ACOUSTICAL DESIGN

Room acoustics

Matias Remes, M.Sc FISE A acoustics
"Good room acoustics means such conditions, that speech or music performed in the room is heard as beautiful, natural and clear in every part of the room."

M. Sc. U. Varjo 1938
Significance of room acoustics

• The purpose of room acoustical design is to control the propagation, reflection and attenuation of sound within a space
  – Direct sound
  – Reverberant sound (reflections)
  – Useful and harmful reflections
  – Sound attenuation and absorption, diffusion

• Design goals according to the use of space, for example:
  – Speech
    → Good speech distinction (e.g. auditorium) / good speech privacy (e.g. open plan office)
  – Music
    → Appropriate reverberation and sense of space in the audience, stage acoustics which support music making

• Room acoustical design ≠ maximising absorption
  – E.g. in a lecture hall the performer must be able to speak without restraining ones voice and so that the audience can distinguish what is being said
  → Need for both sound absorbing and reflecting surfaces
Reflection of sound

• Sound reflects at simplest as light: angle of incidence = angle of reflection (specular reflection), this applies when
  – Sound wavelength is adequately smaller than the dimensions of the object causing the reflection
  – The reflecting surface is even (not sound scattering) and hard (not sound absorbing)

• Sound reflection is complicated phenomenon and depends on frequency and the properties of the reflective surface
Reflection of sound
Significance of reflections

• Example: sound suddenly stops in a large concert hall
  – Number of reflections occurring within the first 1 s is about 8000

• As the number of reflections increases, there is a reverberant sound field in the space in which the listener cannot distinguish single reflections from one another; in large spaces this occurs after about 100 ms

• Sound field in a space comprises of three distinguishable parts:
  – Direct sound
  – Early reflections
  – Reverberant sound field
Sound field in a room

1. Direct sound from source to listener
2. Early reflections within 20...50 ms after direct sound
3. Gradually attenuating reverberant sound field
Sound field in a room

Direct sound, early reflections and reverberant sound and their relations determine how sound is perceived in a space.
Reflection of sound
Significance of reflections

- Sound perception is affected by the level of reflections, their delay in relation to direct sound and the direction from which they reach the listener
- Strong reflections with adequate delay are heard as separate echoes (*disturbance*)
- If the delay between direct sound and early reflections is appropriate (about 50...80 ms), the reflections increase the **loudness** of sound (perceived sound level) → important in the design of speech and music spaces
- Lateral reflections (reaching the listener's ears from the sides) add to the sense **spatial impression** and broadening of the sound source → crucial in the design of concert halls

The effect of single lateral reflection to sound perception (Barron 2003)
Reflection of sound
The effect of basic room geometry

**Rectangle:**
Lateral reflections occur in the entire space

**Fan-shape:**
Reflections scatter and are directed mainly to the rear part of the space (not in the middle)

**Round:**
Reflections from concave surfaces cause sound to strongly focus on some parts of the space
Reflection of sound
Effect of surface geometry
Reflection of sound
Example: reflecting surfaces in a concert hall
Reverberation time
Significance of reverberation time

- The reverberation time in a space correlates with the perceived **clarity** of speech or music: long reverberation → the syllables in speech or separate musical notes attenuate slowly and mask each other → need for controlling the RT

- On the other hand: RT should not be too low, because in an acoustically "dead" space there are no **useful reflections**!
Reverberation time vs. use

OPTIMUM REVERBERATION at 500/1000 Hz for Auditoriums and Similar Facilities
Reverberation time vs. use

<table>
<thead>
<tr>
<th>Tila</th>
<th>V / hlö [m³]</th>
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</thead>
<tbody>
<tr>
<td>Kokoustita</td>
<td>3...5</td>
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<tr>
<td>Auditorio, teatteri</td>
<td>4...6</td>
</tr>
<tr>
<td>Musiikkiteatteri, ooppera</td>
<td>5...8</td>
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<tr>
<td>Kamarimusikisali</td>
<td>6...10</td>
</tr>
<tr>
<td>Konserttisali</td>
<td>8...12</td>
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<tr>
<td>Kirkko</td>
<td>10...14</td>
</tr>
</tbody>
</table>
Reverberation time
Sabine equation

• Sabine equation:

\[ RT_{60} = 0.161 \frac{V}{A} \quad A = \alpha_1 S_1 + \alpha_2 S_2 + \ldots + \alpha_n S_n = \sum_{i=1}^{n} \alpha_i S_i \]

