8 Sound insulation in buildings

ELEC-E5640 - Noise Control P

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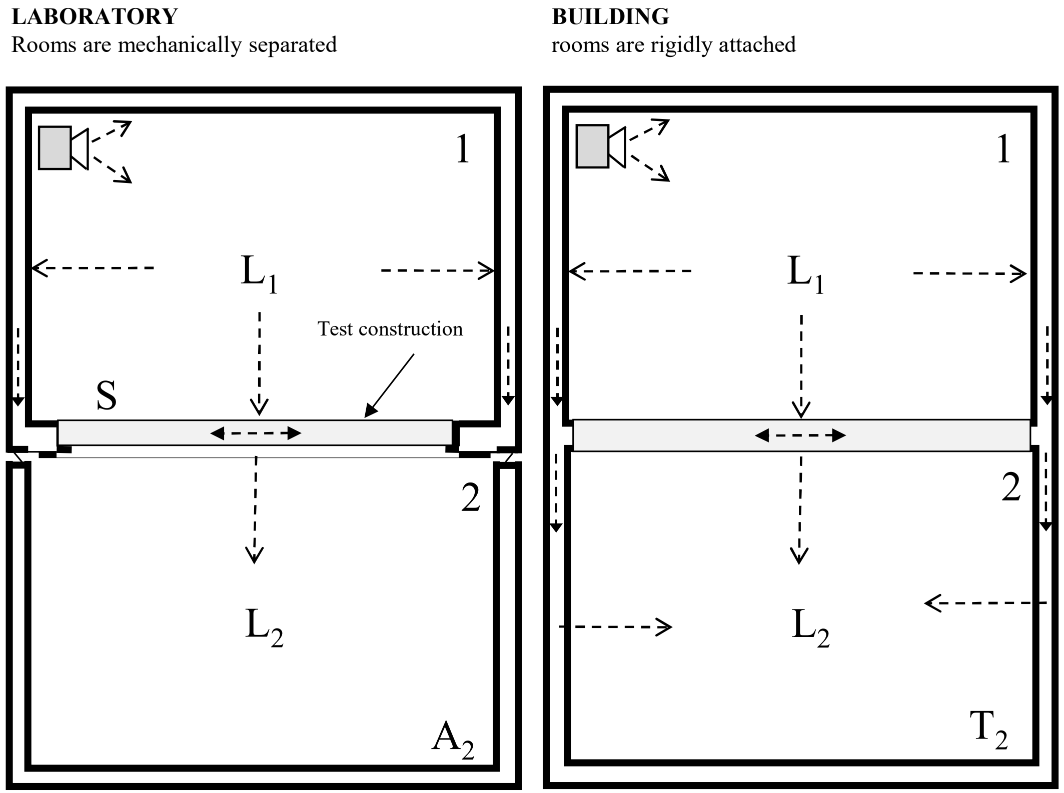
Airborne sound insulation

- ASI means how well the constructions between rooms 1 and 2 are implemented w.r.t. the sound transmission of airborne sounds.
- Physical quantity in building is *standardized SPL difference*, $\mathbf{D_{nT}}$ [dB]. It depends on
  1. Sound reduction index, **R [dB]**, of the separating construction (SC) in laboratory, when all flanking sound is suppressed
  2. Joints around the SC
  3. Sound leaks in the SC
  4. Flanking transmission passing the SC
  5. Other airborne paths
- In the same space, $D_{n,T}>R$, if $V>32$ m^3:

