Acoustics I: absorption-reflection-transmission

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introduction
introduction

Absorption - Reflection - Transmission

introduction

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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 $\alpha$ and $R$ for plane waves:

$$\alpha = 1 - |R|^2$$
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
  - → friction losses

- placement:
  - where sound particle velocity is high
resonance absorber: type Helmholtz
resonance absorber: type Helmholtz

- absorption mechanism:
  - spring-mass system
    - spring = enclosed air volume
    - mass = oscillating air column
  - maximal absorption at resonance

resonance frequency $f_0$ for stiffness $s$ of the spring and mass $m$:

$$f_0 = \frac{\sqrt{s}}{m} \frac{2\pi}{2\pi}$$
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 $l + \text{end correction } l_{\text{corr}}$
  - $l_{\text{corr}} \approx 0.8R$ (radius of cylinder)
  - with $S$: cross sectional area of cylinder follows:

$$m = \rho_0(l + l_{\text{corr}})S$$
resonance absorber: type Helmholtz

stiffness $s$ of the spring:

- piston acting on air volume
- virtual experiment
  - air cavity with volume $V$
  - piston with area $S$
  - external force $F$ makes piston to sink in by $\Delta l$
resonance absorber: type Helmholtz

force $F$ leads to a pressure change $\Delta P$ with

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

penetration depth $\Delta l$ corresponds to $\Delta V$ 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:

$$f_0 = \frac{c}{2\pi} \sqrt{\frac{S}{V(l + l_{corr})}}$$

- for practical applications: introduction of porous damping in the resonator neck (max. velocity)
  - energy loss
  - lowering of the resonator quality
  - 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)

![Diagram of panel with holes]

- spring-mass resonator where:
  - 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 fine 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

<table>
<thead>
<tr>
<th></th>
<th>variant 1</th>
<th>variant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>plate thickness</td>
<td>3 mm</td>
<td>3 mm</td>
</tr>
<tr>
<td>holes diameter</td>
<td>0.4 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>holes spacing</td>
<td>2 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>distance to wall</td>
<td>100 mm</td>
<td>50 mm</td>
</tr>
</tbody>
</table>

![Graph showing absorption coefficients for two variants](image-url)
micro-perforated absorber

- transparent solutions are possible!
resonance absorber: membrane absorber
resonance absorber: membrane absorber

- absorption mechanism:
  - spring-mass system
    - spring = enclosed air
    - mass = vibrating plate or membrane
  - maximum absorption at the resonance frequency

resonance frequency $f_0$ for stiffness $s''$ per unit area and mass $m''$ per unit area:

$$f_0 = \frac{\sqrt{s''}}{2\pi \cdot m''}$$
resonance absorber: membrane absorber

stiffness of air cavity per unit area $s''$: 

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

with

$I_w$: distance to wall (thickness of air cavity)

and consequently:

$$f_0 = \frac{c}{2\pi} \sqrt{\frac{\rho_0}{m'' I_w}}$$
resonance absorber: membrane absorber

- range of application: low frequency absorber
- design rules:
  - minimum plate area $0.4 \text{ m}^2$
  - minimum plate dimensions $0.5 \text{ m}$
  - air cavity has to be filled with porous absorber
- typical absorption $\alpha \approx 0.6$ in range of $1 \ldots 2$ octaves
- sandwich combinations with porous absorber possible
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

<table>
<thead>
<tr>
<th>Method</th>
<th>Angle</th>
<th>Phase</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kundt's tube</td>
<td>normal</td>
<td>(no)</td>
<td>discrete</td>
</tr>
<tr>
<td>impedance tube</td>
<td>normal</td>
<td>yes</td>
<td>spectrum</td>
</tr>
<tr>
<td>reverb. chamber</td>
<td>diffuse</td>
<td>no</td>
<td>third octaves</td>
</tr>
<tr>
<td>impulse response</td>
<td>arbitrary</td>
<td>yes</td>
<td>spectrum</td>
</tr>
</tbody>
</table>
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)
- From $\frac{p_{\text{max}}}{p_{\text{min}}}$, $\alpha$ 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:

\[
p_{\text{max}} = p_e + p_r = p_e(1 + \sqrt{1 - \alpha})
\]

sound pressure minima: destructive interference:

\[
p_{\text{min}} = p_e - p_r = p_e(1 - \sqrt{1 - \alpha})
\]
Kundt’s tube

from:

\[ n = \frac{p_{\text{max}}}{p_{\text{min}}} \]

follows 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)
- determination of the transfer function between two fixed microphone positions
impedance tube