• \( A \) = absorption area (m²-Sab)
• \( \alpha \) = sound absorption coefficients of material \( i \) (-)
• \( S \) = surface area of material \( i \) (m²)
• Sabine equation assumes that the sound field in the room is diffuse
• Air absorption is not included in the above equation (only significant in large hall-like spaces at high frequencies)
Reverberation time
Diffuse sound field

• Sabine equation assumes a diffuse sound field in the room
• Diffuse sound field (one possible definition): equal sound pressure level at each point in the room
  – Condition is satisfied in simple cubic spaces with dimensions $\gg$ sound wavelength and with hard sound reflecting surfaces (reverberant space, not too damped)
  – Condition is not satisfied is the space is large and highly absorbing or if all the absorption material is situated on one surface while the other surfaces are sound reflecting
• Sabine equation can, however, be applied in most spaces with sufficient accuracy
Room modes

- **Room mode** = characteristic resonance of the room, of which the sound field in a room is comprised
- Three types of modes: axial, tangential, oblique
- The amount and spacing of room modes changes with frequency
- At low frequencies there are only a few room modes sparsely spaced → result: reverberation time and sound level vary considerably in different points of the room (consider the placement of a subwoofer in a living room)
- At high frequencies the number of room modes gets high and they are so tightly-spaced, that single room modes cannot be distinguished → sound field approaches the idealisation of **diffusivity**
- The modal frequencies in a rectangular room can be calculated; see e.g. RIL 243-1-2007
Room modes, effect on RT

- Standard deviations of reverberation times measured in 50 empty rooms in a dwelling.
- Each point represents the reverberation time calculated from measurement conducted in 12 points in a room.
- In small rooms sound field is not diffuse at low frequencies, thus the variance in reverberation time increases towards low frequencies.
Absorption vs. reflection

- Acoustical treatment
- Absorption
- Reflection
- Diffusion

Temporal response:
- Direct sound
- Attenuated reflection
- Specular reflection

Spatial response:
- 6 dB
- 10 msec
- Diffusion
- 10 dB

Time - msec
Sound absorbing materials

General

- Sound absorption – three absorption mechanisms:
  - Porous materials (P)
  - Resonant absorbers (R)
  - Membrane / panel absorbers (M)
- Typical absorption behaviour in the figure
Sound absorbing materials
Porous materials – effect of placement

• Sound absorption of porous materials is based on thermal losses caused by friction in the pores of the material

• At the surface of a rigid structure (e.g. wall, roof) sound pressure is at maximum and particle velocity at minimum

• Maximal particle velocity occurs at 1/4\(\lambda\) distance from the surface of the structure
  
  → to achieve effective absorption, there should be absorbing material at this distance
Sound absorbing materials
Porous materials

• Porous material absorbs sound most effectively when the thickness of the material is: \( d \geq \frac{1}{4\lambda} \)
• Example:
  mineral wool 20 mm: \( 20 \text{ mm} \geq \frac{1}{4\lambda} \Leftrightarrow \lambda \leq 80 \text{ mm} \Leftrightarrow f \geq 4290 \text{ Hz} \)
• Note: low-frequency sounds have long wavelength (e.g. 100 Hz \( \Leftrightarrow \) 3.4 m) \( \rightarrow \) thin layers of porous material do not much absorb low frequencies!
Sound absorbing materials
Porous materials

- Absorption coefficients of mineral wool
- Note the effect of suspension height
Sound absorbing materials
Porous materials – examples of use
Sound absorbing materials
Perforated panels (resonant absorbers)

• Perforated panels act as resonant absorbers; the absorption is based on mass-spring resonance caused by the air in the hole acting as mass and the air in the background airspace acting as spring
• Absorption is most effective at the resonance frequency of the mass-spring system
• Resonance frequency and absorption coefficient are affected by:
  – Thickness of the airspace and filling with porous material
  – Size, amount and geometry of holes
  – Thickness of the panel
• Resonance frequency is typically at mid frequencies (500-1000 Hz), below and above which absorption coefficient decreases
• Absorption coefficient of perforated panel absorbers can be increased by filling the background airspace with porous absorption material
Sound absorbing materials
Perforated panels

![Graph showing sound absorption properties of perforated panels with different perforation rates and air gap distances. The x-axis represents the center frequency in Hz, ranging from 125 to 4000 Hz. The y-axis represents the absorption ratio. The graph includes lines for perforation rates of 7% with an air gap of 30 mm, 17% with an air gap of 30 mm, 17% with an air gap of 200 mm, and 17% with an air gap of 200 mm and 50 mm mineral wool.](image-url)
Sound absorbing materials
Panel absorbers

- Structure of a panel (or membrane) absorber: a closed airspace behind an impervious (not perforated) panel which can be filled with porous material.

