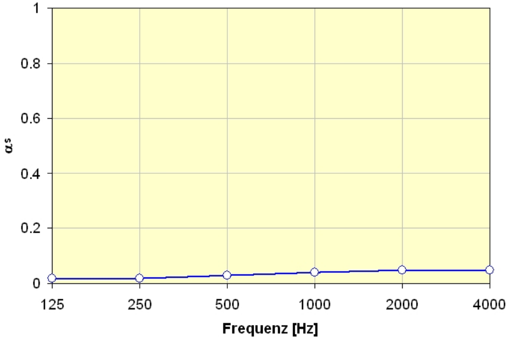
typical absorption coefficients

- carpet, thickness 5 mm



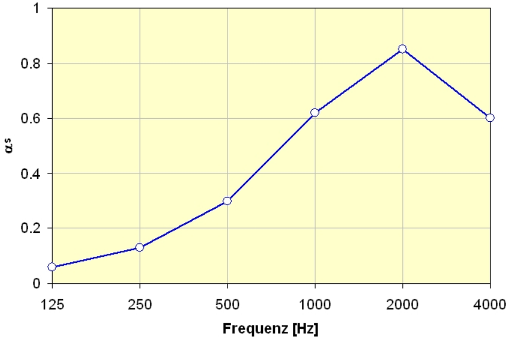
typical absorption coefficients

- standard plaster



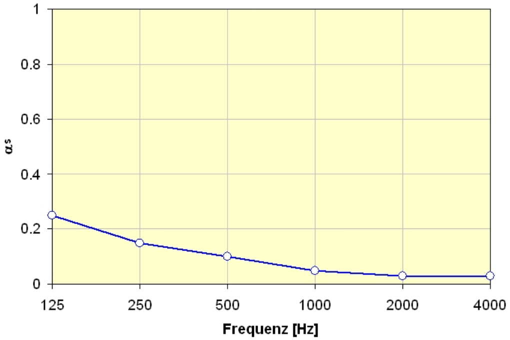
typical absorption coefficients

- acoustically optimized plaster, thickness 20 mm



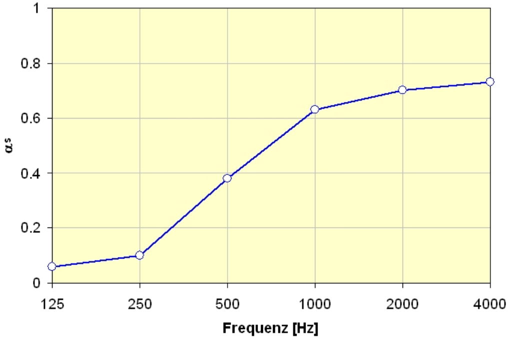
typical absorption coefficients

- window



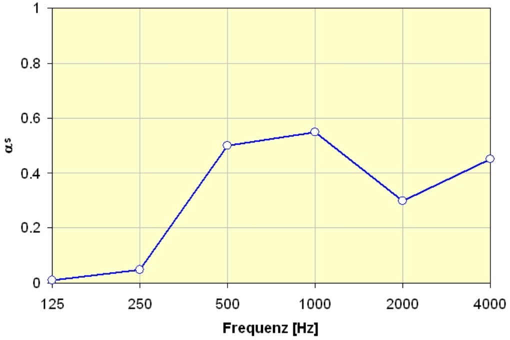
typical absorption coefficients

- heavy curtain



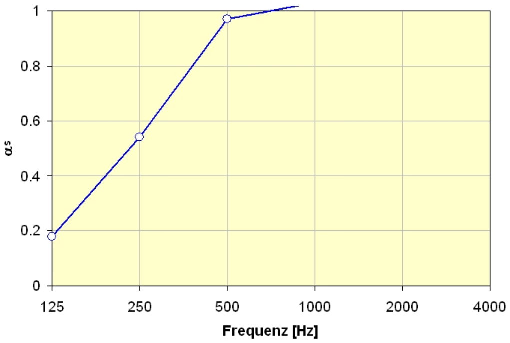
typical absorption coefficients

- egg carton



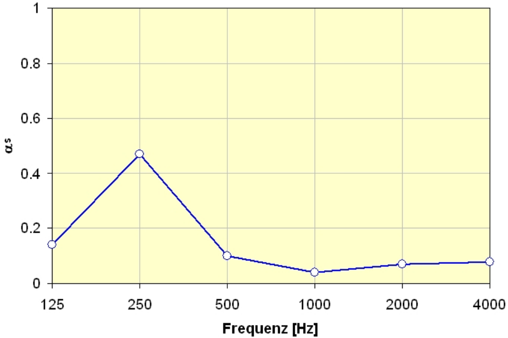
typical absorption coefficients

- glass fiber panel, thickness 50 mm



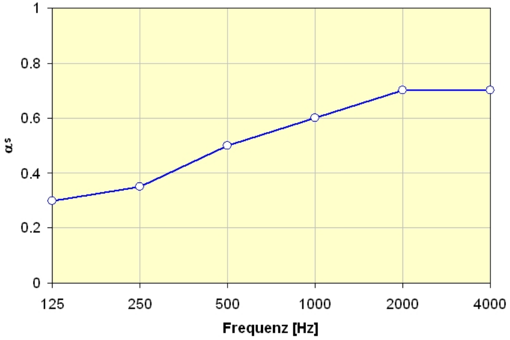
typical absorption coefficients

- panel resonator, 4 mm wood, 120 mm air layer



typical absorption coefficients

- audience on upholstered chairs



covers for porous absorbers

covers for porous absorbers

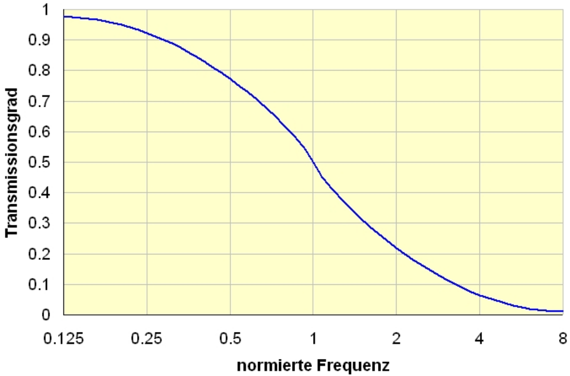
- porous absorbers are usually covered for mechanical protection
  - plates with holes or slits
  - requirement: no significant influence on absorption $\rightarrow$ no relevant transmission loss

covers for porous absorbers

- reason for transmission loss?

covers for porous absorbers

frequency response of transmission of a plate with holes:



covers for porous absorbers

- parameters of the cover:
  - ϵ: ratio of the area of the holes relative to the area of the panel in %
  - hole diameter r [mm]
  - panel thickness l [mm]
  - end correction $2 \cdot \Delta l$ [mm]
  - effective panel thickness $l^* = l + 2 \cdot \Delta l$ [mm]
- empirical formula to estimate the frequency $f_{0.5}$ for 50% transmission:

$$f_{0.5} \approx 1500 \frac{\epsilon}{l^*}$$

covers for porous absorbers

- design of covers:
  - $f_{0.5}$ typically chosen "sufficiently high"
  - $f_{0.5}$ at specific frequency for *mid frequency absorber*

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