02 Sound absorption

ELEC-E5640 - Noise Control D

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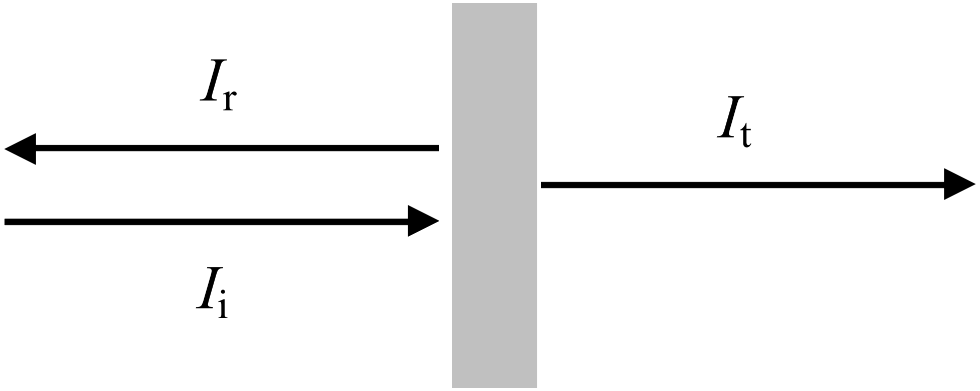
Sound absorption

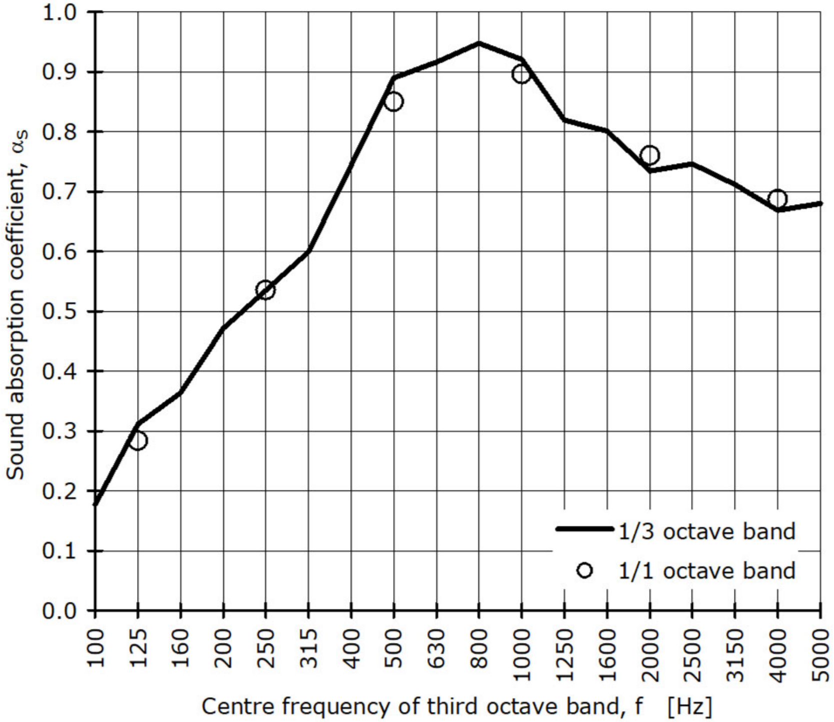
- Absorption coefficient

$$\alpha = \frac{I_i - I_r}{I_i}$$

- Reduction of sound intensity level, D [dB], due to the sound-absorbing material, $D=L_{\mathrm{Ii}} - L_{\mathrm{Ir}}$ [dB], is

$$D = -10\log_{10}(1-\alpha)$$

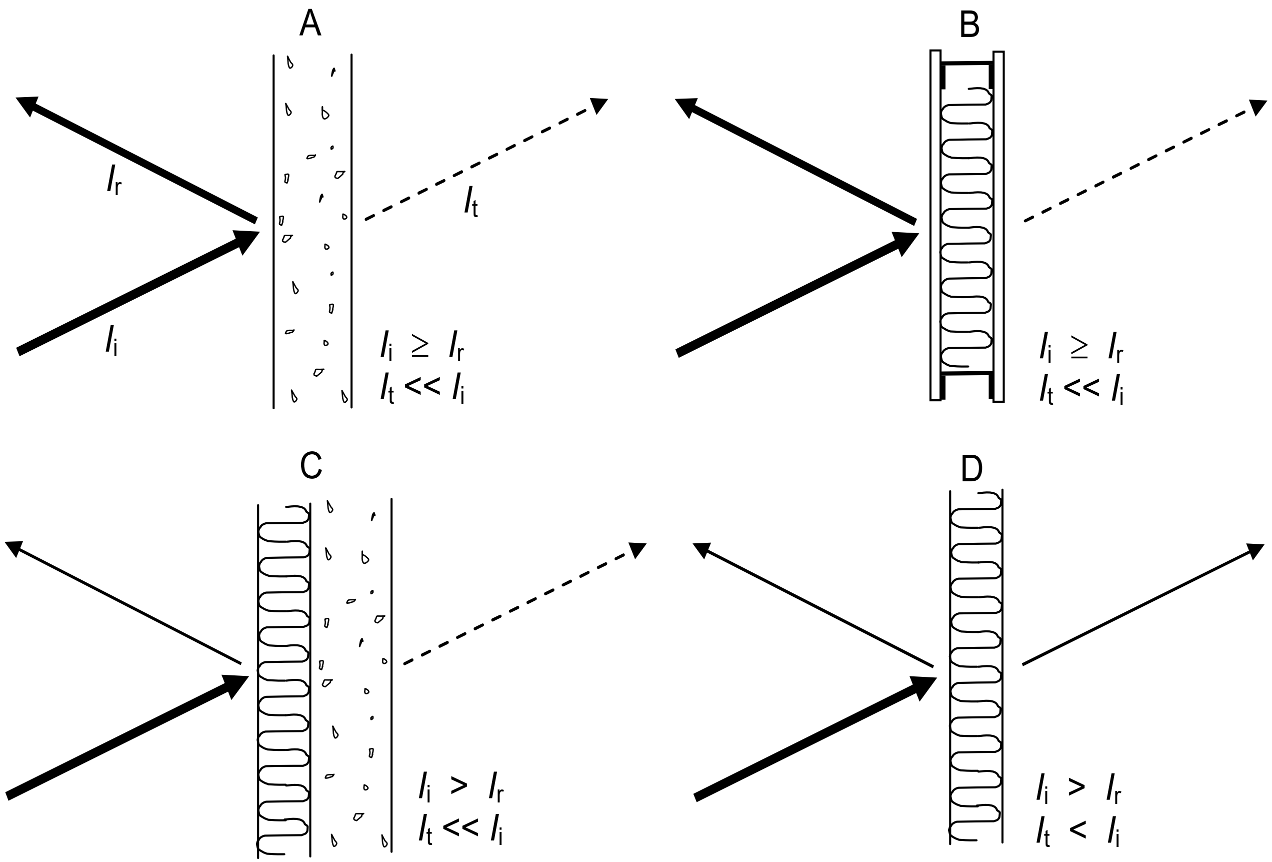




Absorption vs. transmission

A Heavy construction
B Lightweight doublewall construction
C Construction and absorbing material
D Absorbing material alone

- **Good sound insulation:** massive and airtight layers provide large impedance and strong reflection. Energy is not lost but reflected back.
- **Good sound absorption:** porous layers with viscose losses provide low impedance and easy access for the waves to get in but the waves will be dampened and transformed to heat due to friction in the microscopic pores of the material.



Measurement of sound absorption
Impedance method ISO 10534-2

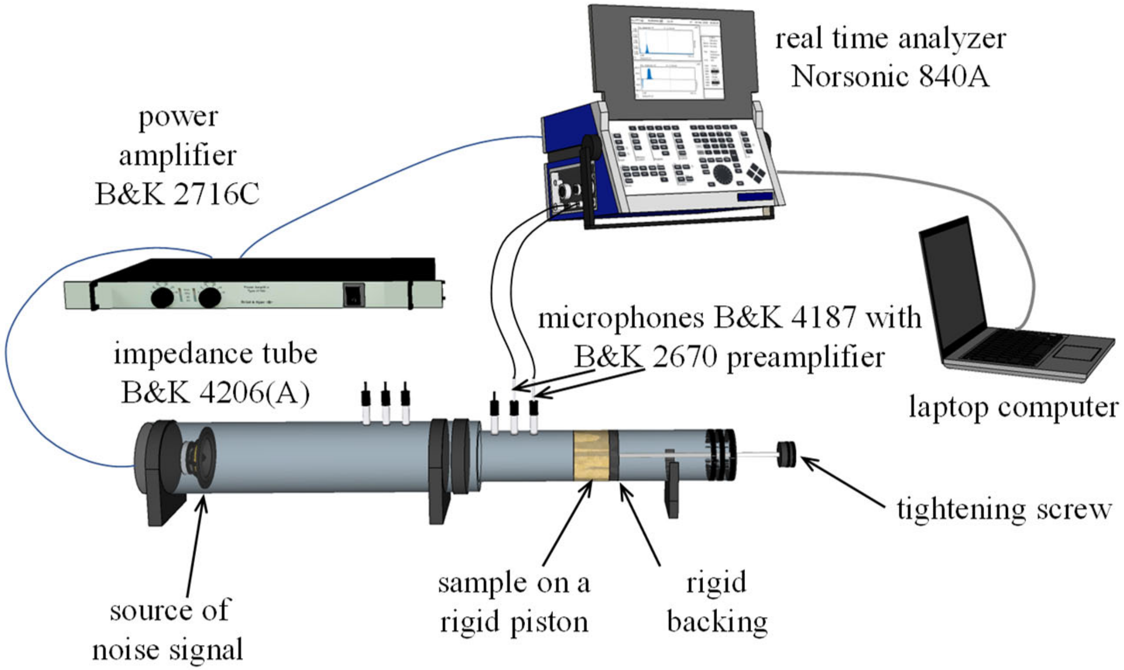
$$\alpha_0(k_0) = 1 - \left| \frac{H_{12}(k_0) - e^{-jk_0 s}}{e^{jk_0 s} - H_{12}(k_0)} \cdot e^{2jk_0 x_1} \right|^2$$

$$H_{12}(k_0) = \frac{p_2(k_0)}{p_1(k_0)}$$

- Fast method for research and development
- Limitation: normal sound incidence. The values are lower than with reverberation room method

- k_0 (1/m) is wavenumber in air, $k_0 = k_0' - jk_0''$, $k_0' = 2\pi f / c_0$
- f [Hz] is frequency
- c_0 [m/s] is speed of sound
- s [m] is distance of microphones
- x_1 [m] is distance between specimen and mic 1
- $p_i(k_0)$ is the FFT spectrum at microphone i

- Loudspeaker produces a plane wave inside the tube when diameter > wavelength
- Specimen either directly against rigid backing or separated from it with air cavity
- Diameters of the tube:
  - 80-800 Hz: 100 mm,
  - 125-2500 Hz: 63.5 mm;
  - 500-8000 Hz: 29 mm
- Water cutting is used to prepare accurately fitting specimen



Characteristic wave number and impedance

- The ratio of pressure p and particle velocity u is denoted by Z_x when one-dimensional sound propagation along x-axis is considered.

$$Z_x = \frac{p(x,t)}{u_x(x,t)}$$

- Porous materials are characterized by two **characteristic** variables:
  - Characteristic wave number $\boldsymbol{\Gamma}_{\mathbf{a}}$ [1/m], also known as propagation constant
  - Characteristic complex impedance $\boldsymbol{Z}_{\mathbf{a}}$ [Pa·s/m]:
- These values are independent on thickness (normalized to 1 m thickness)

$$\mathbf{\Gamma}_a = \Gamma_a' + j\Gamma_a''$$

$$\mathbf{Z}_a = Z_a' + jZ_a''$$

Characteristic wave number $\mathit{\Gamma}_{\mathrm{a}}$

- Complex wavenumber appears in the one-dimensional harmonic plane wave in the following way.

- Wavenumber can be determined by measuring the amplitude as a function of distance:
  - $\mathit{\Gamma}'$: attenuation
  - $\mathit{\Gamma}''$: phase
  - unit [1/m]
- Wavenumber is usually not measured since it has to be done inside the material

$$\mathbf{\Gamma}_a = \Gamma'_a + j\Gamma''_a$$

$$p(x,t) = \hat{p}e^{-\mathbf{\Gamma}_a x} e^{j\omega t}$$

$$= \hat{p}e^{-\mathit{\Gamma}'_a x} e^{-j\mathit{\Gamma}''_a x} e^{j\omega t}$$

loss term
decay with distance

vibration term
no attenuation

$$e^{i\theta} = \cos\theta + i\sin\theta$$

Wave number and impedance in air

- The losses in the media are described by
  - the real part of $\boldsymbol{\Gamma}_{\mathbf{a}}$;
  - the imaginary part of $\boldsymbol{Z}_{\mathbf{a}}$
- The losses are negligible in air and the wave number in air, $\boldsymbol{\Gamma}_{\mathbf{0}}$, is imaginary but frequency-dependent

$$p(x,t) = \hat{p}e^{j(\omega t - k_0 x)}$$

$$\boldsymbol{\Gamma} = \Gamma' + j\Gamma'' \cong jk_0$$

- The characteristic impedance of air is constantly $Z_0 = \rho_0 c_0 = 413$ kg/sm^2
  - ρ_0 [kg/m^3] is the density of air, 1.2041 kg/m^3 at 20 °C
  - c_0 [m/s] is the speed of sound in air, 343 m/s

$$k_0 = \frac{2\pi}{\lambda} = \frac{\omega}{c_0} = \frac{2\pi f}{c_0}$$

$$c_0 = 331 + 0.6 \cdot T$$

Specific flow resistivity

- Specific flow resistivity is used to predict the characteristic impedance of porous materials.
- Flow resistance *R* [Pa·s/m³]

$$R = \frac{\Delta p}{q_v}$$

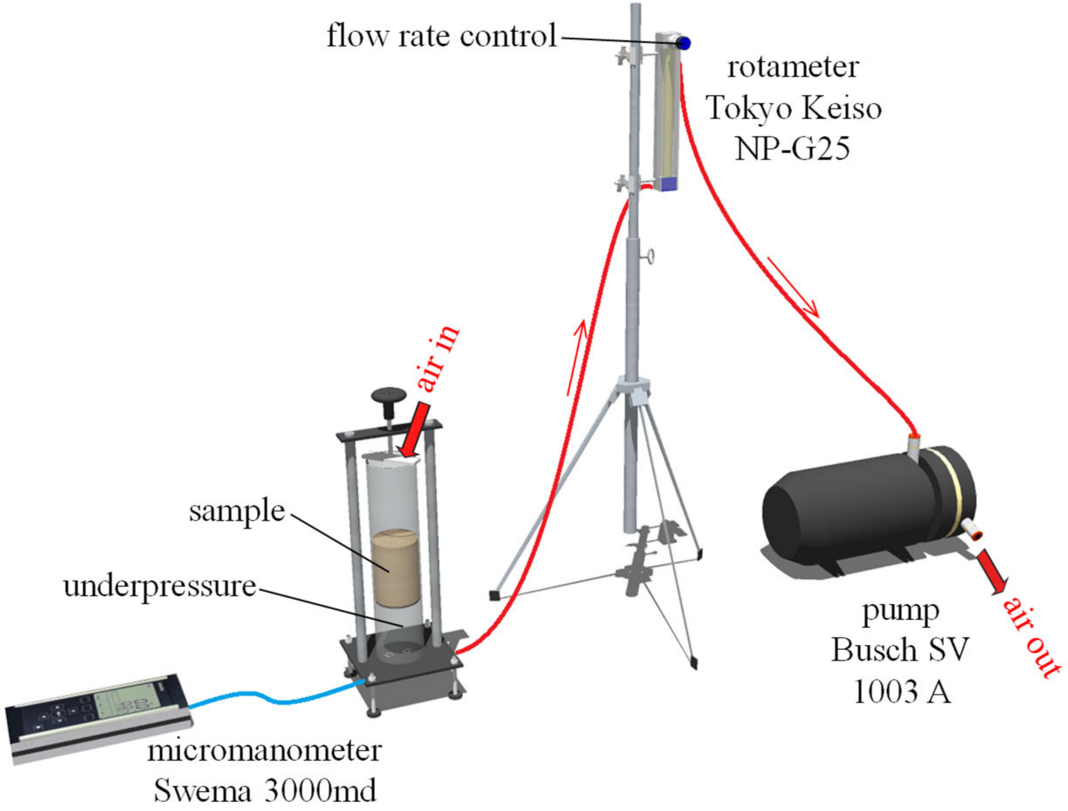
  - pressure difference over the specimen Δp [Pa]
  - flow rate through the specimen q_v [m³/s].
- Specific flow resistance R_s [Pa·s/m]

$$R_s = RA$$

  - *A* [m²] is the specimen area
- **Specific flow resistivity** ***r***, [Pa·s/m², Rayl/m] is the specific flow resistance per one cubic meter of specimen:

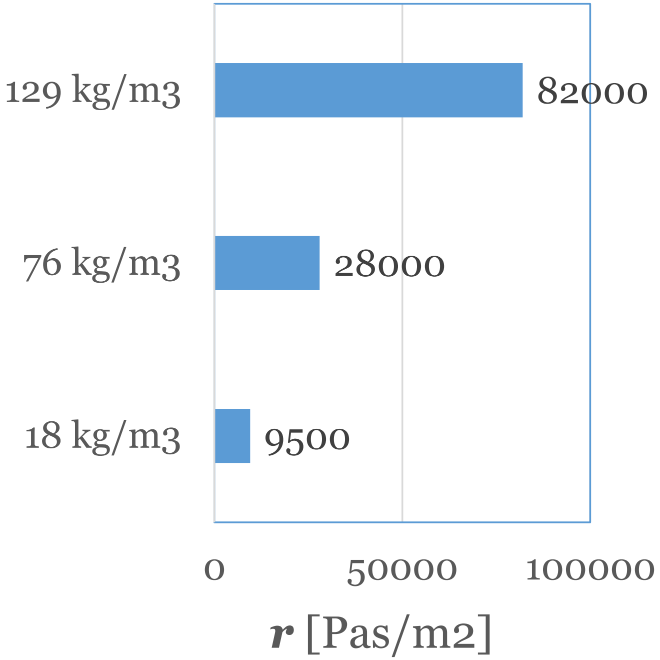
$$r = \frac{R_s}{d}$$

  - *d* [m] is the specimen thickness



Pump – flow meter – pressure meter – specimen.
Specimen is inside vertical metal tube.

Effect of wool density and speficic flow resistivity on α_0



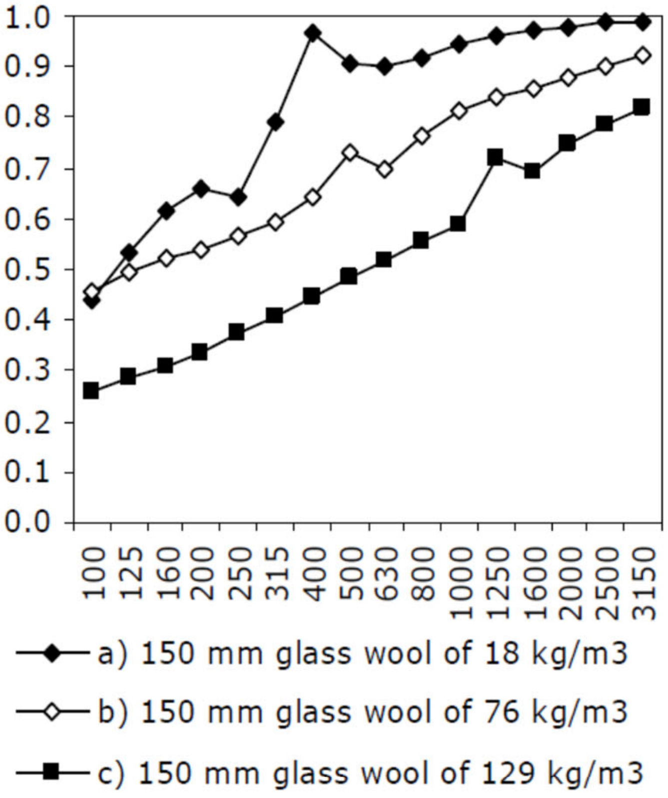


Figure 3.1.2.3 The influence of the glass wool density. Thickness 150 mm, Materials 1, 2 and 3.