- Absorption coefficient is highest at low frequencies around the resonance frequency.

- Resonance frequency depends on the surface mass of the panel and thickness of the airspace:

\[ f_0 = \frac{60}{\sqrt{m \cdot d}} \]

- Note: at high and mid frequencies panel absorbers are sound reflecting structures!
Sound absorbing materials
Panel absorbers

![Graph showing sound absorption properties for different materials.]

- Kipsilevy 13 mm, mineraalivilla 50 mm
- Kipsilevy 13 mm, mineraalivilla 100 mm
- Kipsilevy 13 mm, ilmaväli 100 mm
- 2 x kipsilevy 13 mm, mineraalivilla 50 mm
Sound absorbing materials
Miscellaneous materials and structures

![Graph showing sound absorption properties of different materials]

- 20 mm mineraalivilla, liimattu betonia vasten
- 70 mm mineraalivilla, liimattu betonia vasten
- 20 mm mineraalivilla, takana 200 mm ilmaväli
- Rei’itetty kipsilevy, takana 200 mm ilmaväli, reikääla 18 %
- Kokolattiamatto, kuidun paksuus 8 mm
- Pehmeä toimistotuoli, tynyn paksuus 30 mm
- Puuvillaverhot, 330 gr/m², laskostettu 75 % pinta-alasta
- Kevytväliseinä (kipsi + villa + kipsi)
- Betoni- tai tiiliseinä, kovapintainen lattia
- Kirjahylly, täynnä tavaraa
Rating of absorption materials
Measurement of absorption coefficient

- Absorption coefficient is a frequency-dependent quantity
- Measured usually in one-third bands 100-5000 Hz in a reverberation chamber (ISO 354)
- Different single-number descriptors can be calculated from the measurement results (e.g., Absorption Class, ISO 11654)
Rating of absorption materials
Absorption classes

- According to EN 11654 (classes A-E)
- Measured absorption coefficient is compared to a reference curve, the sum of unfavourable deviations ≤ 0,10
- Note: definition of absorption class does not consider frequencies below 200 Hz!
Sound scattering structures (diffusors)

[Salter et al. 1999]
Speech parameters

STI

• Objective parameters describing **speech intelligibility**:  
  – Speech Transmission Index STI  
  – Rapid Speech Transmission Index RASTI

• STI depends on the sound level of speech, reverberation time, reflections, distance between speaker and listener and background noise level

• STI is based on distinction of speech syllables in a space, value range 0...1  
  – STI = 0 → none of the syllables are heard correctly  
  – STI = 1 → all the syllables are heard correctly

• In auditoria and other speech spaces the goal is to achieve a high value of STI (good speech intelligibility), whereas in spaces such as open plan offices the goal is as low STI-value as possible (good speech privacy between work stations)
## Speech parameters

### STI

<table>
<thead>
<tr>
<th>STI alue</th>
<th>Puheen erotettavuus</th>
<th>Esimerkkejä tiloista</th>
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<tbody>
<tr>
<td>Alle 0,30</td>
<td>Kelvoton</td>
<td>Kivikirkko</td>
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<td>0,30–0,45</td>
<td>Huono</td>
<td>Kaikuisa auditorio tai konserttisali</td>
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<td>0,45–0,60</td>
<td>Välttävä</td>
<td>Hyvin suunniteltu suuri auditorio</td>
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<tr>
<td>0,60–0,75</td>
<td>Hyvä</td>
<td>Hyvin suunniteltu luokkahuone tai pieni auditorio</td>
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<tr>
<td>Yli 0,75</td>
<td>Erinomainen</td>
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### VIEREKÄISTEN TOIMITOTYÖPISTEIDEN VÄLILLÄ

<table>
<thead>
<tr>
<th>STI alue</th>
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<th>Esimerkkejä tiloista</th>
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<tbody>
<tr>
<td>Alle 0,05</td>
<td>Täydellinen</td>
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<td>Erittäin hyvä</td>
<td>Normaalisti eristettyjen työhuoneiden välillä, ovet kiinni</td>
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<td>Työhuoneiden välillä, ovet auki käytävälle</td>
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<td>Kohtalainen</td>
<td>Avotoimisto, akustisesti hyvin toteutettu</td>
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<td>0,55–0,70</td>
<td>Välttävä</td>
<td>Avotoimisto, akustisessa toteutuksessa pieniä puutteita</td>
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<td>0,70–0,85</td>
<td>Huono</td>
<td>Avotoimisto, akustikassa merkittävä puutteita</td>
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<tr>
<td>Yli 0,85</td>
<td>Ei ole</td>
<td>Avotoimisto, akustinen suunnittelu puutuu</td>
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Screens