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

$$H = \frac{p(B)}{p(A)} = \frac{e^{-jk s} + R \cdot e^{-jk(s+2l)}}{1 + R \cdot e^{-j2k(s+l)}}$$
resolved for $R$:

$$R(f) = \frac{e^{-jks} - H(f)}{H(f) - e^{jks}} e^{j2k(l+s)}$$

- from $R$: impedance can be calculated (complete information) and thus $\alpha$
- broadband excitation (white noise, frequency discrimination with help of FFT)
- high quality microphones necessary, calibration with exchanged microphones
reverberation chamber
reverberation chamber

- measurement of the reverberation time $T$ with and without probe material ($10.\ldots12 \text{ m}^2$)
- by usage of empirical relation between $\alpha$ and $T$, $\alpha$ can be determined
- reverberation time formula found by Sabine (diffuse field assumption!):

$$T = \frac{0.16V}{A}$$
reverberation chamber

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

reverberation chamber at Empa:
reverberation chamber

reverberation chamber at Empa:

![Graph showing sound absorption over frequency](image-url)
in situ impulse response measurement
in situ impulse response measurement

- in situ determination of absorption coefficients:
  - 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

element transparent noise barrier:
in situ impulse response measurement

eexample transparent noise barrier:
in situ impulse response measurement

- points to consider:
  - the size of the element under test has to be large enough (critical at low frequencies → Fresnel zone)
  - measurement geometry should allow to separate different contributions (critical at low frequencies)
  - reflection contributions have to be compensated for the additional geometrical divergence
  - relatively large measurement uncertainty for non-flat surfaces
  - standardized procedure: EN 1793-5 (Adrienne)
absorption and impedance
normal incidence
absorption and impedance: normal incidence

situation: plane wave in medium with impedance $Z_0$ hits a medium with $Z_1$
absorption and impedance: normal incidence

incident wave: $p_1$, $v_1$ with

\[
\frac{p_1}{v_1} = Z_0
\]

reflected wave: $p_{\|}$, $v_{\|}$ with

\[
\frac{p_{\|}}{v_{\|}} = Z_0
\]

On the surface holds:

\[
p = p_1 + p_{\|}
\]

\[
v = v_1 - v_{\|}
\]

with:

\[
\frac{p}{v} = Z_1
\]
absorption and impedance: normal incidence

\[ p_I + p_{II} = Z_1 \left( \frac{p_I}{Z_0} - \frac{p_{II}}{Z_0} \right) \]

follows:

\[ \frac{p_{II}}{p_I} = R = \frac{Z_1 - Z_0}{Z_1 + Z_0} \]

\[ Z_1 = Z_0 \rightarrow R = 0, \quad \alpha = 1 \]
\[ Z_1 \gg Z_0 \rightarrow R \rightarrow 1, \quad \alpha \rightarrow 0 \]
absorption and impedance: normal incidence

- porous absorber in front of hard wall:
  - hard termination increases resulting impedance → reduction of the absorption
  - thickness of the absorber $> \lambda/4$ (if possible)
  - thin layers should be mounted with distance to the hard termination
oblique incidence
absorption and impedance: oblique incidence

- locally reacting absorber
  - only sound propagation in the absorber 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

- 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

\(\phi\): angle of sound incidence direction relative to the surface normal direction

- \(Z_1 = \frac{Z_0}{\cos(\phi_g)} \rightarrow R = 0, \ \alpha = 1\)

- \(\phi \rightarrow 90^\circ \rightarrow R \rightarrow -1, \ \text{phase} = 180^\circ, \ \alpha \rightarrow 0\)
typical absorption values
typical absorption values

- stone floor

![Graph showing typical absorption values for stone floor](graph.png)
typical absorption values

- parquet floor
typical absorption values

- carpet, thickness 5mm
typical absorption values

▶ plaster
typical absorption values

- acoustically optimized plaster, thickness 20mm
typical absorption values

- window

![Graph showing absorption values vs. frequency](image-url)
typical absorption values

- heavy curtain
typical absorption values

- egg carton

![Graph showing absorption values over frequency (Hz)]
typical absorption values

- glass fiber panel, thickness 50 mm
typical absorption values

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

![Graph showing typical absorption values](image)
typical absorption values

▶ audience on upholstered chairs

![Graph showing typical absorption values vs. frequency (Hz)]
covers for porous absorbers
covers for porous absorbers

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

- reason for transmission loss?
  - inertia of the mass of the oscillating air columns in the openings
  - acceleration of the air columns has to be low
covers for porous absorbers

frequency response of the degree of transmission of a cover with holes:

![Graph showing the frequency response of transmission for a cover with holes. The x-axis is labeled 'normierte Frequenz' and the y-axis is labeled 'Transmissionsgrad'. The graph shows a downward trend as the frequency increases.]
covers for porous absorbers

- parameters of the cover:
  - $\varepsilon$: 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]

- calculation of the frequency $f_{0.5}$ for a degree of transmission of 0.5:

$$f_{0.5} \approx 1500 \frac{\varepsilon}{l^*}$$
covers for porous absorbers

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