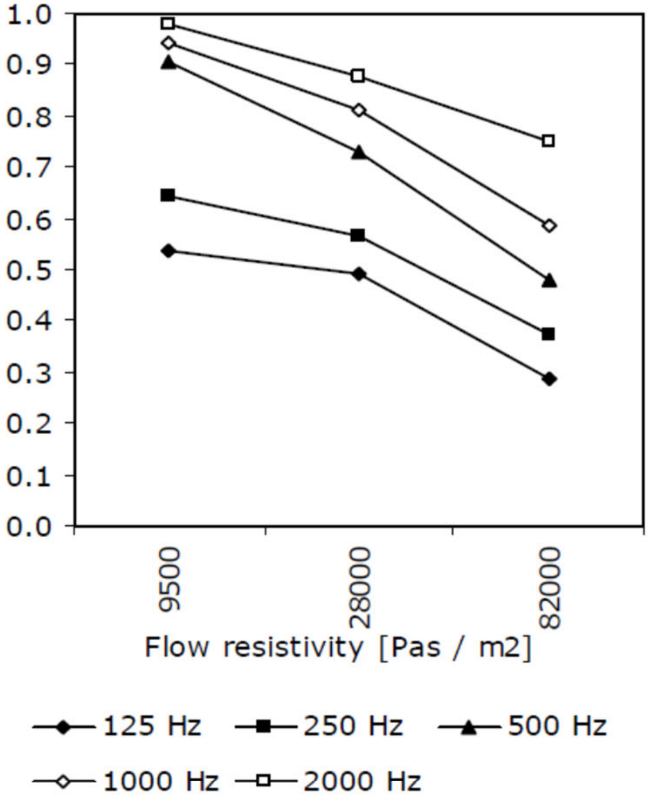
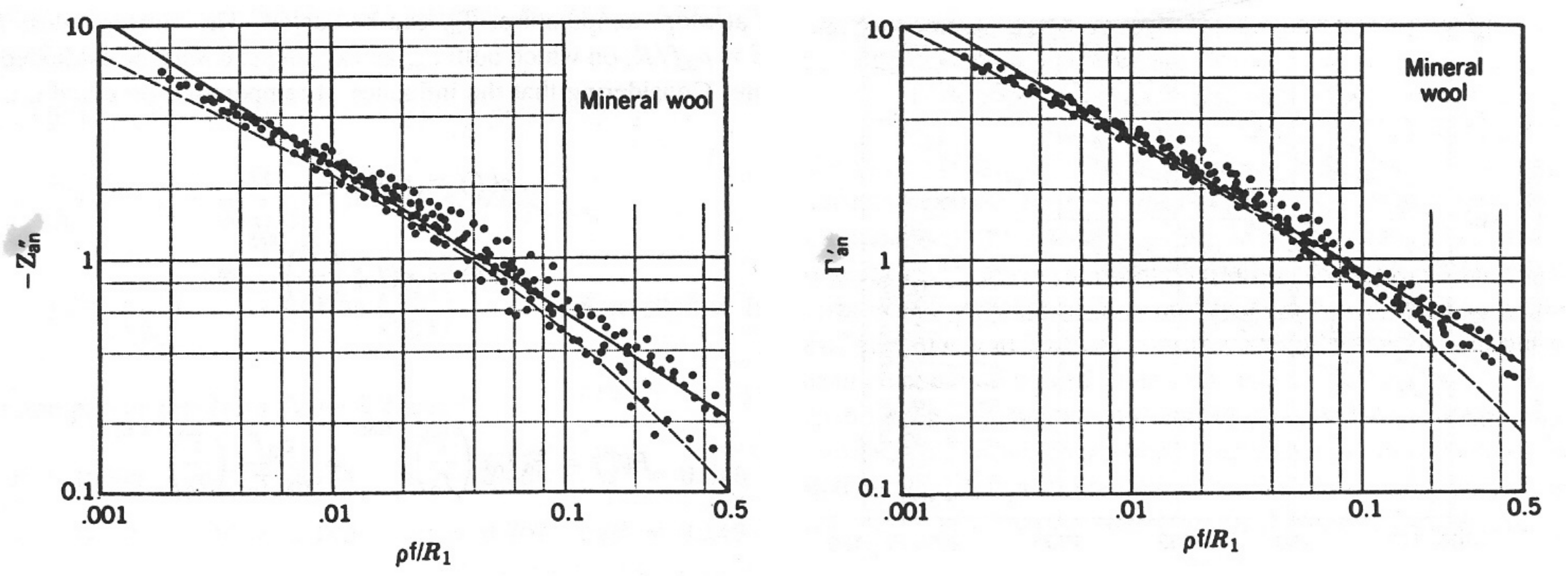


Figure 3.1.2.4 The influence of the flow resistivity with 150 mm thick glass wools. Flow resistivities 9500, 28000 and 82000 Pas/m^2 correspond with densities 18, 76 and 129 kg/m^3, respectively.

Oliva, Häggblom & Hongisto (2010) Finnish Inst. Occup. Health

Empirical relationships between Z, Γ, and *r*



Delany & Bazley (1968 Appl Acoust): Flow resistivity, impedance and wavenumber was measured for several hundreds of porous materials.

Characteristic properties of porous materials

- Based on Delany & Bazley (1968), complex specific impedance $\mathbf{Z}_a$ and wavenumber Γ_a can be predicted when ***r*** is known.

$$\boldsymbol{\Gamma}_a = \Gamma'_a + j\Gamma''_a = \frac{\omega}{c_0}\left[1 + 0.0978E^{-0.700} - j0.189E^{-0.595}\right]$$

$$\mathbf{Z}_a = Z'_a + jZ''_a = \left|\mathbf{Z}_a\right| e^{j\varphi} = \rho_0 c_0 \left[1 + 0.0571E^{-0.754} - j0.087E^{-0.732}\right]$$

- The four constants shown here are suggested later by Cox and D’Antonio (2004).
- φ is phase angle.

$$E = \frac{\rho_0 f}{r}$$

Cox TJ, D'Antonio P, Acoustic absorbers and diffusers, Theory, Design and Application, Spon Press, London, 2004.

Porosity and tortuosity

- High porosity leads to low impedance and high sound absorption if the pores are inter-connected and sound can propagate inside the material and the sound energy easily turns into thermal energy due to friction

- *Porosity* h [ ] is defined as the ratio of air volume V' [m^3] to the total volume of the material V [m^3]:
  - The more air pockets, the higher h.

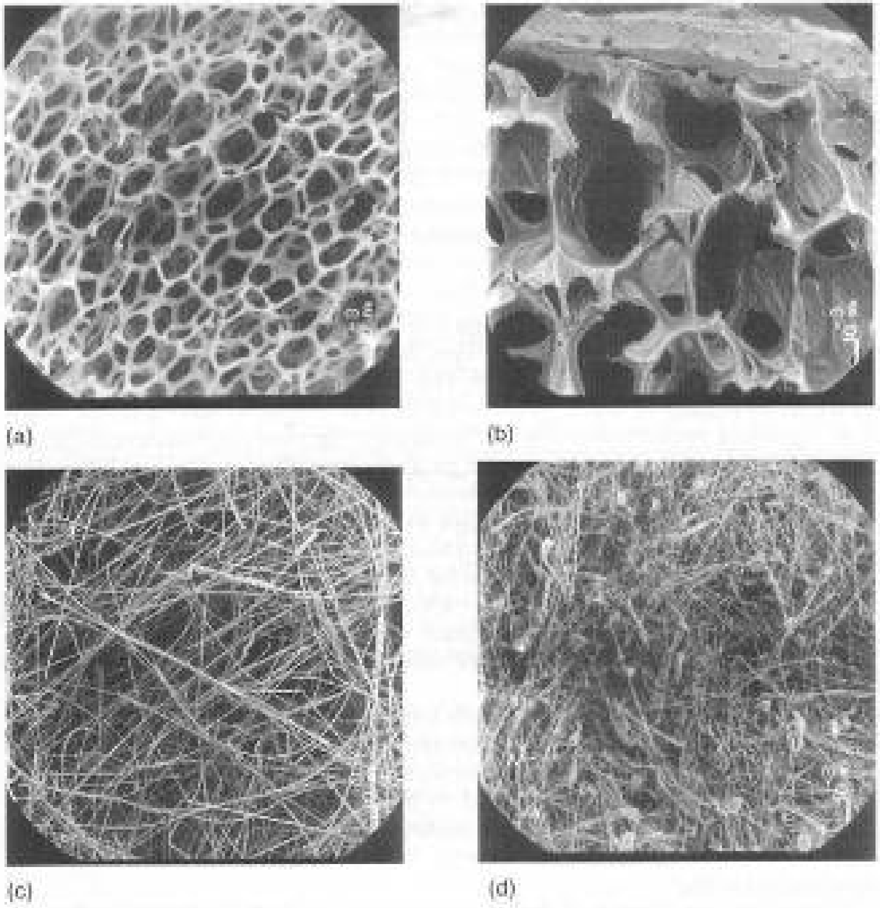
$$h = \frac{V'}{V}$$

- Particle velocity inside the material, u [m/s], is

$$u \cong s\frac{u'}{h}$$

  - s is tortuosity [ ]
  - u' is the particle velocity in air [m/s]

- Tortuosity, or structure factor, describes how the pores are interconnected. It is difficult to measure.



Fahy 2001

Different structure factors:

(a) foam rubber – full grid structure

(b) foam rubber – partial grid structure

(c) glass wool mat

(d) mineral wool 96 kg/m^3.

Characteristic impedance vs. surface impedance

- **Characteristic impedance $\mathbf{Z}_a$** expresses the relationship between sound pressure and particle velocity for a plane wave inside the material.
- **Surface impedance $\mathbf{Z}_1$** expresses the impedance on the surface of the material. The reflection from and transmission inside the material depends only on $\mathbf{Z}_1$.
- $\mathbf{Z}_1$ depends on
  - the characteristic impedance Z_a of the material, and
  - the surface impedance behind the material layer (reflection from the next layer).

$$\mathbf{Z}_a = \frac{\mathbf{p}(x,t)}{\mathbf{u}(x,t)}$$

Reflection in the boundary of two infinite material layers
Perpendicular incidence

- Consider a boundary of two materials: air (0) and absorbent (1), **both having infinite thickness** so that reflections from next boundary do not exist
- Absorption coefficient

$$\alpha = \frac{I_i - I_r}{I_i} = 1 - \frac{I_r}{I_i}$$

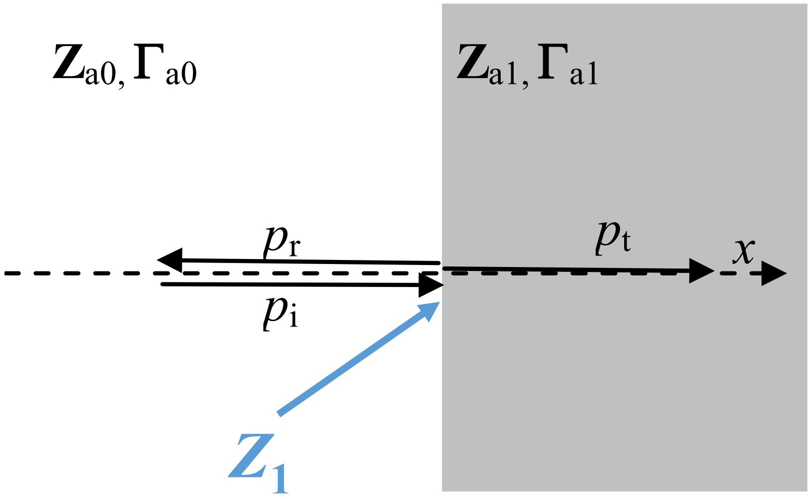
- Wave theory results in

$$\alpha = 1 - |\mathbf{R}|^2 = 1 - \left| \frac{\mathbf{Z}_{a1} - Z_0}{\mathbf{Z}_{a1} + Z_0} \right|^2$$

- Reduced form without complex notation becomes

$$\alpha = 1 - |\mathbf{R}|^2 = \frac{4Z'_{a1} Z_0}{\left(Z'_{a1} + Z_0\right)^2 + Z''^2_{a1}}$$

- NOTE: Maximum absorption, α =1, is reached when $Z_{a1}=Z_0$ (air). The closer Z_{a1} and Z_0 are, the higher α is.

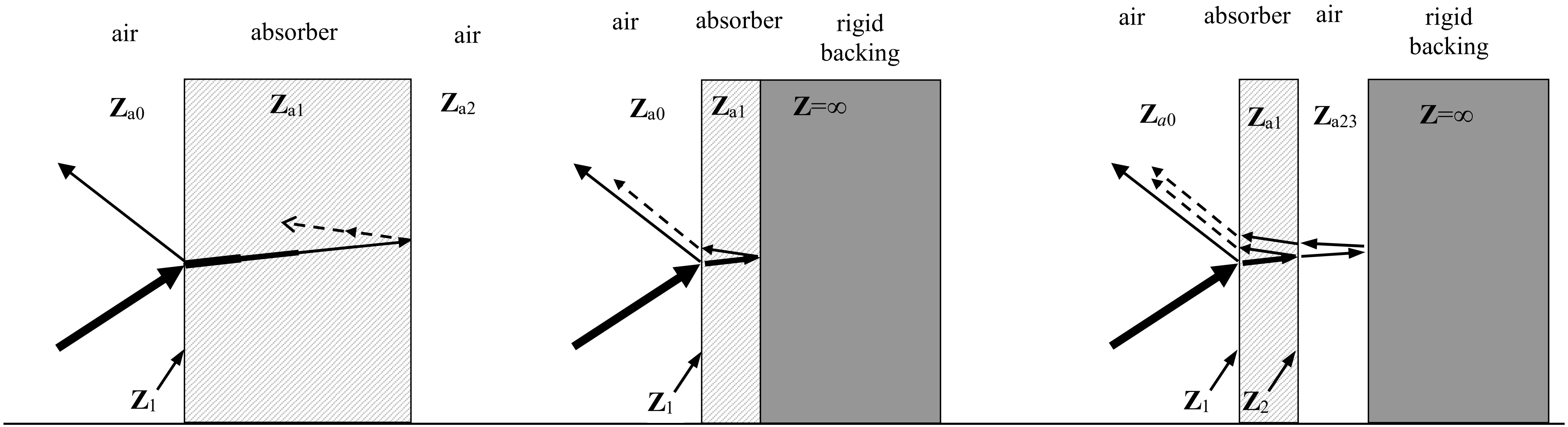


Sound absorption coefficient for a porous absorber

Three cases according to the surrounding materials

a) thick absorber surrounded by infinite air
b) thin absorber against rigid backing
c) thin absorber against a cavity + rigid backing

Z_a characteristic impedance
Z_1 surface impedance



a) $\mathbf{Z}_{a0}=\mathbf{Z}_{a2}=Z_0$

b) $\mathbf{Z}_{a0}=Z_0$

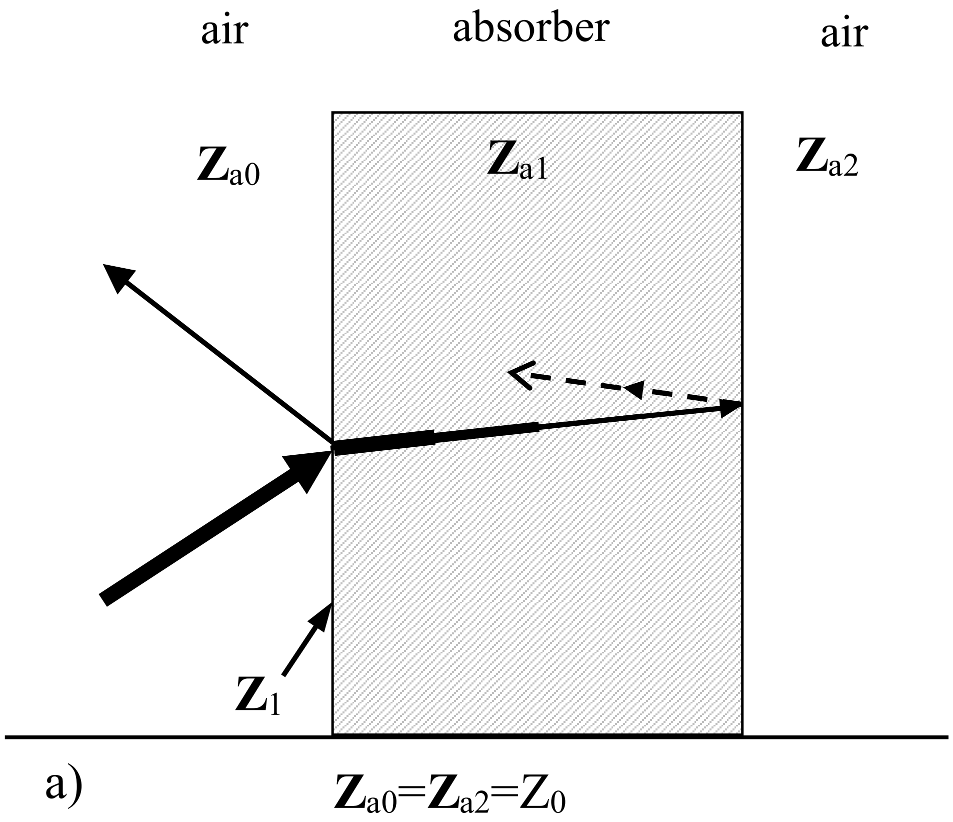
c) $\mathbf{Z}_{a0}=\mathbf{Z}_{a2}=Z_0$

a) Thick porous absorber

- The board is ”thick” if the thickness is at appr. 32% of the wavelength, λ_a, inside material:

$$\Gamma'_a d = \frac{2\pi d}{\lambda_a} > 2$$

- Such a thickness guarantees that the reflection from the backside is attenuated so much that it does no longer contribute to $\mathbf{Z}_1$, and $\mathbf{Z}_1=\mathbf{Z}_{a1}$.
- Absorption coefficient is purely depending on characteristic impedance



$$\alpha = 1-|\mathbf{R}|^2 = \frac{4Z'_{a1}Z_0}{(Z'_{a1}+Z_0)^2+Z''^2_{a1}}$$

2.1

Calculate sound absorption coefficient for a board of infinite thickness at 1 kHz.

r	8000	Pas/m2
f	1000	Hz

b) Finite absorber against rigid backing

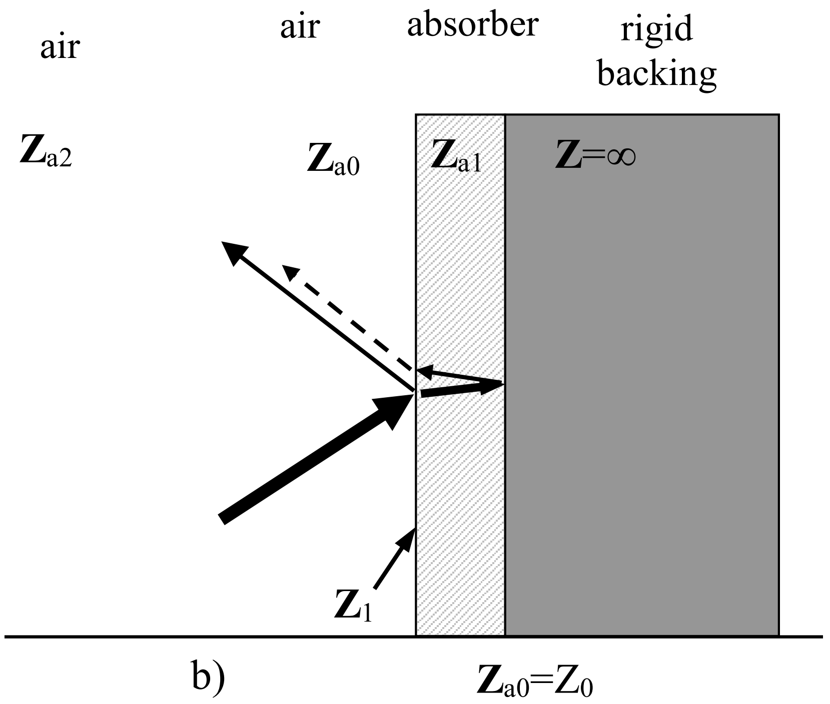
- Consider an absorber of thickness *d* [m].
- Both reflection from rigid backing and characteristic impedance $\boldsymbol{Z}_{a1}$ contribute to surface impedance $\boldsymbol{Z}_1$:

$$\mathbf{Z}_1 = -j\mathbf{Z}_a \cot\left(\boldsymbol{\Gamma}_a d\right) = \mathbf{Z}_a \coth\left(j\boldsymbol{\Gamma}_a d\right)$$