- Screen: wall element for dividing space, does not extend to ceiling height, thus sound is diffracted over the screen.
- Applications: speech blocking in open plan offices etc., noise blocking in factories, road noise barriers, sound absorption if the screen is acoustically treated.
- The sound attenuation of a screen, \( D \) [dB], is determined as *insertion loss*: \( D = L_{p,1} - L_{p,2} \)

  where \( L_{p,1} \) is the measured sound pressure level at listener position without the screen and \( L_{p,2} \) is the SPL with the screen in place.
Screens

• The effect of screen height on sound attenuation (calculated; see RIL 243-1-2007)
• Solid lines are sound reduction indexes (mass law values) of two different walls
• Note: the sound attenuation of a solid wall is always higher than that of any screen
• The values apply to free-field i.e. no reflections; because of reflections, in real rooms the attenuation is lower, screens mainly attenuate the direct sound from source to listener but have little impact on reverberant sound
• Attenuation is especially affected by sound absorption of the ceiling and wall surfaces close to the screen
Screens

Effect of sound reflections on attenuation

- Example: factory hall with screen constructed around a work station with noisy activity
- Although the screen height was 6 m, the screen only attenuated sound by 1dB(A) to its surroundings
- Reasons:
  - Ceiling and wall surfaces were sound reflecting, reverberation time of the hall was high
  - Screen height was only about 1/3 of the room height
Classrooms

- Most important room acoustical consideration: good **speech intelligibility** from the teacher to pupils
- Some guidelines from SFS 5907:
  - Reverberation time 0.5...0.8 s, STI ≥ 0.70
  - When class A sound absorbing material is used (absorption coefficient > 0.9), the centre part of the ceiling should be left sound reflecting (absorption coefficient 0...0.20), from which sound is reflected to the mid and rear part of the room → this improves speech intelligibility
  - If class C material is used, the material can be positioned on the whole ceiling surface because the material also reflects sound
  - The amount of class A material needed is about 70 % of the floor area and for class C material correspondingly 100 %
  - Absorption material should also be placed on the walls to avoid distracting flutter echoes
Open plan offices

- Acoustics is a key component of indoor climate in open plan offices
- The most distracting sound is **speech** heard from surrounding work stations
- Acoustical design goal is to maximise speech privacy between work stations, thus **minimise speech intelligibility** (note: opposite goal to e.g. classrooms)
- In open plan offices there are no sound insulating partitions, but only screens → speech privacy must be mainly achieved by means of room acoustics

*Figure 1. How often are these environmental factors harmful at your workplace?*

[Haapakangas et al. 2007]
Open plan offices

• Good speech privacy between work stations requires that three factors are considered:
  1. Direct sound path between work stations must be truncated using **screens**, preferrable screen height is > 150 cm
  2. Sounds reflecting from room surfaces must be adequately attenuated → sufficient amount of **sound absorbing material** correctly positioned on the surfaces of the room (ceiling, floor, walls, screens, furnishings)
  3. **Masking sound** → sufficiently high background sound level in the space to mask speech sounds, preferrably implemented artificially using loudspeakers to produce the masking sound, recommende sound level 40...45 dBA
Auditoria

• Most important room acoustical consideration: good speech intelligibility

• Essential to good speech intelligibility:
  – Appropriate *reverberation time* (remember the masking effect from previous slides…)
  – **Direct sound path** from speaker to listener (other audience members must not be in the way to block the direct sound)
    → raised floor on the audience area in large halls
  – Directioning of *early reflections* towards the audience (to strengthen the direct sound and, thus, improve speech intelligibility)
    → positioning of sound reflecting and absorbing surfaces
Concert halls and music performance spaces

• Some things to consider…
  – What is the hall used for and by which kind of performers?
    Classical/rock/chamber/symphony/theatre/other?
  – Different uses → (room) acoustical variability? Compromise?
  – Acoustics experienced by the performers vs. acoustics experienced by the performers?
  – Also other than room acoustical considerations! (e.g. sound insulation, noise control)
  – Volume, basic shape, seating capacity…

• **Subjective parameters**: characteristics of sound that can be perceived in a hall (e.g. ”warmth”, ”intimacy”)

• **Objective parameters**: measurable quantities which try to describe the subjective perceptions