- Absorption coefficient is

$$\alpha = 1 - \left|\mathbf{R}\right|^2 = \frac{4Z'_1 Z_0}{\left(Z'_1 + Z_0\right)^2 + Z''^2_1}$$

$$\coth \boldsymbol{\Gamma} = \frac{e^{\boldsymbol{\Gamma}} + e^{-\boldsymbol{\Gamma}}}{e^{\boldsymbol{\Gamma}} - e^{-\boldsymbol{\Gamma}}} = \frac{\cos\Gamma''\left(e^{\Gamma'} + e^{-\Gamma'}\right) + j\sin\Gamma''\left(e^{\Gamma'} - e^{-\Gamma'}\right)}{\cos\Gamma''\left(e^{\Gamma'} - e^{-\Gamma'}\right) + j\sin\Gamma''\left(e^{\Gamma'} + e^{-\Gamma'}\right)}$$

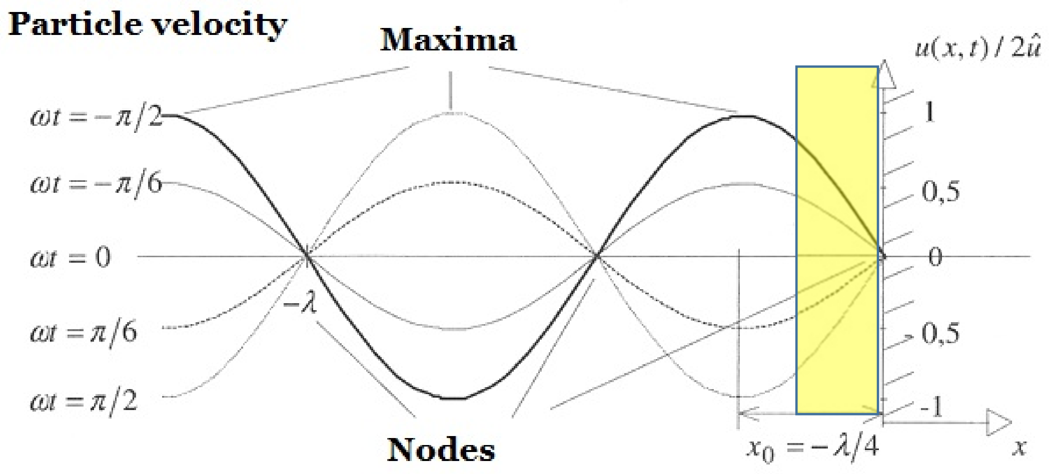


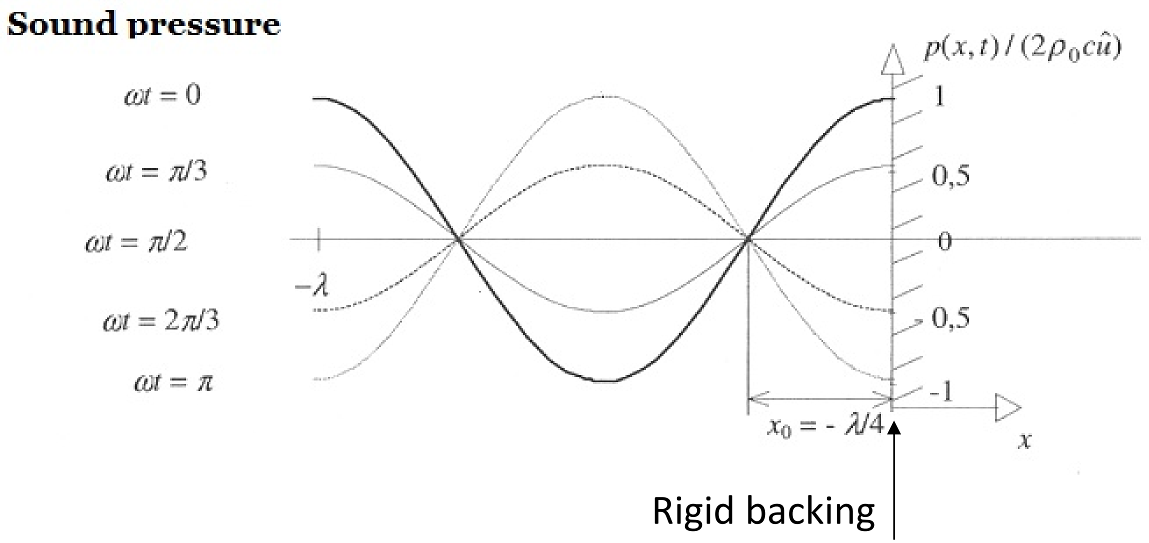
Complex numbers in Excel

- Form: a+bj
- Sum: =IMSUM()
- Subtract: =IMSUB()
- Absolute: =IMABS()
- Cotangent: =IMCOT()
- Product: =IMPRODUCT()
- Division: =IMDIV()
- Real part: =IMREAL()
- Imag. part: =IMAG()

Optimum thickness of absorber against rigid backing

- Due to rigid edge conditions, a standing wave is always formed when sound enters a rigid wall.
- Absorption performance is maximized when the material is located at particle velocity maximum of the standing wave.
- Perfect absorption can only be achieved by material thickness of λ/4
  - 100 Hz: λ=3.4 m, λ/4=0.85 m
  - Wedges in anechoic rooms are usually thicker than 80 cm.

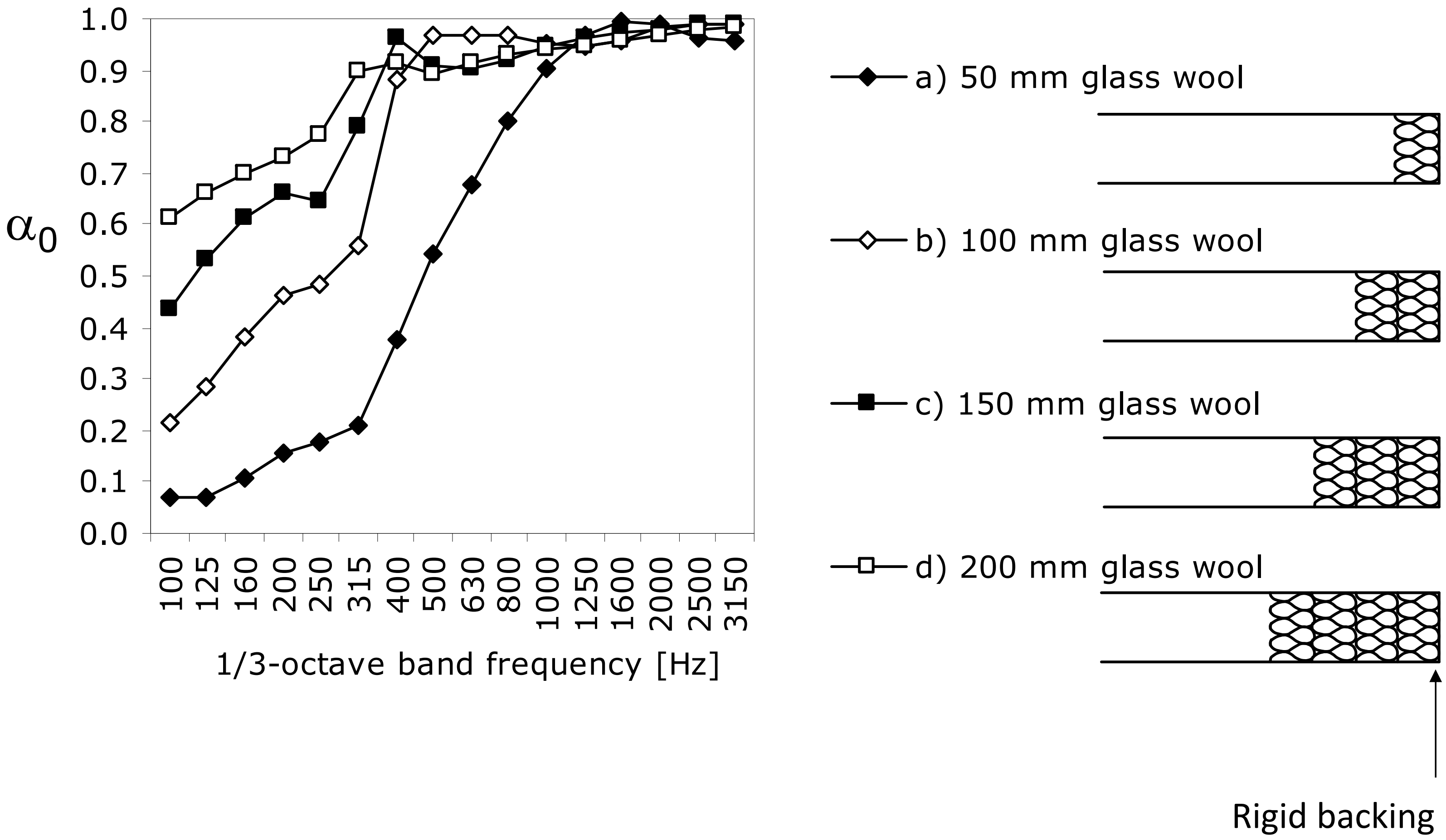




Rigid backing

Effect of glass wool thickness: against rigid backing

- Three thicknesses of the same mineral wool of density 18 kg/m^3
- Specific flow resistivity r=9600 Pa·s/m^2



Oliva, Häggblom & Hongisto (2010)

c) Thin absorber against a cavity + rigid backing

- Surface impedance of air cavity having thickness *t* [m] behind the absorber (in front of cavity):

$$\mathbf{Z}_2 = -jZ_0 \cot\left(k_0 t\right)$$

- Reflection coefficient from the backing of the absorber:

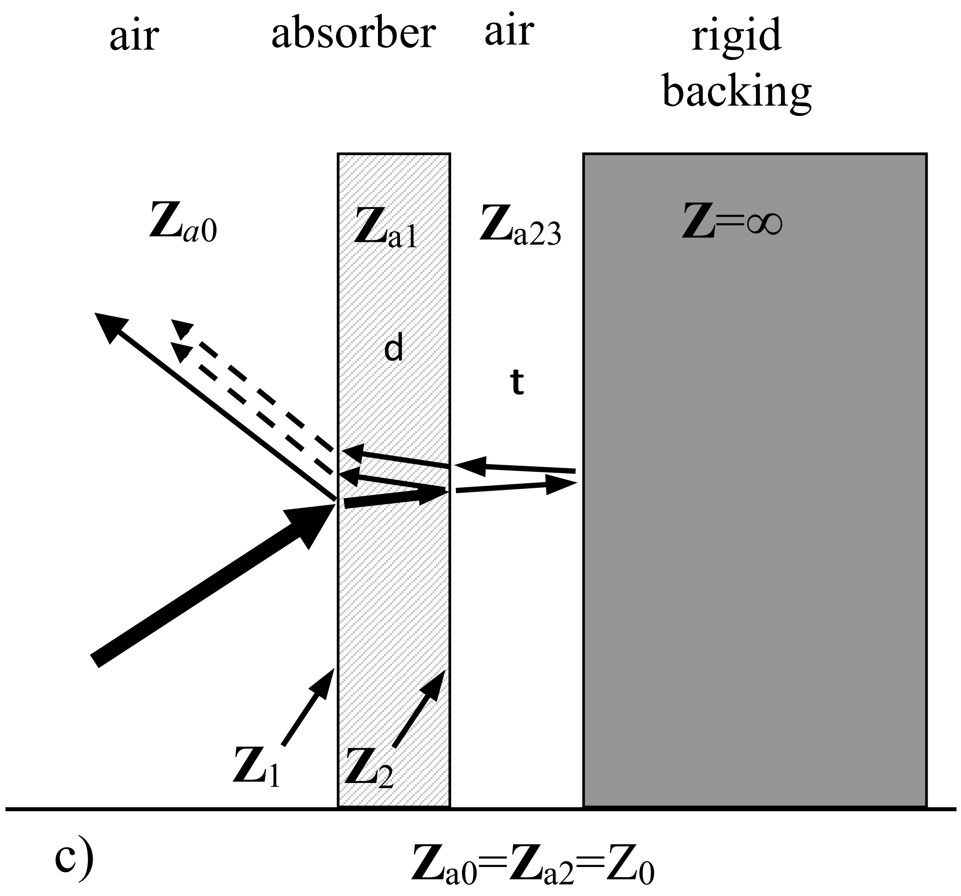
$$\mathbf{R} = \frac{\mathbf{Z}_2 - \mathbf{Z}_{a,1}}{\mathbf{Z}_2 + \mathbf{Z}_{a,1}}$$

- Surface impedance of the porous absorber having a thickness *d* [m]:

$$\mathbf{Z}_1 = \mathbf{Z}_a \frac{\mathbf{Z}_2 \cosh \mathbf{\Gamma}_a d + \mathbf{Z}_a \sinh \mathbf{\Gamma}_a d}{\mathbf{Z}_a \cosh \mathbf{\Gamma}_a d + \mathbf{Z}_2 \sinh \mathbf{\Gamma}_a d}$$

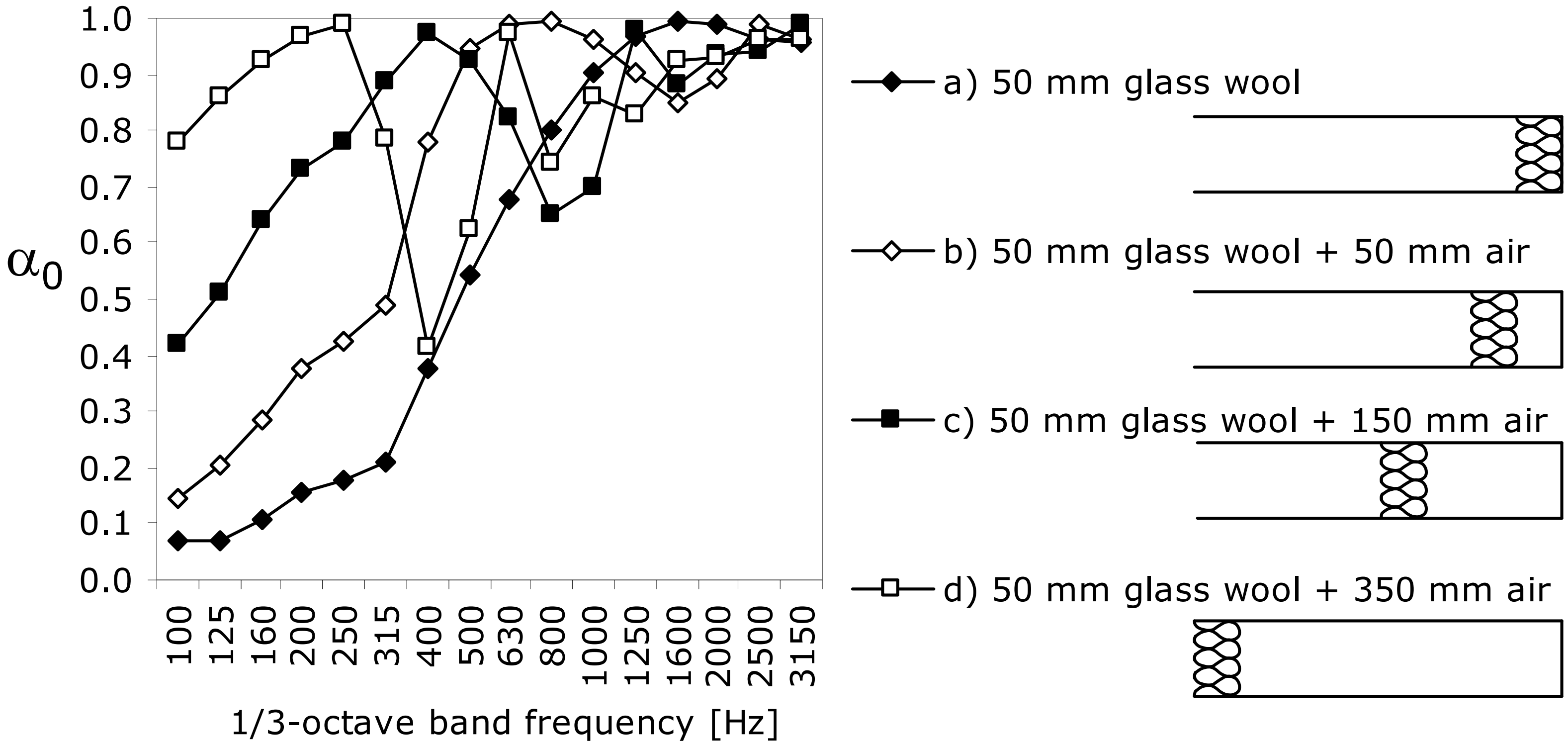
- Absorption coefficient:

$$\alpha = 1 - \left|\mathbf{R}\right|^2 = \frac{4Z'_1 Z_0}{\left(Z'_1 + Z_0\right)^2 + Z''^2_1}$$



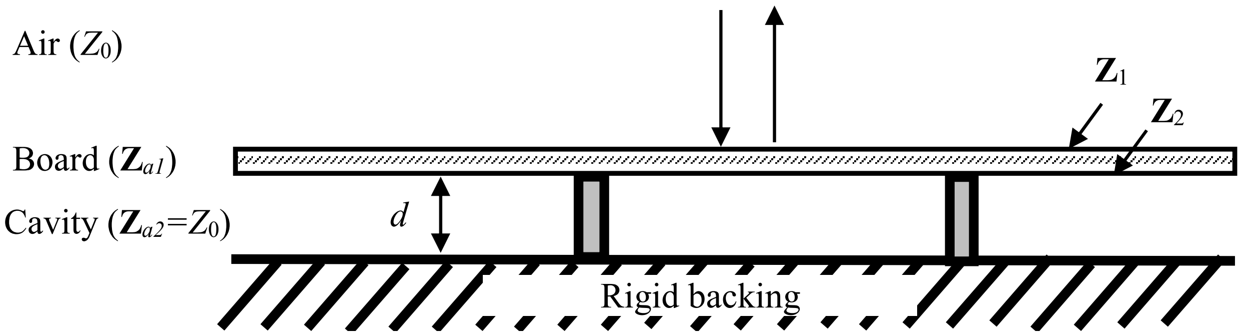
Effect of cavity thickness 50 mm wool absorption

- Wool thickness d=50 mm
- Wool density ρ=18 kg/m^3
- Specific flow resistivity r=9600 Pa·s/m^2



Oliva, Häggblom & Hongisto (2010)

Panel resonator



- Air-tight unperforated board of surface mass m' [kg/m^2] backed by a cavity of thickness d [m] acts as a resonator against a rigid backing
- $k_0 = 2\pi f/c_0$ is the wavenumber in air
- Impedance is large and real part is small (low dissipation)
- Resonator has a sound absorption maximum at the resonance frequency, which occurs when the imaginary part of $\mathbf{Z}_1$=0
- Panel types:
  - Double wall constructions
  - plastic foils on top of porous materials
  - air-tight paintings on top of porous materials
- Cavity can be empty or filled with sound absorber.

- Characteristic impedance of board: $\mathbf{Z}_{a1} = j\omega m'$
  - m' [kg/m^2]
- Surface impedance of cavity: $\mathbf{Z}_2 = -jZ_0 \cot(k_0 d)$
- Surface impedance of board: $\mathbf{Z}_1 = \mathbf{Z}_2 + \mathbf{Z}_{a1}$
- Absorption coefficient:

$$\alpha = 1 - |\mathbf{R}|^2 = \frac{4Z'_1 Z_0}{(Z'_1 + Z_0)^2 + Z''^2_1}$$

- **Resonance frequency** where the absorption maximum takes place,
  - empty cavity: $f_0 = \dfrac{62}{\sqrt{m'd}}$
  - sound absorbing cavity: $f_0 = \dfrac{50}{\sqrt{m'd}}$

Example 2.2

Calculate the resonance frequency:

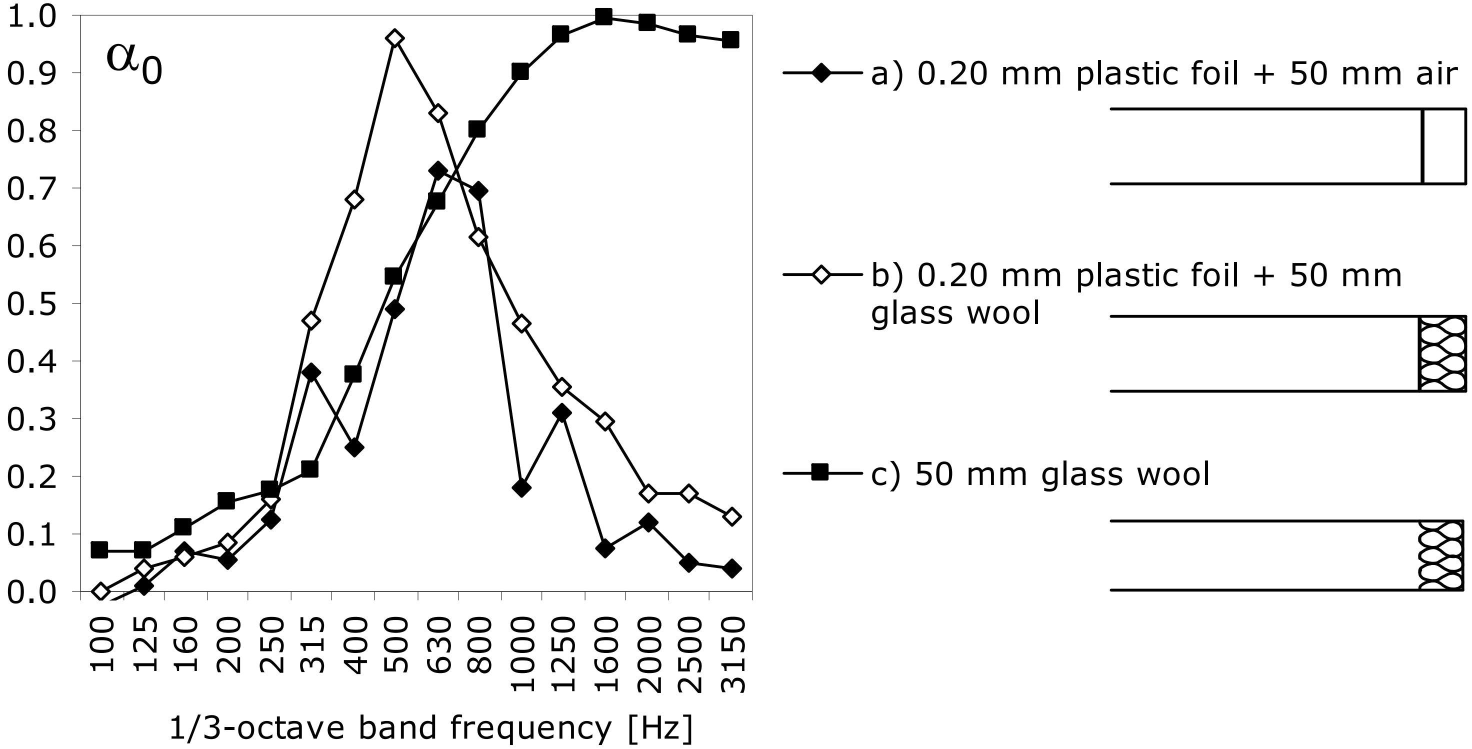
a) Wool 50 mm covered by plastic foil 100 gr/m2.

b) Wool 50 mm covered with hard board 3.2 mm, 2.5 kg/m2

$$f_0 = \frac{60}{\sqrt{m't}} \qquad f_0 = \frac{50}{\sqrt{m't}}$$

Panel resonator vs. porous absorber

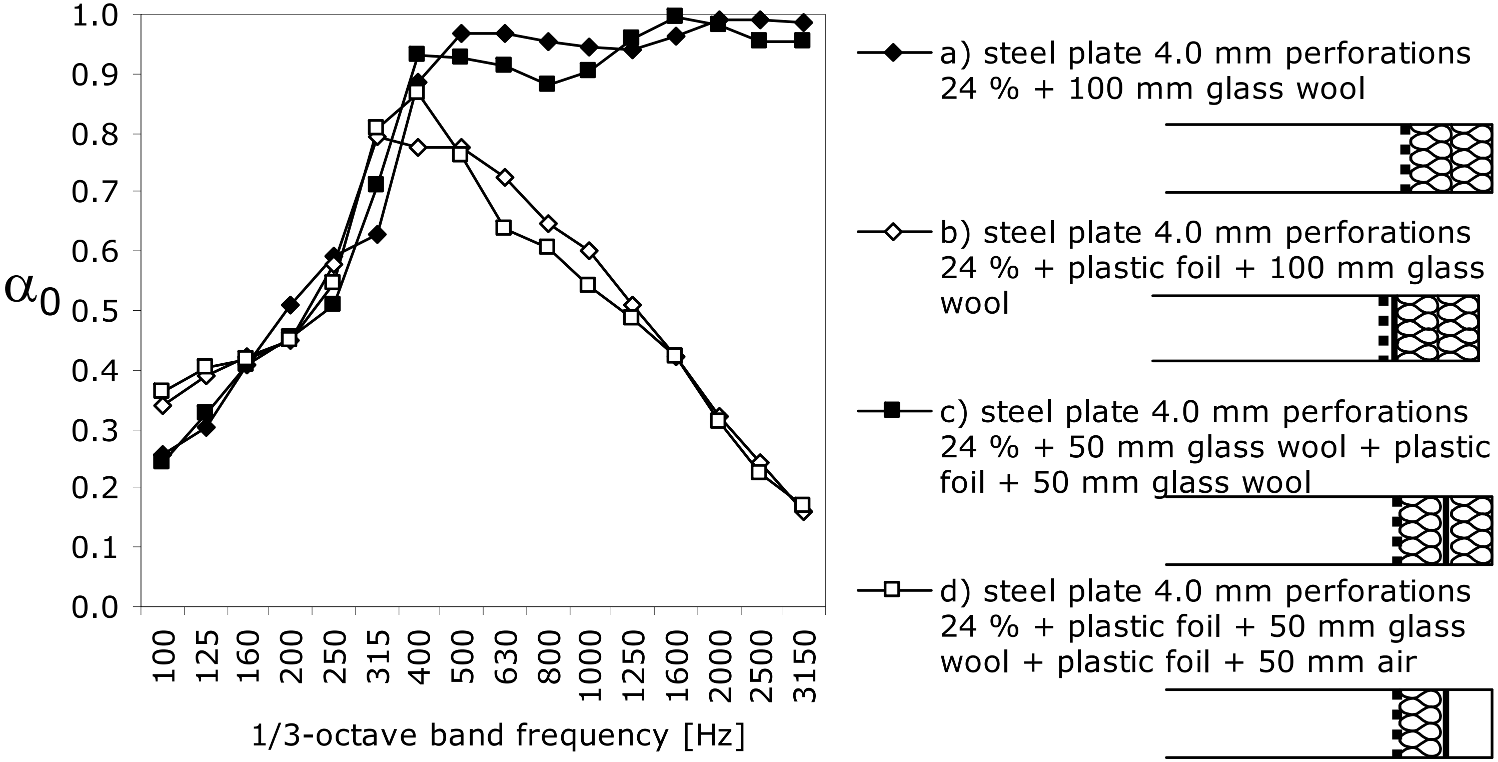
- Plastic foil has a large impedance compared to wool because it is impermeable tight
- Foils are used in facades to protect constructions from humid air especially during winter time
- Foil on top of mineral wool prevents sound propagation to the wool at high frequencies



Oliva, Häggblom & Hongisto (2010)

Effect of plastic foil on top of a mineral wool

- Structures b and d act as a resonator since the foil is on top of the wool.
- Resonance is avoided by sinking the foil inside the wool.
- The moisture isolation properties of the facade may not suffer if the plastic foil is sank at a maximum of 1/4th of the wool thickness.



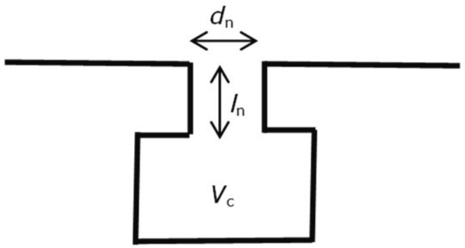
Oliva, Häggblom & Hongisto (2010)

Helmholtz-resonator

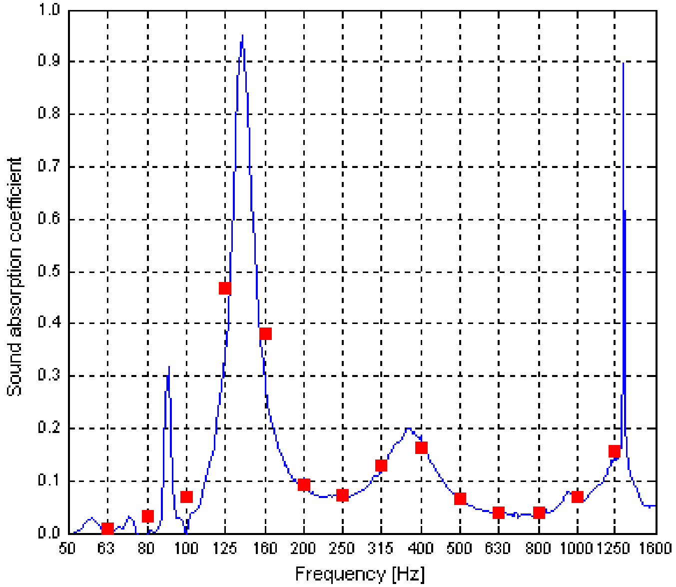
- Neck and volume form a resonator
- Maximum absorption is achieved at a very narrow resonance frequency (Tanttari, 2011)

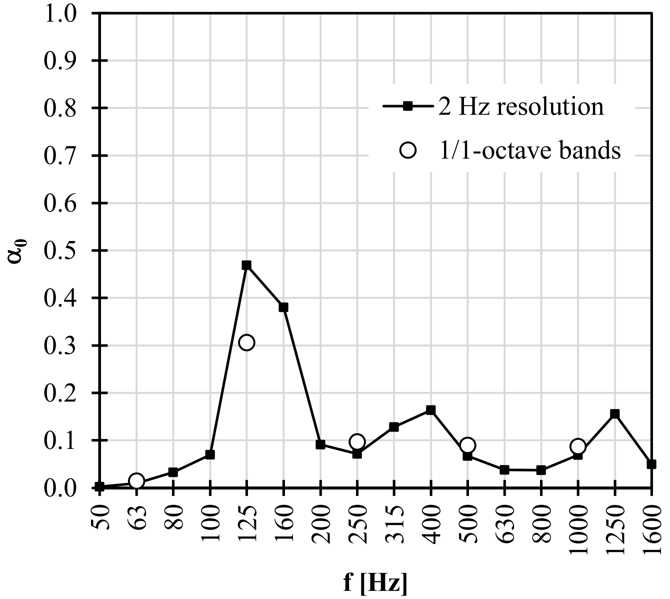
$$f_0 = \frac{c_0}{2\pi}\sqrt{\frac{S_n}{l_{n,eq}V_c}}$$

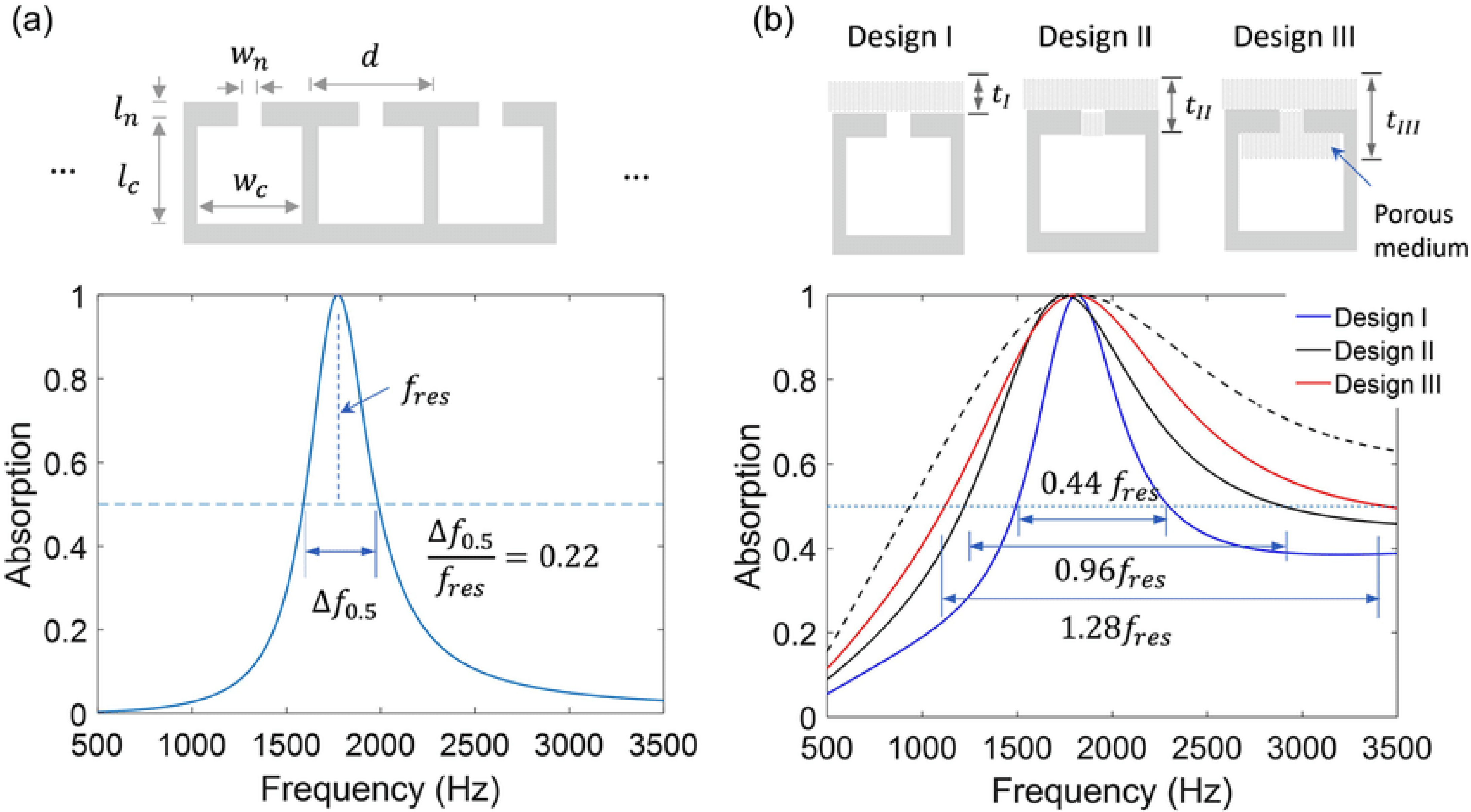
  - S_n cross-sectional area of the neck [m^2],
  - $l_{n,eq}$ equivalent length of the neck [m]
    - $= l_n + 0.82\ d_n$
  - V_c volume of the cavity [m^3]
- Single Helmholz resonators are seldom used in room acoustics but they are applied in exhaust silencers to remove fixed tonal components. Examples of frequency behavior are shown in **Ventilation noise**.



S_s = xx m^2
L = xx m
V_0 = xx m^3







Lee et al. 2019 Sci. Rep.

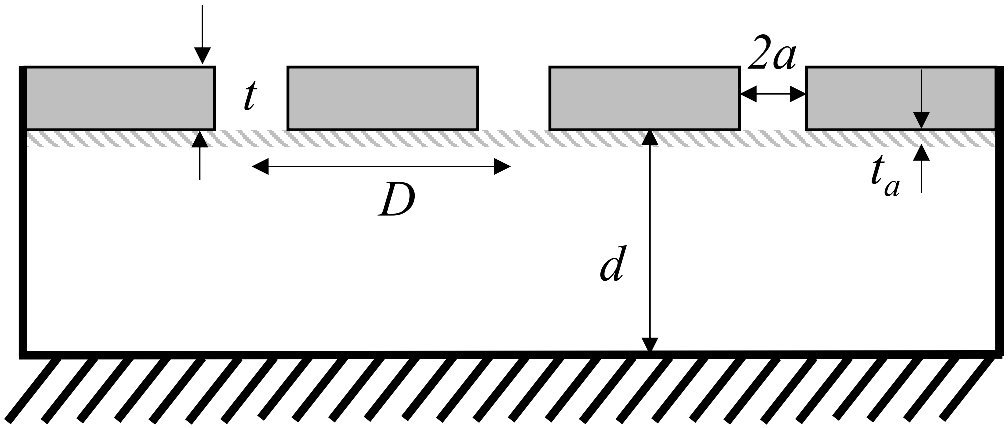
Perforated board

- The most usual application of Helmholz-resonator
- Neck – felt – shared cavity
- Absorption is a **very complex** function of felt resistance, cavity thickness, hole shape and perforation ratio
- If there are no holes, or perforation ratio is very small, the system turns into a panel resonator

$$Z_1 = Z_1' + jZ_1''$$

$$\alpha = 1 - |\mathbf{R}|^2 = \frac{4Z'_1 Z_0}{(Z'_1 + Z_0)^2 + Z''^2_1}$$

$$f_0 = \frac{c_0}{2\pi}\sqrt{\frac{\varepsilon}{t'd}}$$



Perforated board
Porous layer behind board

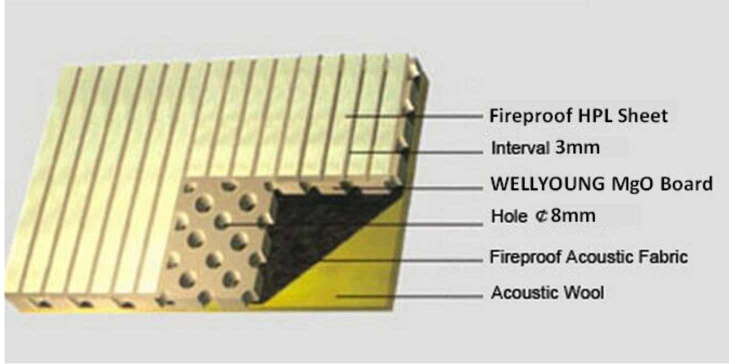
Airtight cavity, edges blocked

Rigid backing

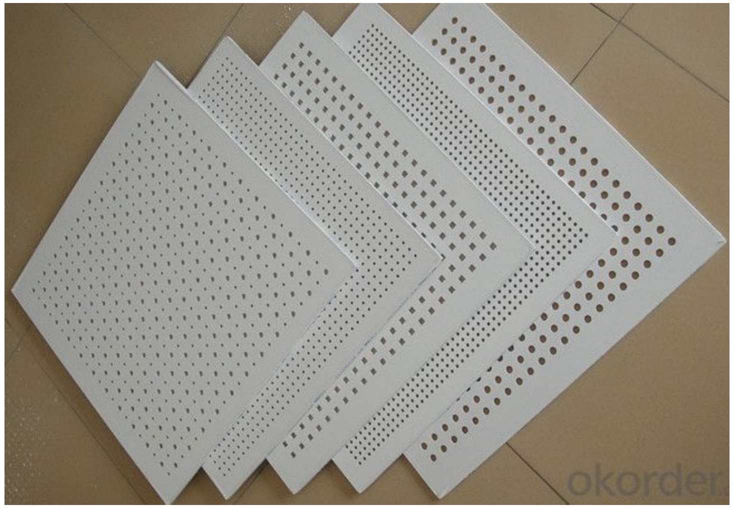
Cox TJ, D'Antonio P, Acoustic absorbers and diffusers, Theory, Design and Application, Spon Press, London, 2004.

Perforated board

A. Perforated MDF board with thin felt. Additional wool behind.
B. Perforated gypsum boards, thin felt behind.
C. Perforated brick. Backed by mineral wool.
D. Perforated steel with thin felt. Backed by wool.



A

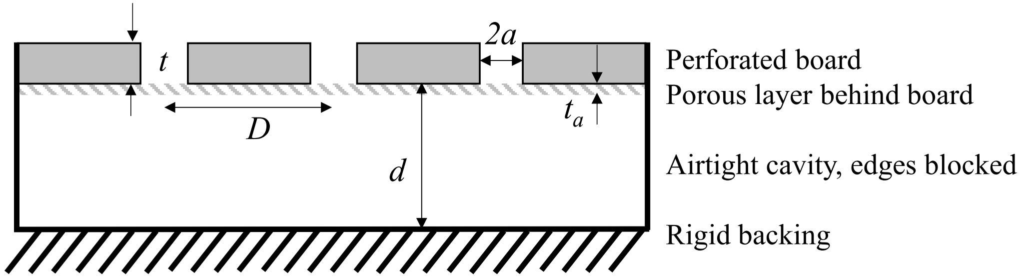


B

C

D

Perforated board



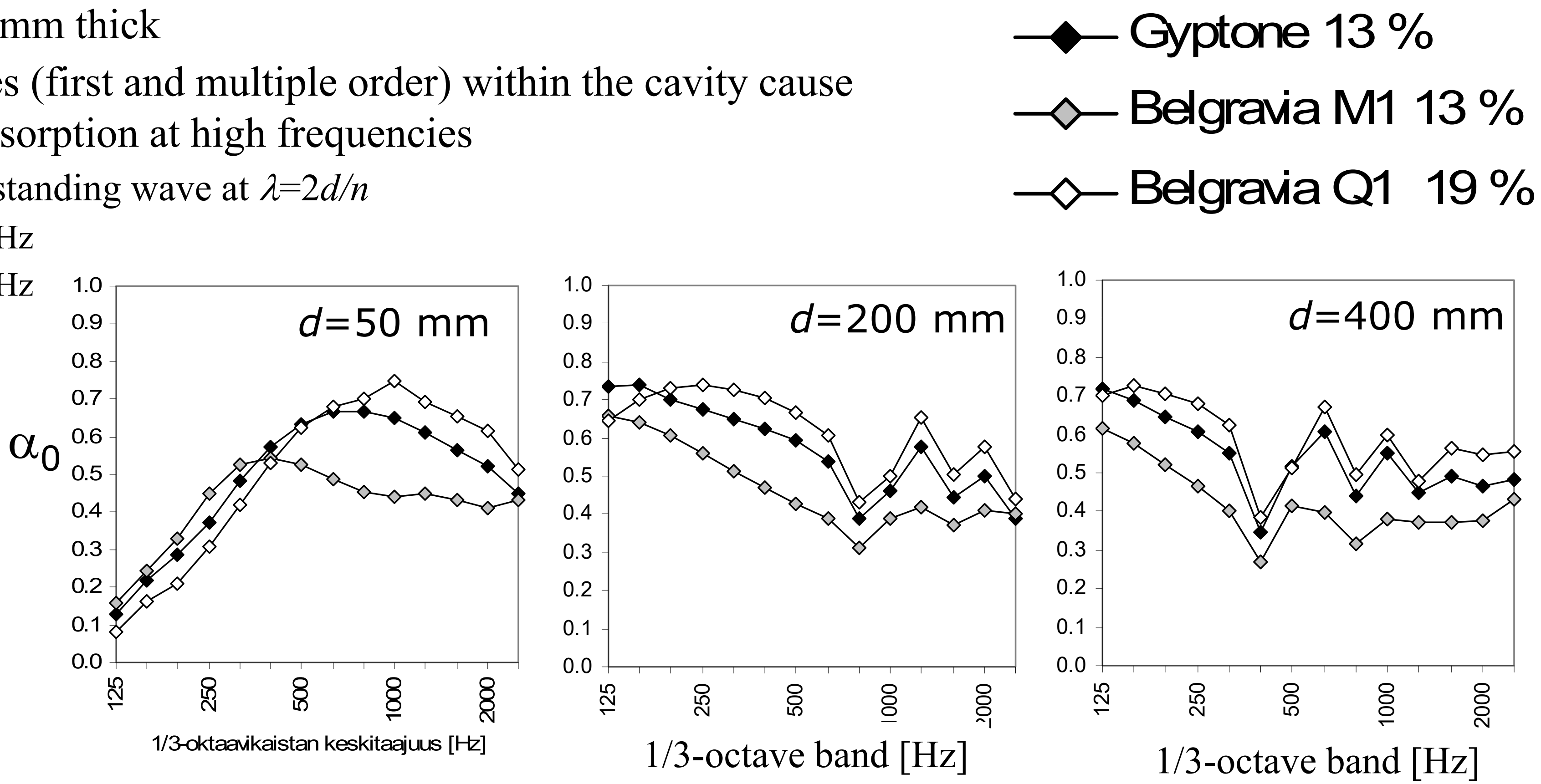
- Total resistance $Z'_1 = Z'_{felt} + Z'_{air}$
- Reactance of air in holes: $Z_1'' = \omega m' - \rho_0 c_0 \cot(kd)$
- Resistance of air in holes: $Z'_{air} = \frac{\rho_0}{\varepsilon}\sqrt{8\nu\omega}\left(1 + \frac{t}{2a}\right)$
- Perforation ratio: $\varepsilon = \frac{\pi a^2}{D^2}$
- Resistance of porous layer, if not behind holes: $Z'_{felt} = r t_a$
- Resistance of porous layer, if right behind holes: $Z'_{felt} = \frac{r t_a}{\varepsilon}$
- Surface mass of air in holes: $m' = \frac{\rho_0 t'}{\varepsilon}$
- Efficient height of neck t: $t' = t + 2\delta a + \sqrt{\frac{8\nu}{\omega}\left(1 + \frac{t}{2a}\right)}$
- End correction: $\delta = 0.8\left(1 - 1.4\sqrt{\varepsilon}\right)$

If holes do not exist, the vibrating mass is the board, not the air in the holes = panel resonator

Cox TJ, D'Antonio P, Acoustic absorbers and diffusers, Theory, Design and Application, Spon Press, London, 2004.

Perforated board: effect of cavity thickness *d* for 3 products

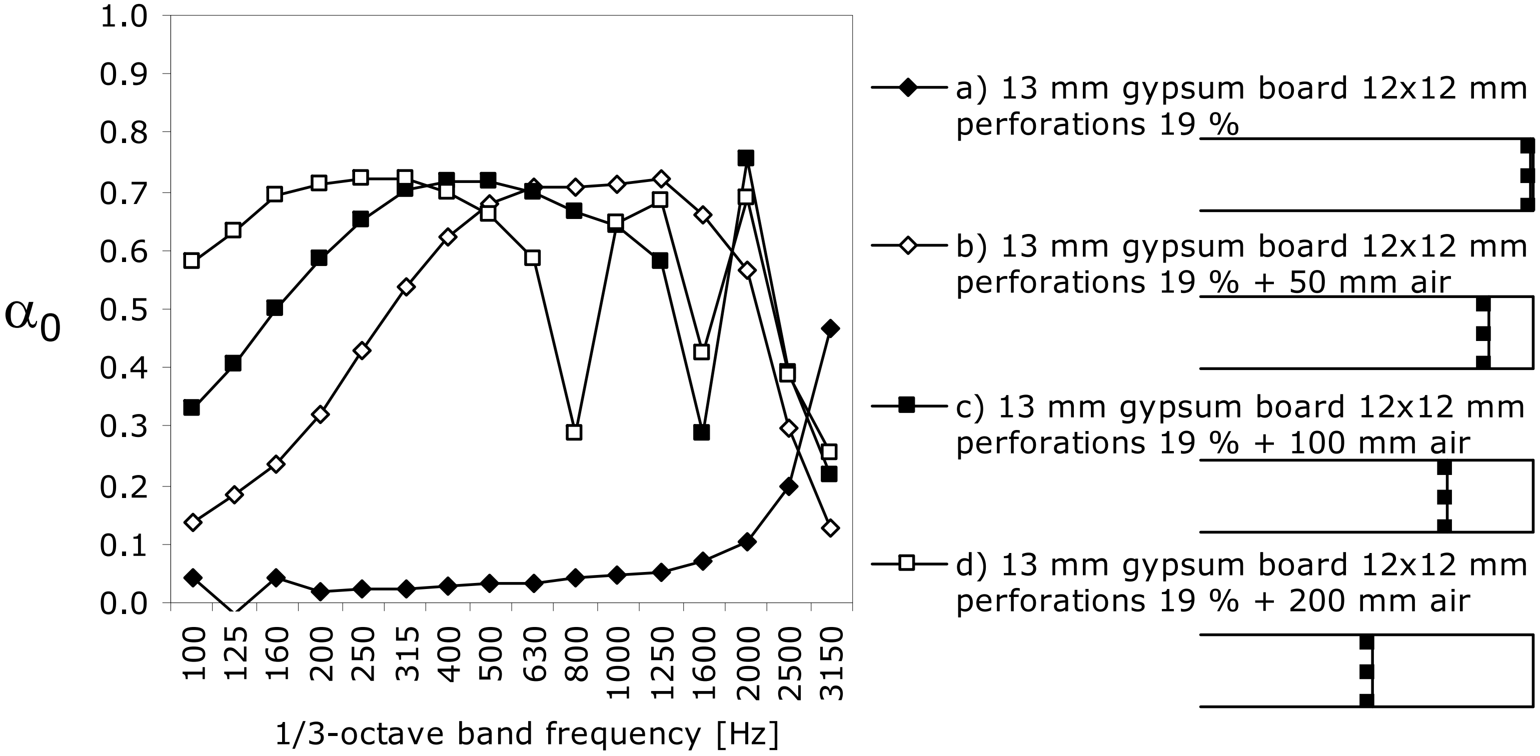
- Resonance frequency reduces with increasing cavity thickness **d**
- Boards are 12 mm thick
- Standing waves (first and multiple order) within the cavity cause variation of absorption at high frequencies
  - *d*=400 mm: standing wave at $\lambda=2d/n$
    - ➢n=1: 428 Hz
    - ➢n=2: 856 Hz



Oliva, Häggblom & Hongisto (2010)

Perforated board: effect of cavity thickness *d* – empty cavity

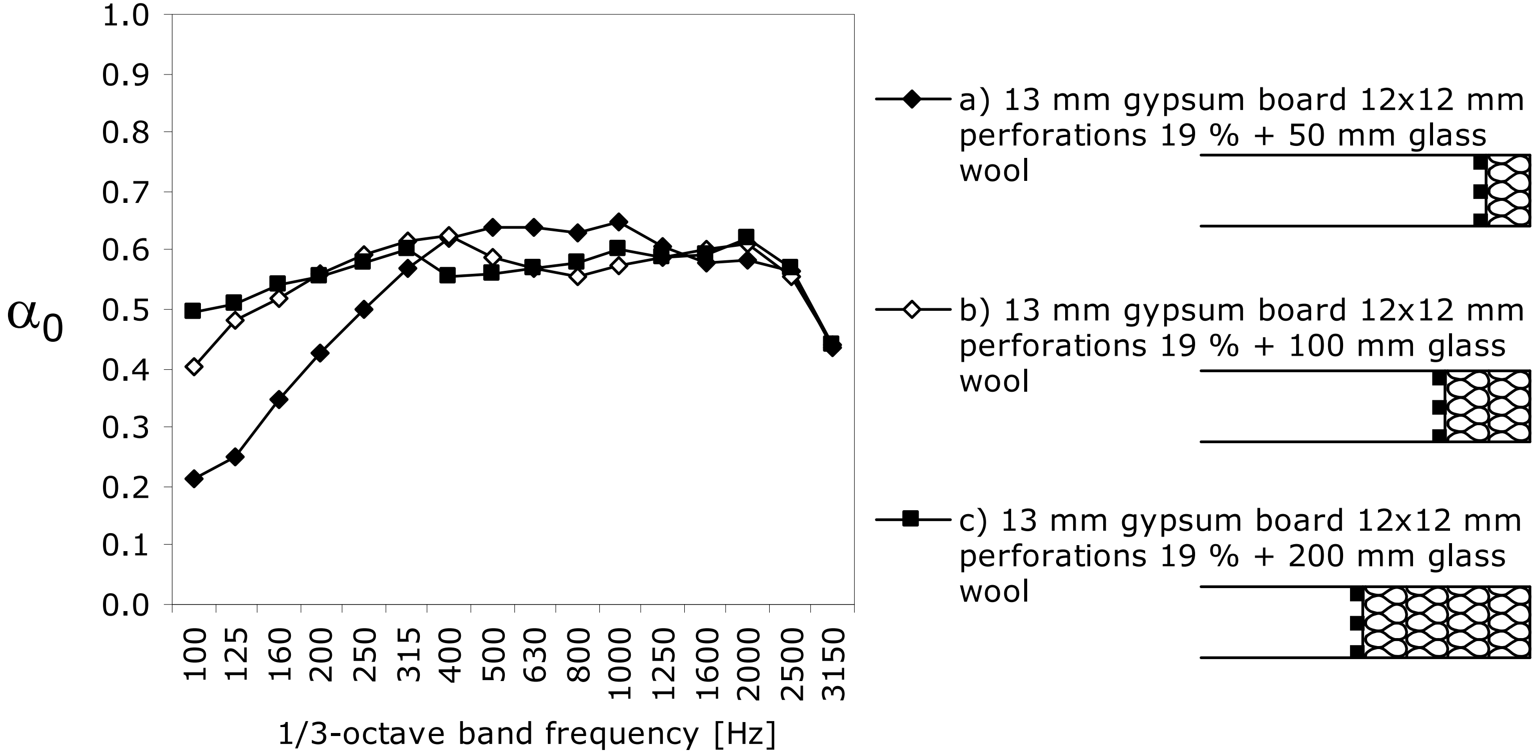
- Perforated board 13 mm incolving a felt behind the board (r=1183 Pas/m).
- Cavity is empty.



Oliva, Häggblom & Hongisto (2010)

Perforated board: effect of cavity thickness *d* – filled cavity

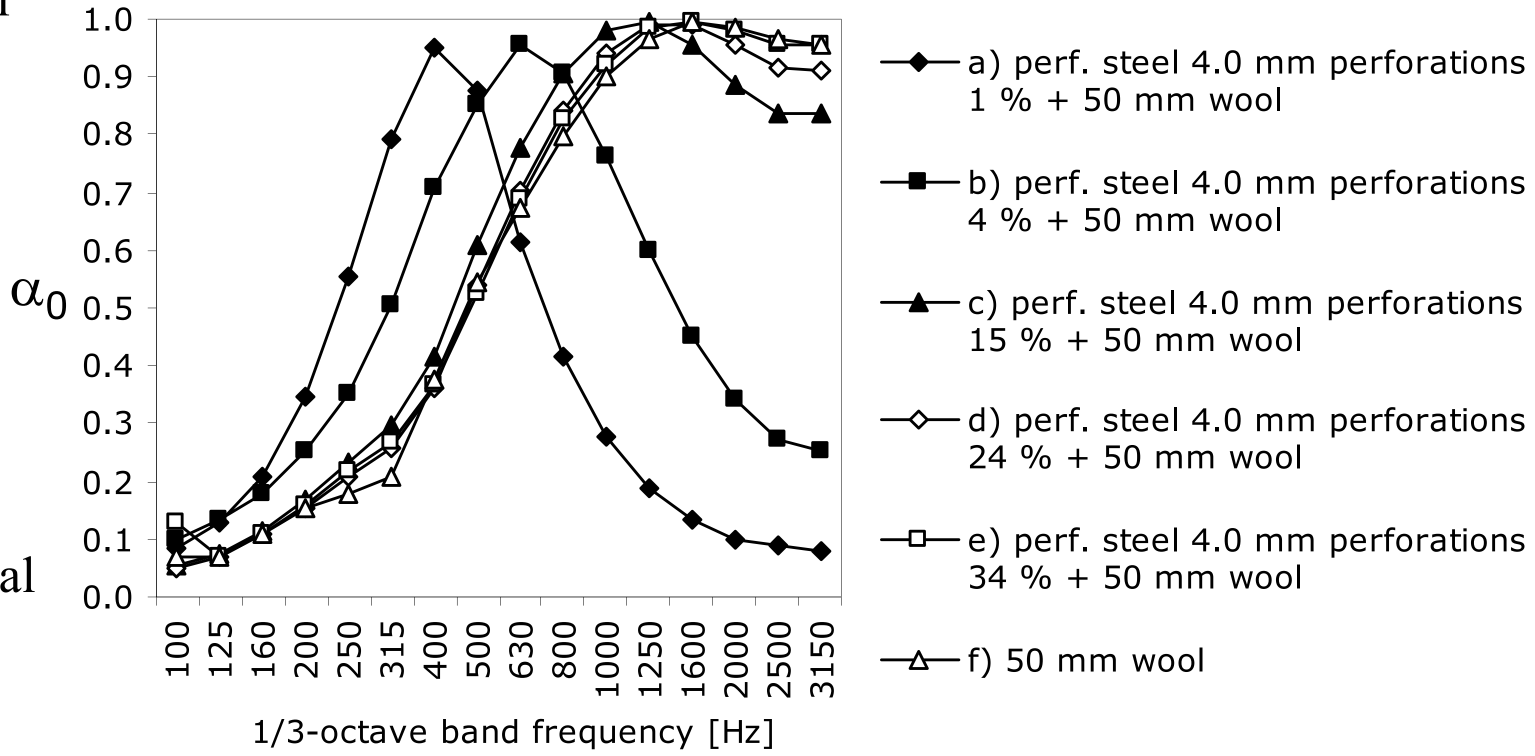
- Perforated board 13 mm incolving a felt behind the board (r=1183 Pas/m).
- Cavity filled with wool (ρ=18 kg/m3, r=9600 Pa·s/m2).

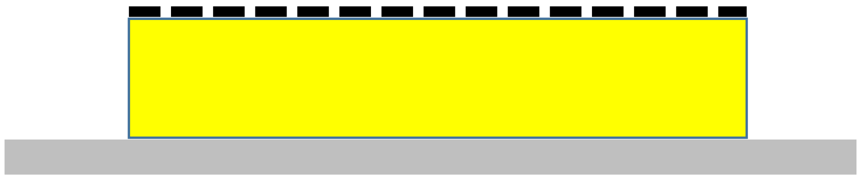


Oliva, Häggblom & Hongisto (2010)

Perforated board
Effect of perforation ratio when board is backed by mineral wool

- Consider a mineral wool installed against rigid wall
- Wool is covered by perforated board with different perforation ratios
- Thin metal board, thickness 0.9 mm and cavity 50 mm
- Cavity filled with mineral wool (d=50 mm, ρ=18 kg/m^3, r=Pa·s/m^2).
- Perforation ratio is the percentage of perforated area of the total area.



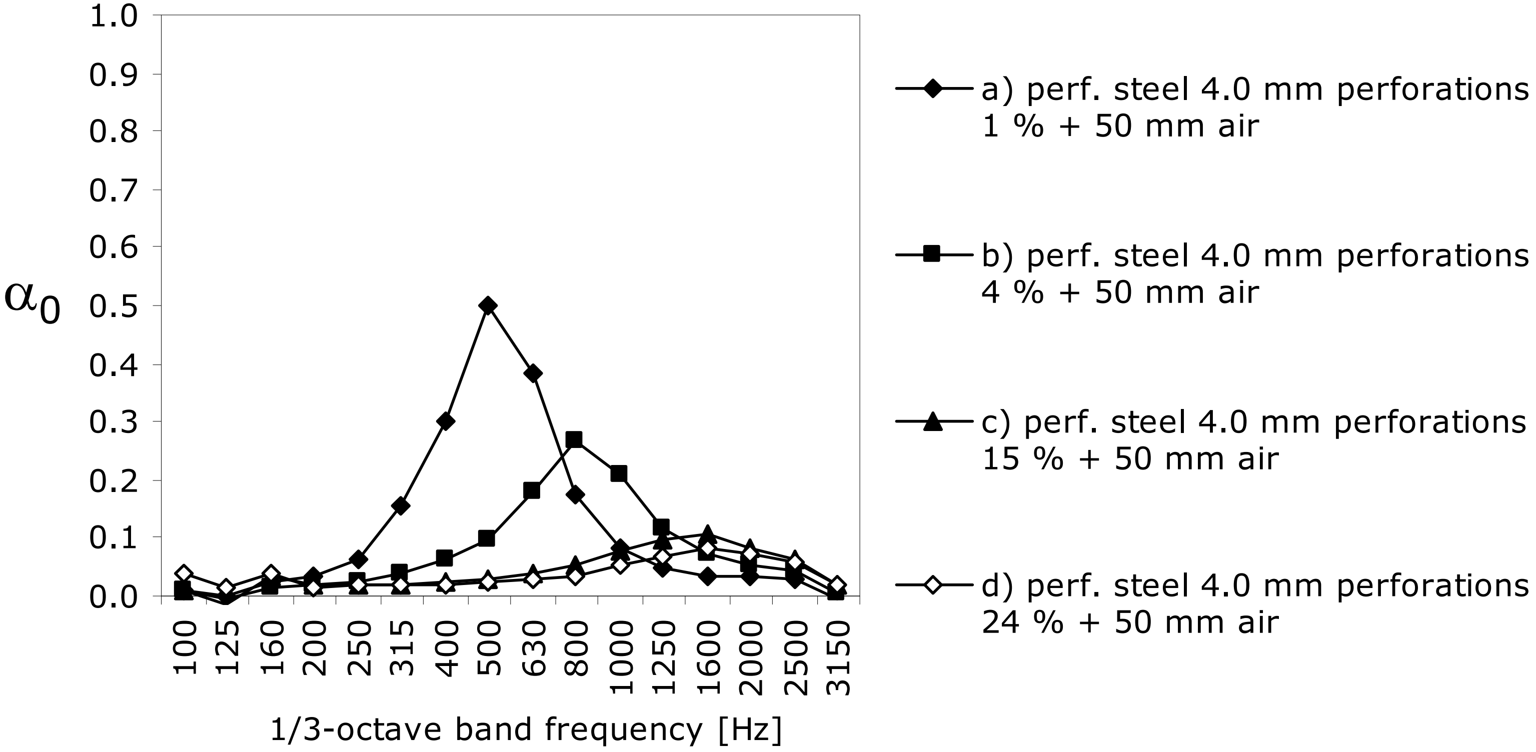


Oliva, Häggblom & Hongisto (2010)

Perforated board

Effect of perforation ratio when board is backed by empty cavity

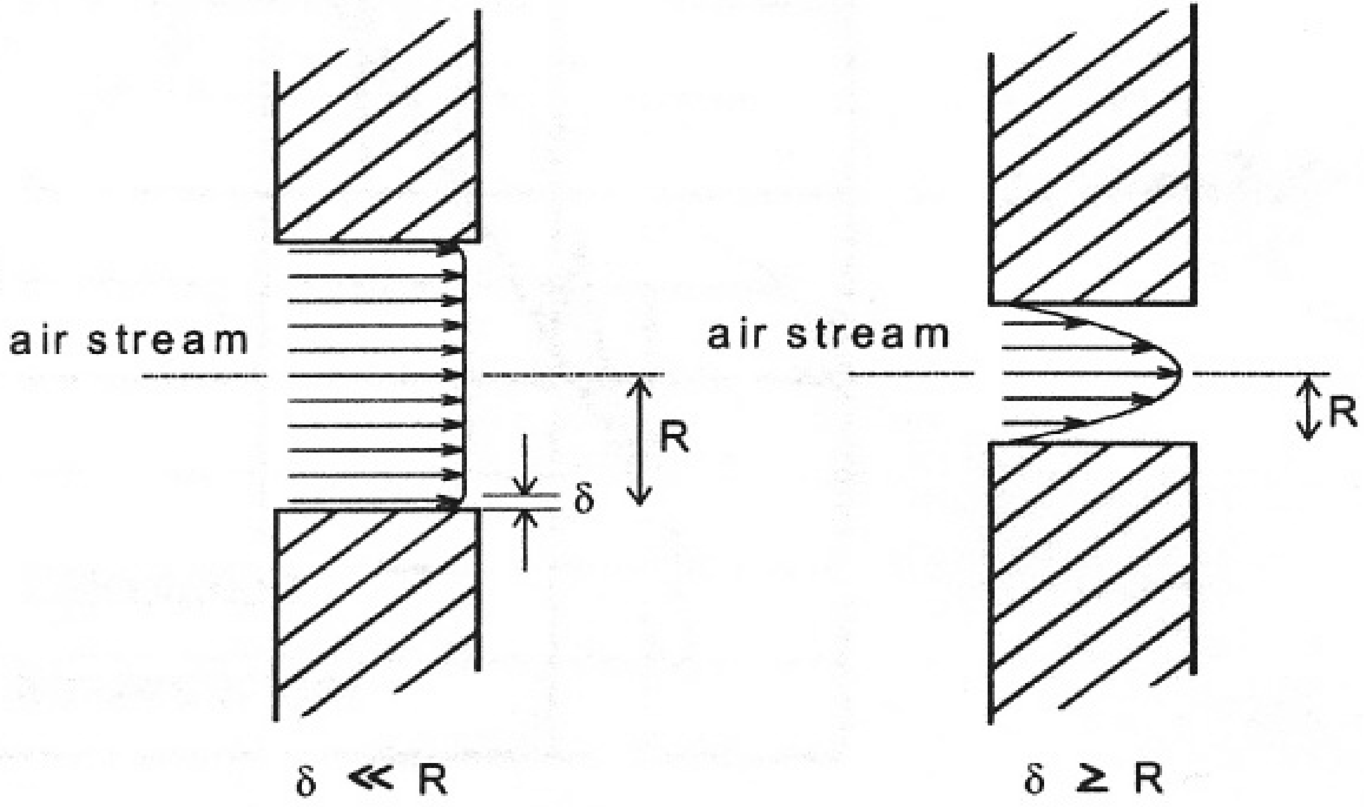
- Thin metal board, thickness 0.9 mm and cavity 50 mm.
- Cavity is empty.



Oliva, Häggblom & Hongisto (2010)

Microperforated boards

- Viscosity of a perforation contributes to the sound absorption when the perforation diameter is under 1 mm.
- Microperforation enables transparent sound absorbers.
- www.microsorber.com




BARRISOL
© 2016 Normalu

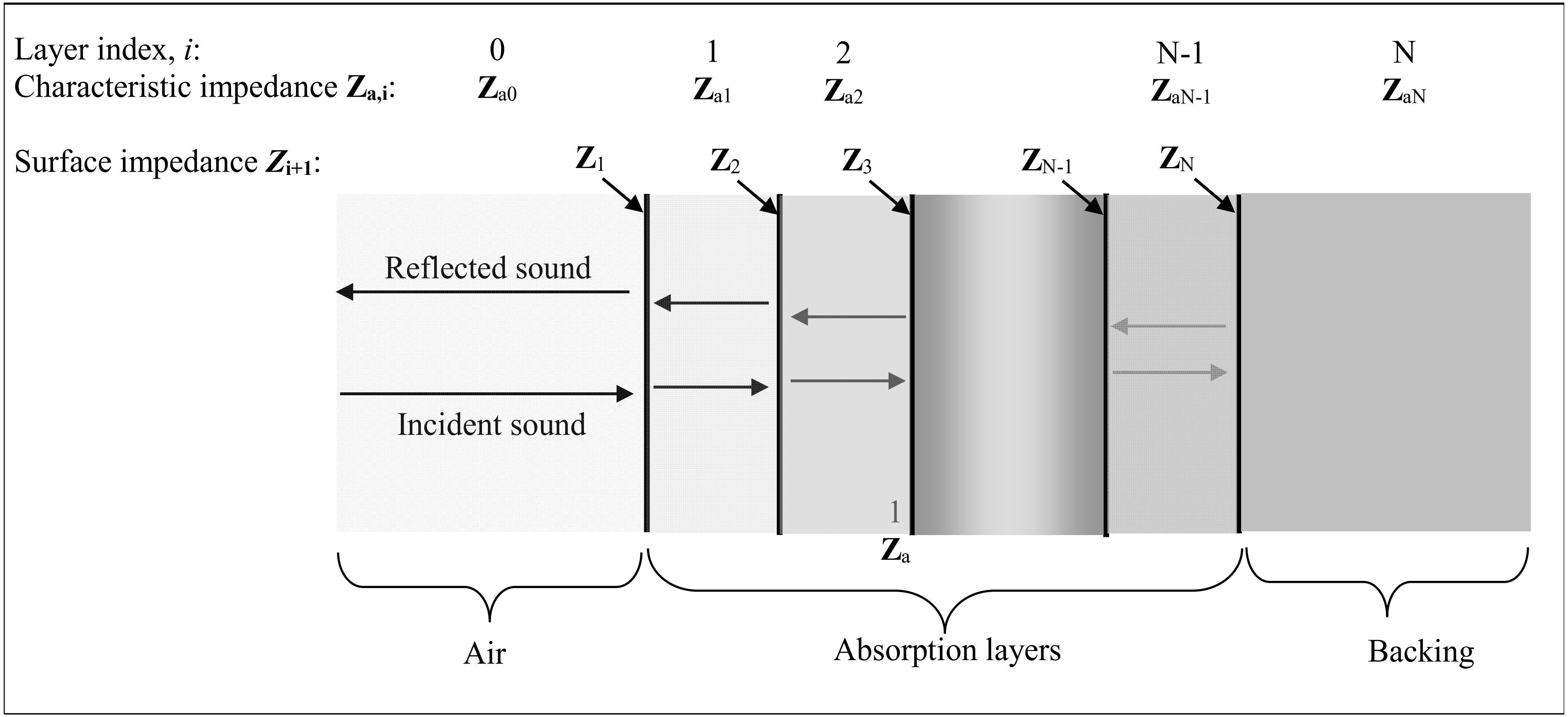
Modeling of a multilayer absorber – Basic approach

Absorption coefficient:

$$\alpha_0 = 1 - |R|^2 = 1 - \left|\frac{Z_1 - Z_0}{Z_1 + Z_0}\right|^2$$

Surface impedance:

$$Z_i = \frac{Z_{ai}Z_{i+1}coth(\Gamma_{ai}d_i) + Z_{ai}^2}{Z_{i+1} + Z_{ai}coth(\Gamma_{ai}d_i)}$$



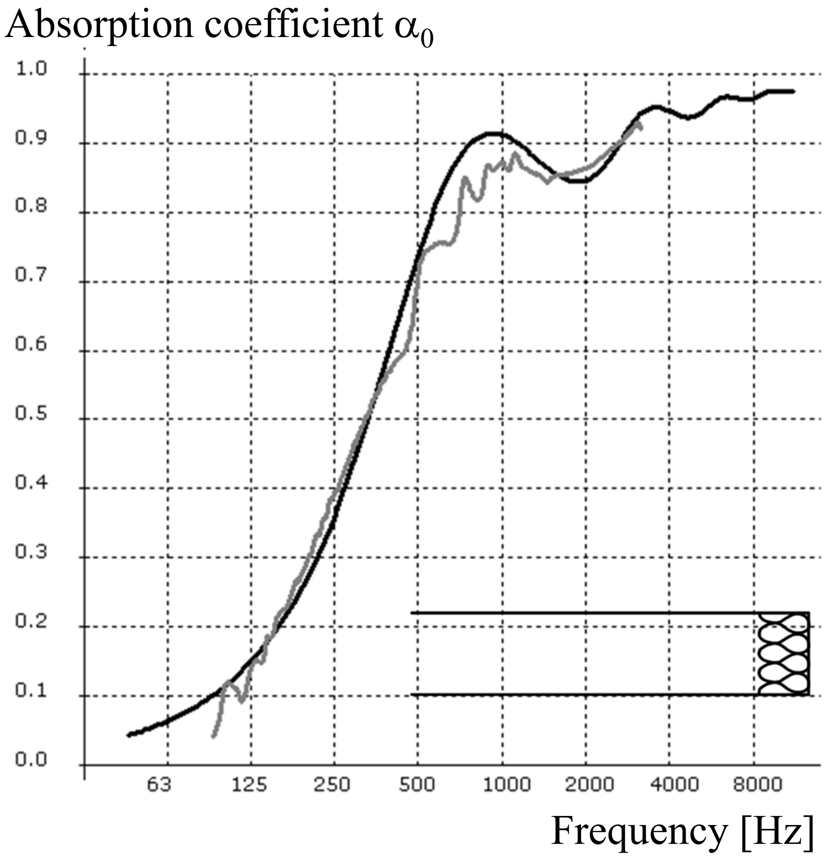
Oliva & Hongisto 2009 **Akustiikkapäivät**

Predicted vs. measured values - wools

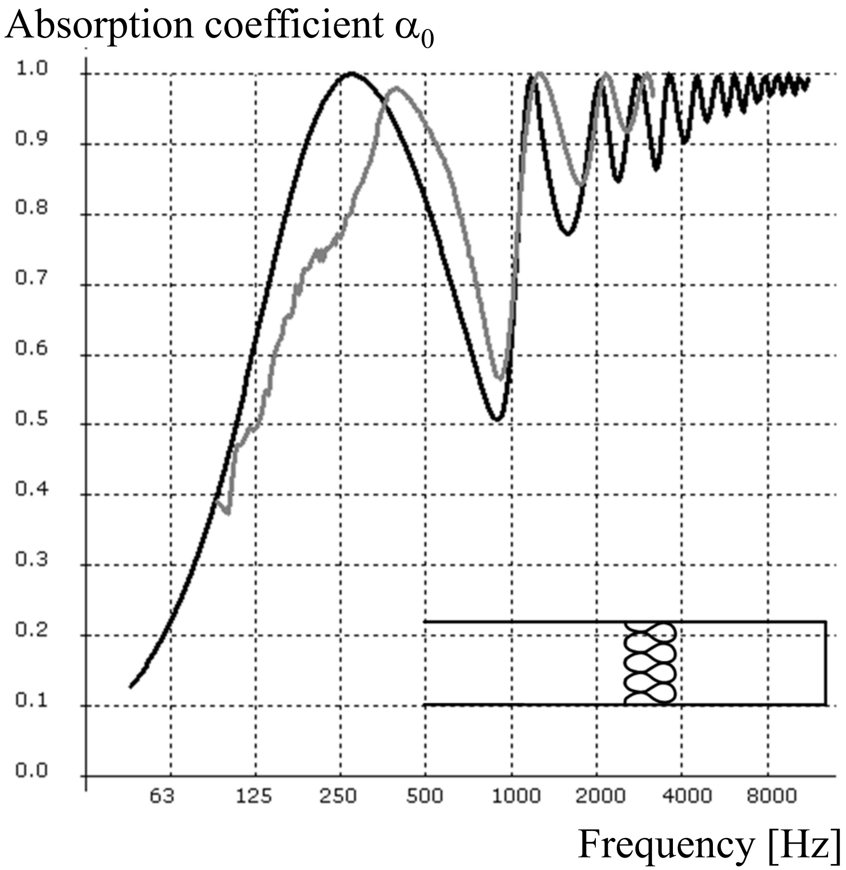
Predictions were made with the model described in previous slides.

Normal sound incidence.

Measured values with impedance tube.



50 mm wool, 76 kg/m3, 28000 rayl/m + reflecting backing



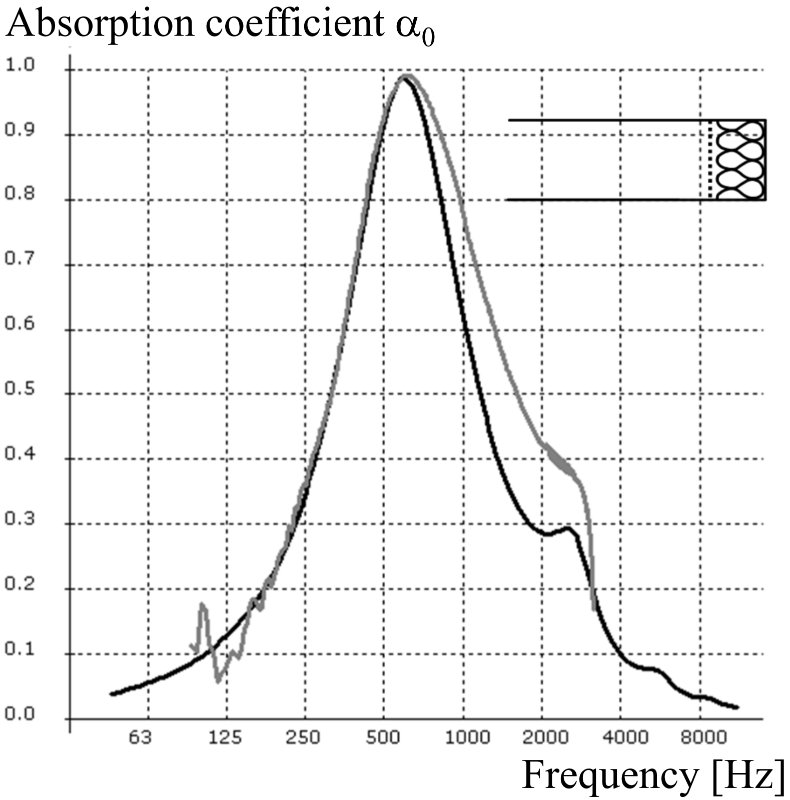
50 mm wool, 18 kg/m3, 9600 rayl/m
+ 150 mm empty cavity + reflecting backing

Predicted vs. measured values - Perforated panels

Predictions were made with the model described in previous slides.

Normal sound incidence.

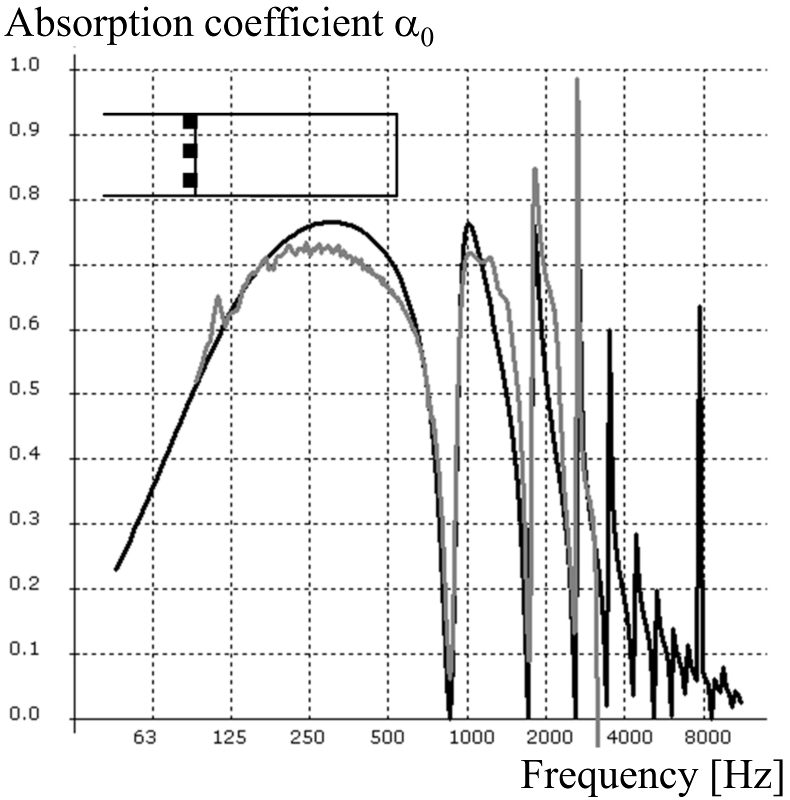
Measured values with impedance tube.



0.9 mm thick perforated steel sheet

- perforation diameter 1.3 mm,
- perforation ratio 1.3 %

50 mm wool, 18 kg/m3, 9600 rayl/m^3



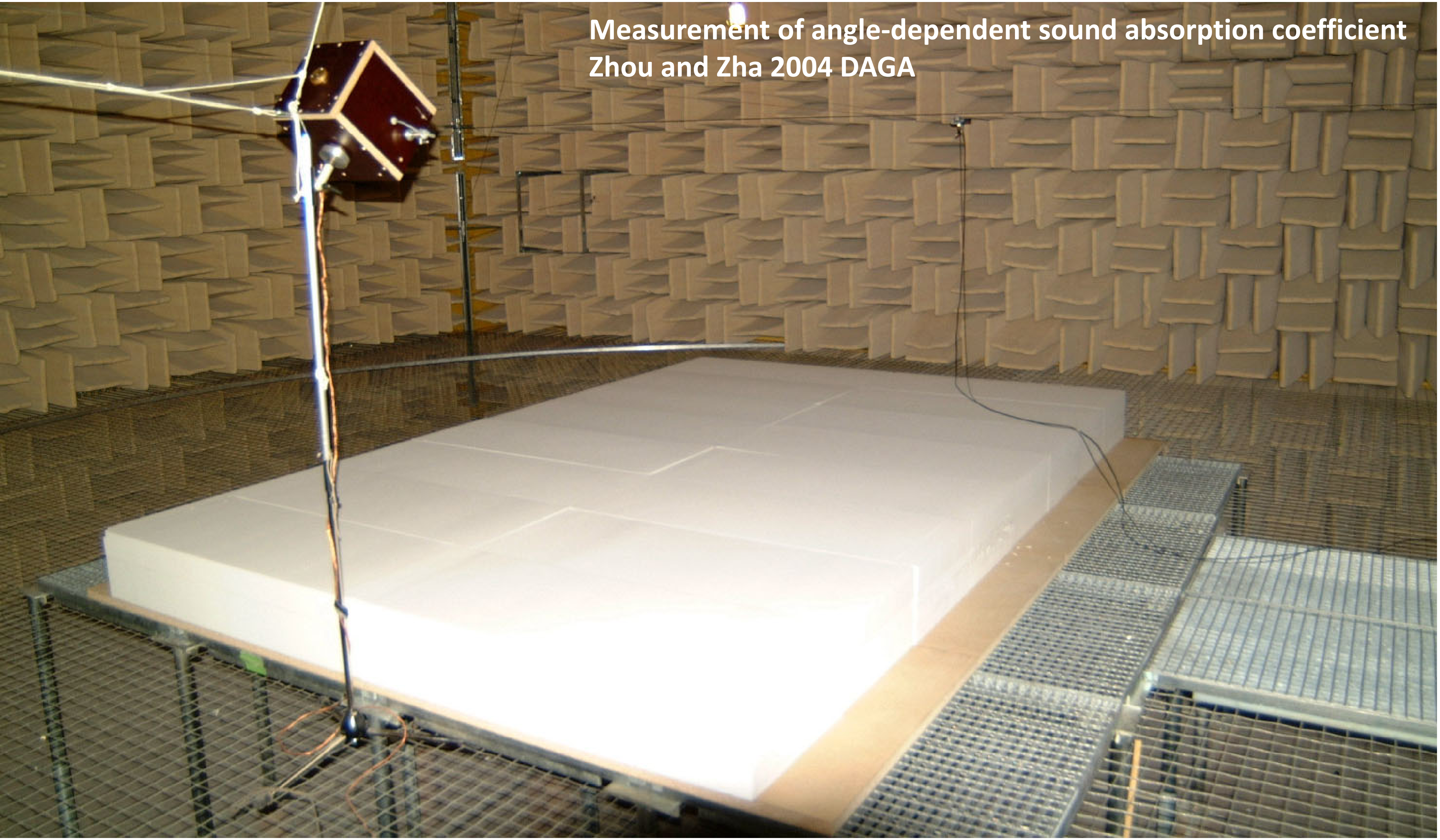
13 mm thick perforated gypsum

- 12x12 mm, 19 %,
- felt 91000 rayl/m

200 mm thick empty cavity

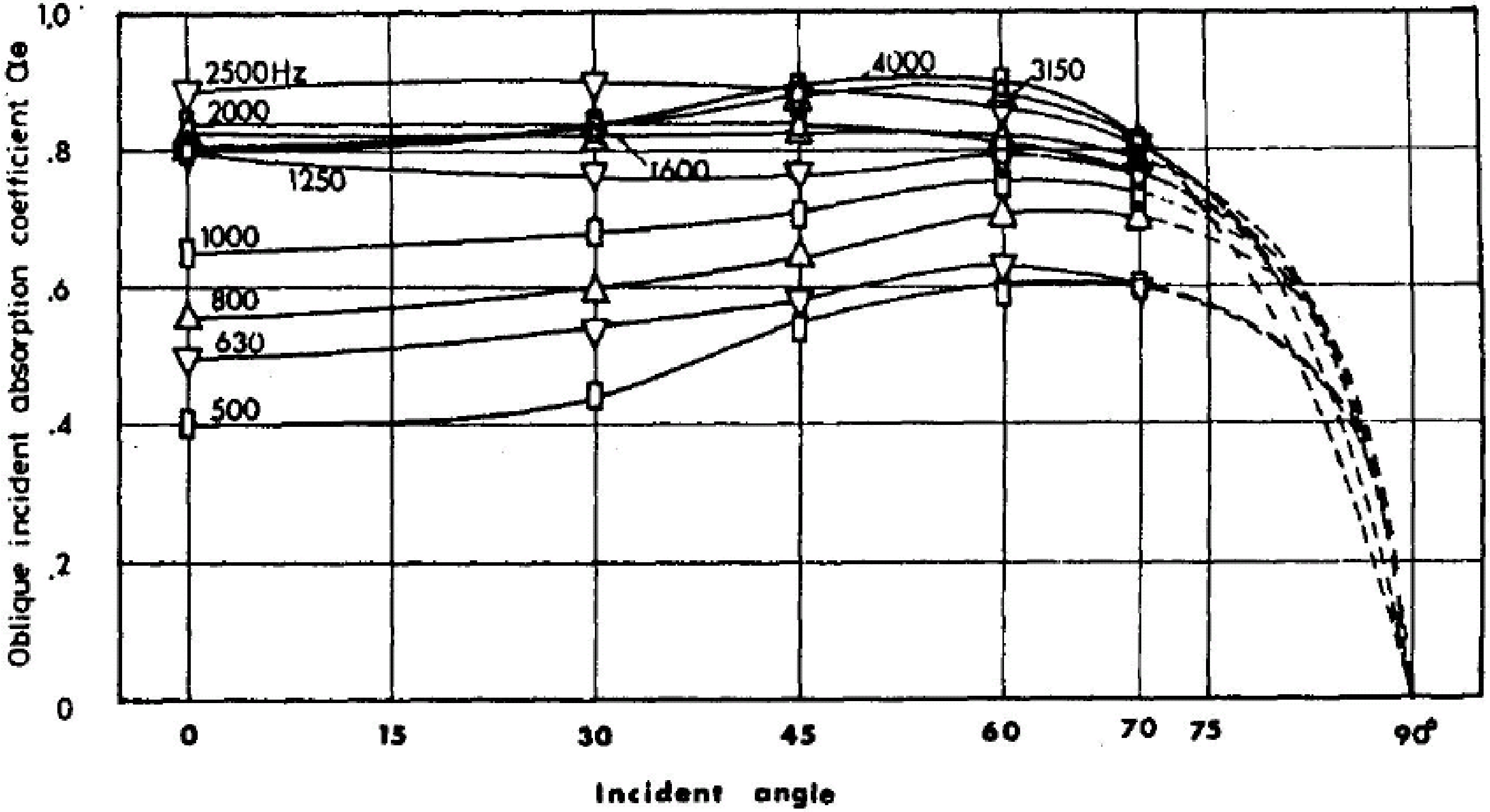
Measurement of angle-dependent sound absorption coefficient

Zhou and Zha 2004 DAGA



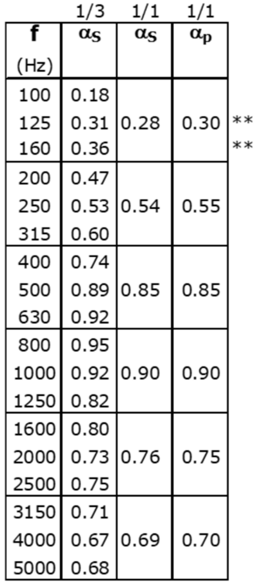
Dependence of absorption coefficient on sound incidence angle

- Yuzawa (1975) studied angle-dependence of sound absorption for glass wool
- The values smaller at 0 ° incidence than at 60 ° incidence.
- The values are zero at grazing incidence (90°).

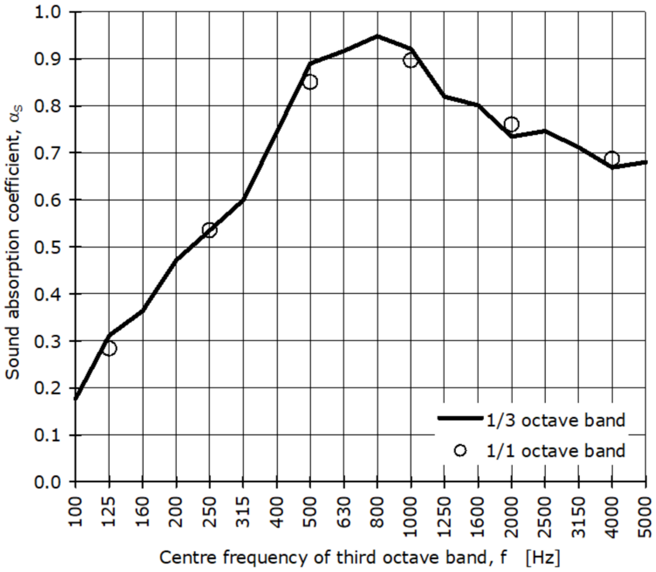


Measurement of sound absorption
Reverberation room method ISO 354

- Statistical absorption coefficient α_S
- It considers all incidence angles unlike impedance tube
- Reverberation time is measured with and without the specimen, which is usually place on the floor
- Room is large (150-250 m^3), highly reverberant, and produces a diffuse field within 100-5000 Hz
- Relative humidity is larger than 60 % during the test
- Specimen size 10-12 m^2
- Values can exceed 1.00. Why?
- Large inter-laboratory differences
- Prediction models are less accurate.

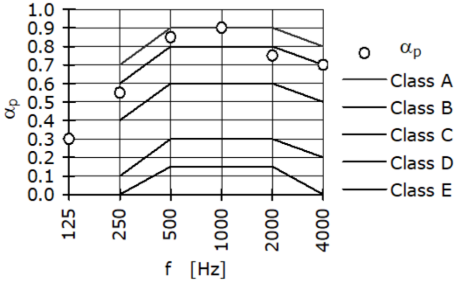


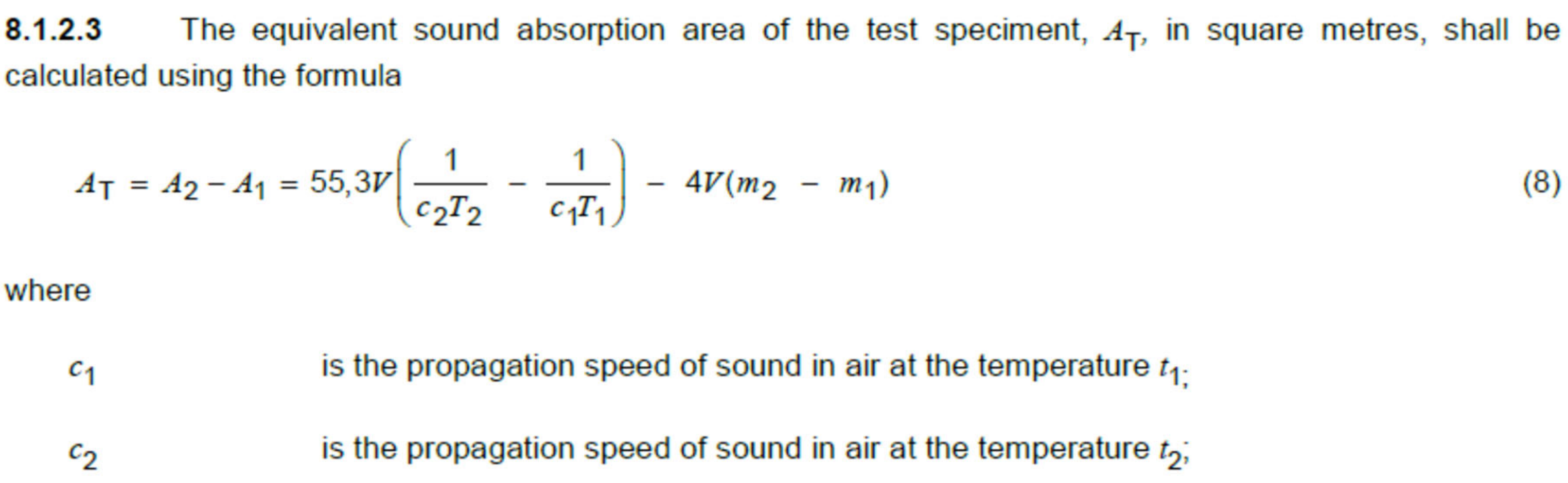
f (Hz)	1/3 α_S	1/1 α_S	1/1 α_p	
100	0.18	0.28	0.30	
125	0.31			**
160	0.36			**
200	0.47	0.54	0.55	
250	0.53			
315	0.60			
400	0.74	0.85	0.85	
500	0.89			
630	0.92			
800	0.95	0.90	0.90	
1000	0.92			
1250	0.82			
1600	0.80	0.76	0.75	
2000	0.73			
2500	0.75			
3150	0.71	0.69	0.70	
4000	0.67			
5000	0.68			



Absorption class (EN ISO 11654)
B

FINAS
Finnish Accreditation Service
T013 (EN ISO/IEC 17025)





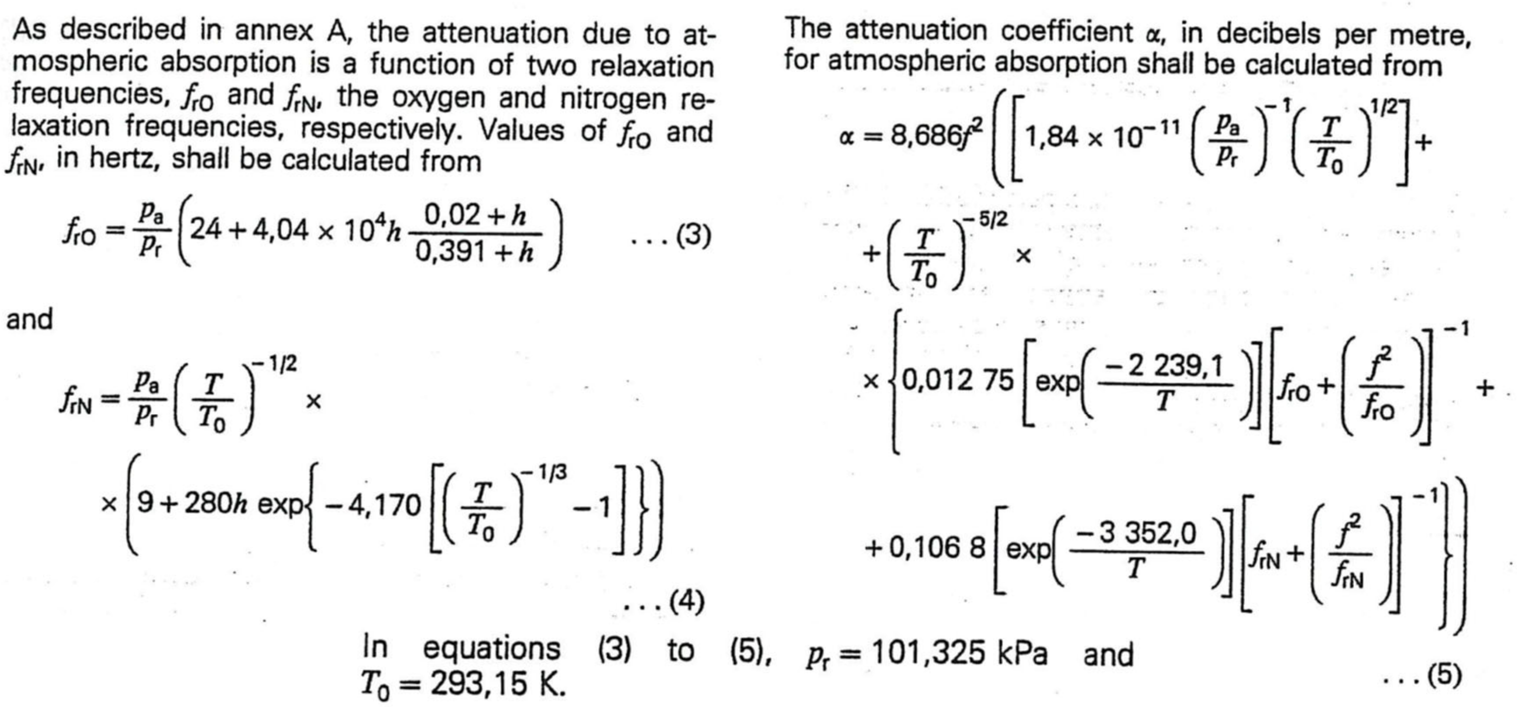
8.1.2.3 The equivalent sound absorption area of the test speciment, A_T, in square metres, shall be calculated using the formula

$$A_T = A_2 - A_1 = 55{,}3V\left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1}\right) - 4V(m_2 - m_1) \qquad (8)$$

where

c_1 is the propagation speed of sound in air at the temperature t_1;

c_2 is the propagation speed of sound in air at the temperature t_2;



As described in annex A, the attenuation due to atmospheric absorption is a function of two relaxation frequencies, f_{rO} and f_{rN}, the oxygen and nitrogen relaxation frequencies, respectively. Values of f_{rO} and f_{rN}, in hertz, shall be calculated from

$$f_{rO} = \frac{p_a}{p_r}\left(24 + 4{,}04 \times 10^4 h \frac{0{,}02 + h}{0{,}391 + h}\right) \qquad \ldots (3)$$

and

$$f_{rN} = \frac{p_a}{p_r}\left(\frac{T}{T_0}\right)^{-1/2} \times \left(9 + 280h \exp\left\{-4{,}170\left[\left(\frac{T}{T_0}\right)^{-1/3} - 1\right]\right\}\right) \qquad \ldots (4)$$

The attenuation coefficient α, in decibels per metre, for atmospheric absorption shall be calculated from

$$\alpha = 8{,}686 f^2 \left(\left[1{,}84 \times 10^{-11}\left(\frac{p_a}{p_r}\right)^{-1}\left(\frac{T}{T_0}\right)^{1/2}\right] + \left(\frac{T}{T_0}\right)^{-5/2} \times \left\{0{,}012\,75\left[\exp\left(\frac{-2\,239{,}1}{T}\right)\right]\left[f_{rO} + \left(\frac{f^2}{f_{rO}}\right)\right]^{-1} + 0{,}106\,8\left[\exp\left(\frac{-3\,352{,}0}{T}\right)\right]\left[f_{rN} + \left(\frac{f^2}{f_{rN}}\right)\right]^{-1}\right\}\right) \qquad \ldots (5)$$

In equations (3) to (5), $p_r = 101{,}325$ kPa and $T_0 = 293{,}15$ K.

$$m = \frac{\alpha}{10\,\lg(\mathrm{e})}$$

m [1/m] is the power attenuation Coefficient.

α [dB/m] is the atmospheric attenuation coefficient defined by ISO 9613-1

p

$\mathbf{p_a}$ [Pa] is the current measured athmospheric pressure

h [%] is the current measured molar concentration of water vapor

T [K] is the current measured temperature

$$\alpha_S = \frac{A_T}{S}$$

Measurement of sound absorption
Reproducibility of ISO 354

- Round Robin test of 23 laboratories was conducted in 2010
- Three materials were tested
  - A: 15 mm hard wool
  - B: 50 mm soft wool
  - C: perforated gypsum
- Inter-laboratory differences (reproducibility values) were significant especially below 250 Hz where the diffuse field conditions are not fulfilled
  - too few modes per 1/3 octave band

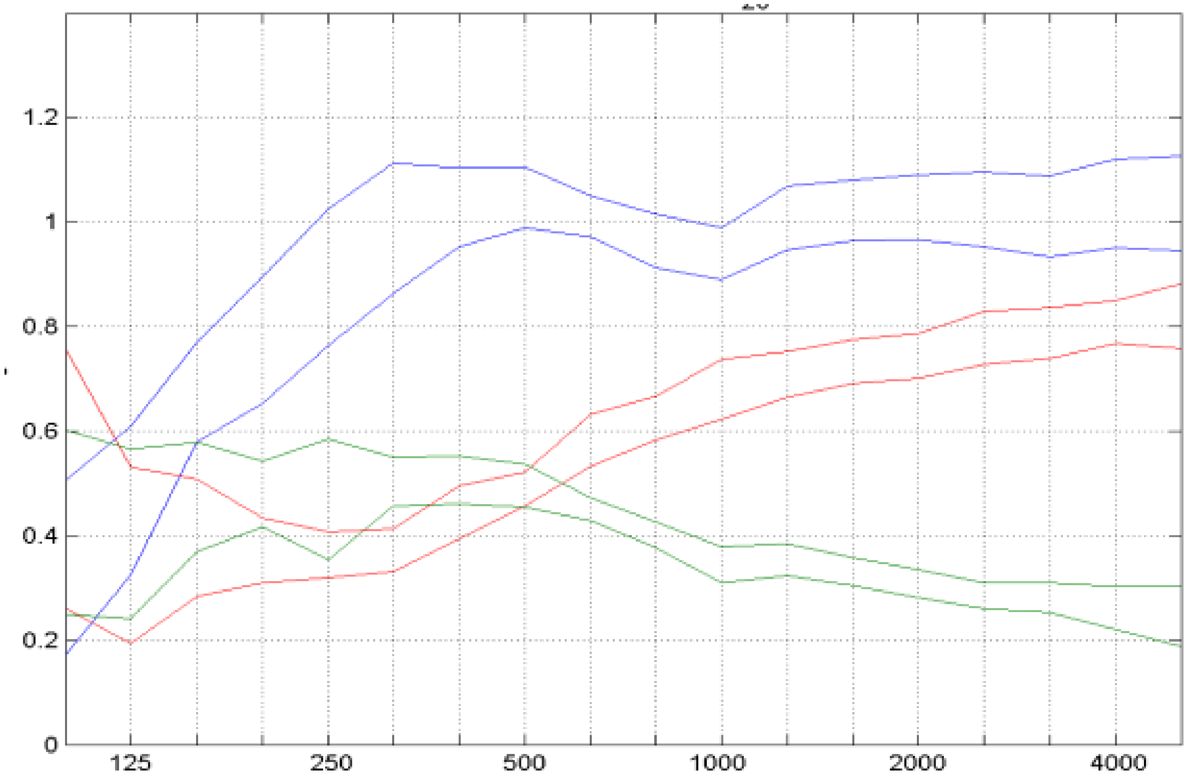


Figure 2. Spread of sound absorption coefficients for selected laboratories. ____ Product A, ____ Product B, ____ Product C.

Andersson N-Å, Forum Acusticum 2011

Prediction of statistical sound absorption coefficient

- For *bulk reacting* absorbents (e.g., mineral wools where sound continues propagating in oblique incidence), the statistical absorption coefficient can be estimated from the angle-dependent sound absorption coefficient α(θ) by:

$$\alpha_{st} = 2\int_0^{\pi/2} \alpha(\theta)\cos(\theta)\sin(\theta)d\theta$$

- Estimation of α(θ) requires other models not presented here.
- For *locally reacting* absorbents (e.g. perforated boards where sound wave is forced to perpendicular direction), the calculation is straightforward:

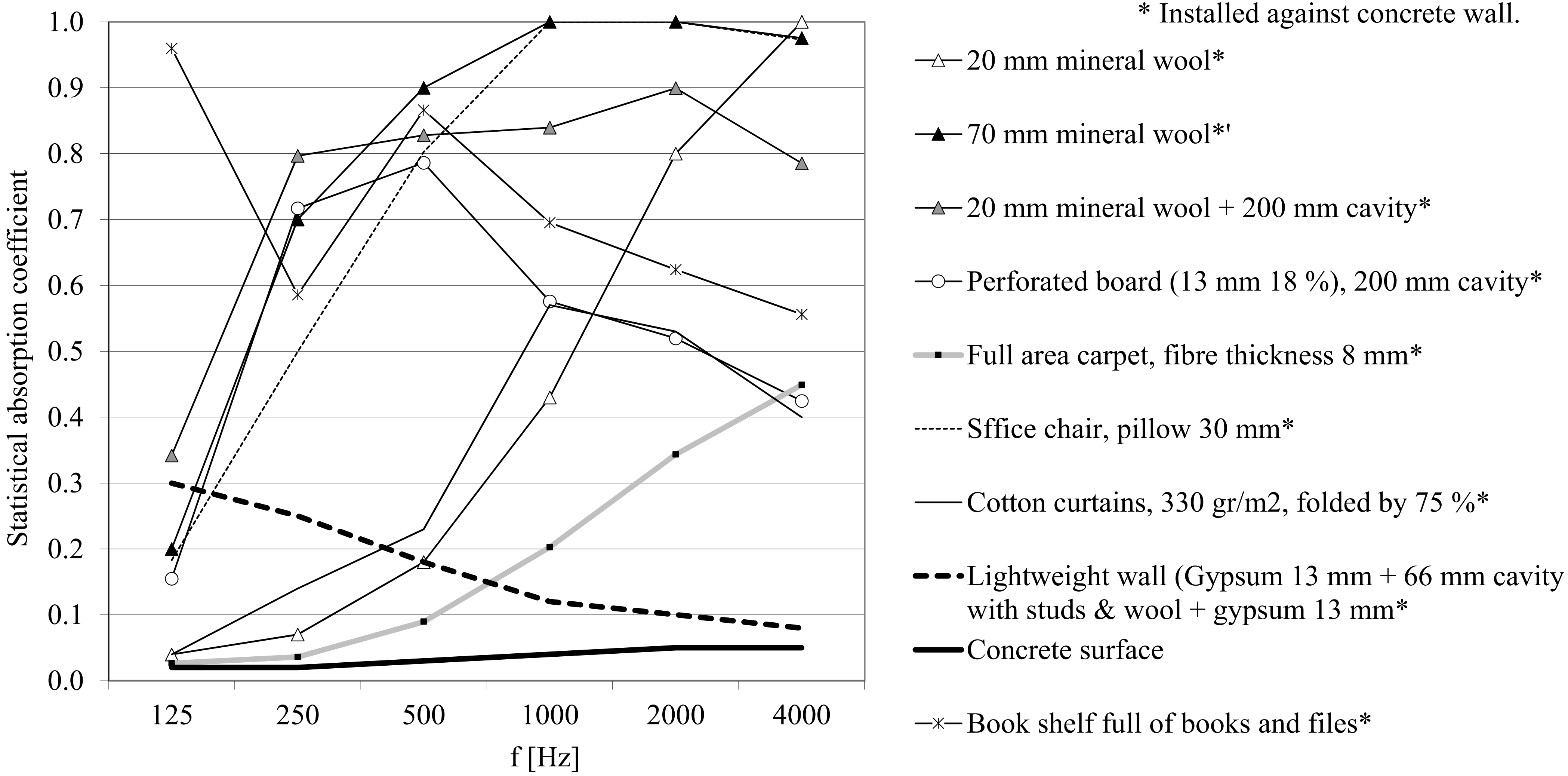
$$\alpha_{st} = 8\frac{z'}{z'^2+z''^2}\left[1-\frac{z'}{z'^2+z''^2}\ln\left(1+2z'+z'^2+z''^2\right)+\frac{1}{z''}\frac{z'^2-z''^2}{z'^2+z''^2}\arctan\left(\frac{z''}{1+z'}\right)\right]$$

  - z' is the normalized surface impedance at normal sound incidence angle

- NOTE: Comparison between predicted and measured values of α_{st} contains large uncertainties since the inter-laboratory differences of ISO 354 are large.

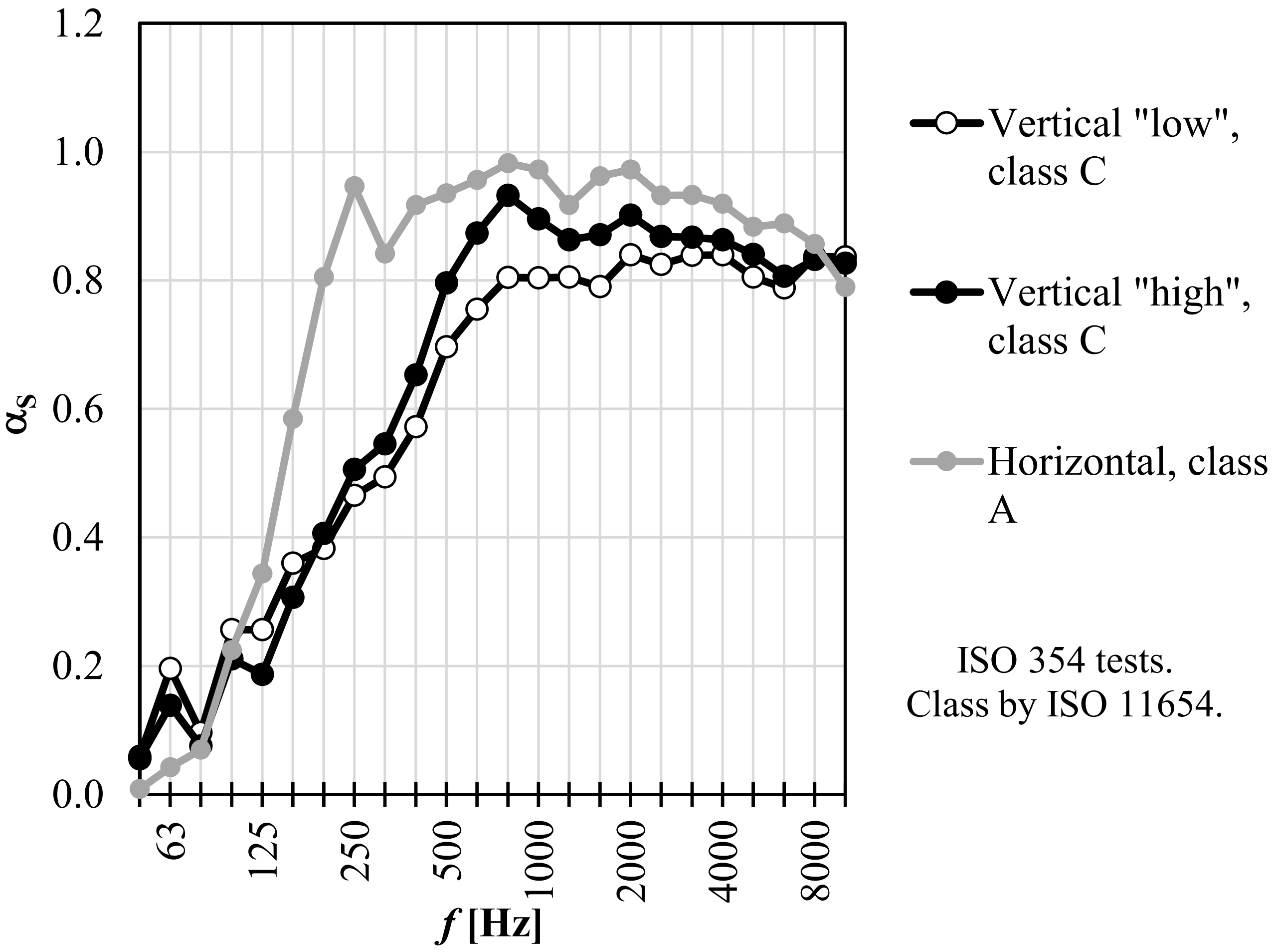
Some selected statistical sound absorption coefficients

MORE VALUES: e.g. http://www.acoustic.ua/st/web_absorption_data_eng.pdf



* Installed against concrete wall.

The effect of spatial position – ISO 354



ISO 354 tests.
Class by ISO 11654.

Vertical "low“
- four screens
- both sided

area 12.8 m^2

Vertical “high“
- four screens
- both sided

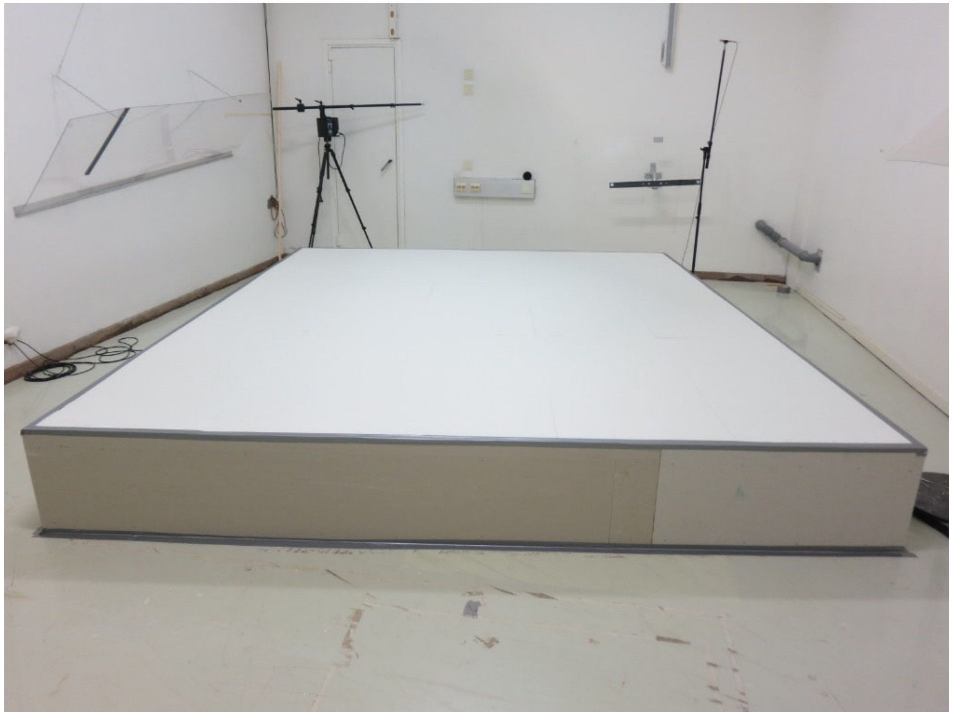
area 12.8 m^2

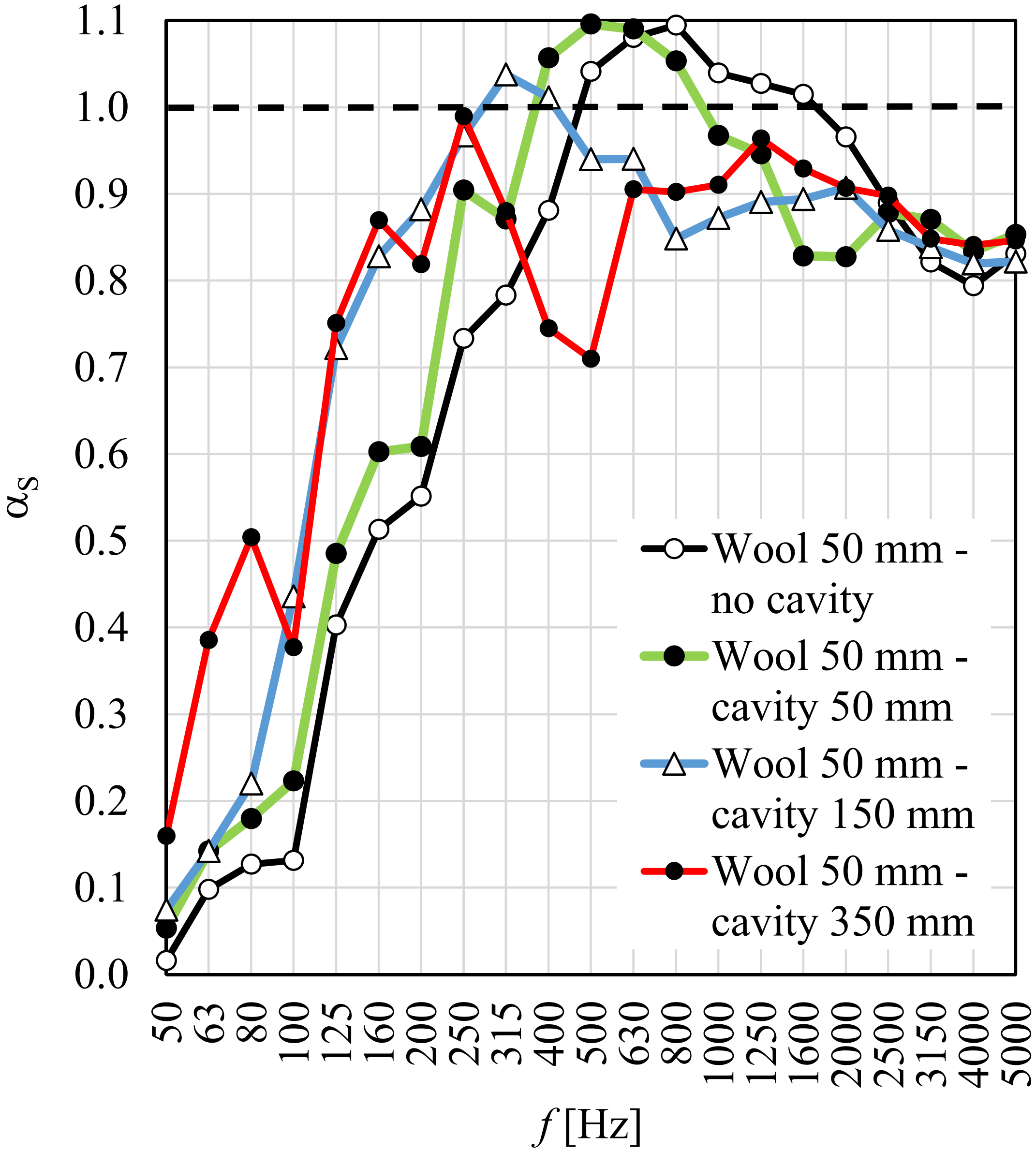
Horizontal
- four screens
- one-sided

area 11.2 m^2

Effect of cavity thickness on 50 mm wool – ISO 354

- Photo corresponds to cavity 350 mm
- Vertical edges air-tight and reflecting
- The results are difficult to predict





Characteristic impedance Z_a

- $\mathbf{Z}_a$ depends on the speed of sound c_a in the material
- **High sound absorption**:
  - small c_a and small impedance
  - imaginary component is small
  - real component is small and matches well with air,
    - $Z_0=r_0c_0=413$ kg/sm^2 in air in 20 °C
  - always poor sound insulation: sound is easily propagating through the material and very little is reflected back.
- **High sound insulation**:
  - large c_a and large impedance
  - imaginary component is large
  - real component can be very small or negligible
  - always poor sound absorption: reflection is strong due to strong impedance mismatch with Z_0
- Any single piece of material cannot be both highly sound absorbing and sound insulating. Hybrid solution is needed to reach them both.

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