$$R - D_{n,T} = 10 \cdot \log_{10}\left(\frac{3.13 \cdot S}{V_2}\right)$$



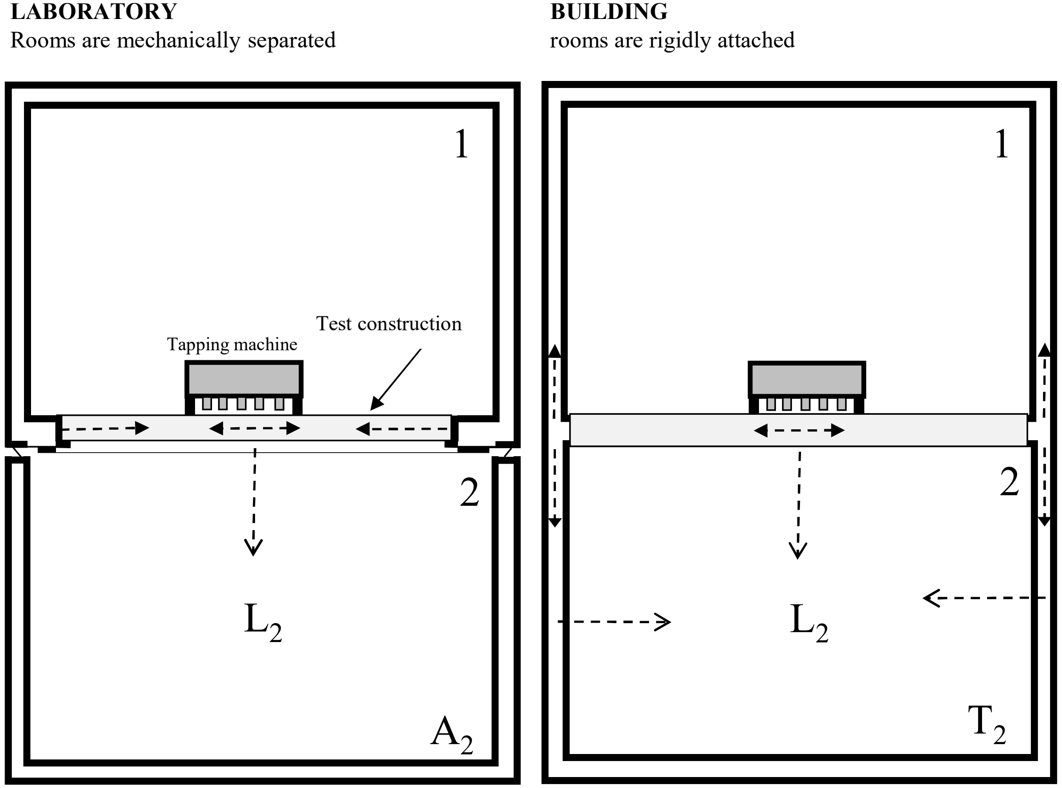
$$R = L_{p,1} - L_{p,2} + 10 \cdot \log_{10}\left(\frac{S}{A_2}\right) \qquad D_{n,T} = L_{p1} - L_{p2} + 10 \cdot \log_{10}\left(\frac{T_2}{T_0}\right)$$

- $L_{p,1}$ [dB] SPL in room 1
- $L_{p,2}$ [dB] SPL in room 2
- S [m^3] area of SC
- A_2 [m^2] absorption area of room 2
- T_2 [s] reverberation time of room 2
- T_0=0.5 s

Impact sound insulation

- It means how well the constructions between rooms 1 and 2 are implemented w.r.t. the SPL produced by tapping machine in room 2.
- Physical quantity in building is *standardized impact SPL*, **L'$_{nT}$** [dB]. It depends on
  1. *Normalized impact SPL* of the separating construction (SC) in laboratory, **L_n** [dB], when all flanking sound is suppressed
  2. Joints around the SC,
  3. Flanking transmission passing the SC
- In the same space, $L_n > L_{n,T}$, if V > 32 m^3:

$$L_n - L'_{n,T} = 10 \cdot \log_{10}\left(\frac{V_2}{31.3}\right)$$



$$L_n = L_2 + 10 \cdot \log_{10}\left(\frac{A_2}{A_0}\right)$$

$$L'_{n,T} = L_2 - 10 \cdot \log_{10}\left(\frac{T_2}{T_0}\right)$$

- L_2 [dB] on äänitaso vastaanottohuoneessa 2
- A_2 [m^2] on vastaanottohuoneen absorptioala
- T_2 [s] on vastaanottohuoneen jälkikaiunta-aika
- T_0=0.5 s ja A_0 = 10 m^2

Regulations

- Sound insulation in buildings is regulated by a **acoustic environment decree** involving at least one apartment and another apartment of any use
- Additional target values can be found from the **acoustic environment instructions** (2018) for schools, offices, health-care buildings, etc.
- Voluntary target values are also found in SFS 5907:2004.
- The regulated values in buildings are presented by a single-number quantity, weighted sound level difference $\mathbf{D_{nT,w}}$.
  - During years 1998–2017, a *single-number quantity* weighted sound reduction index, $\mathbf{R'_w}$, was used and it still concerns buildings licenced before 2018.
- The component properties tested in laboratory are still reported with $\mathbf{R_w}$. The use of different symbols in in buildings and laboratory facilitates the communication.

Decree 796-2017 of the Ministry of the Environment on the acoustic environment of buildings. 24 November 2017, Helsinki, Finland.

- https://www.finlex.fi/fi/laki/alkup/2017/20170796
- In Finnish.

Ministry of the Environment (2018). **Instructions** on the acoustic environment of buildings, Helsinki, Finland.

- http://www.ym.fi/download/noname/%7B2852D34E-DA43-4DCA-9CEE-47DBB9EFCB08%7D/138568
- In Finnish.

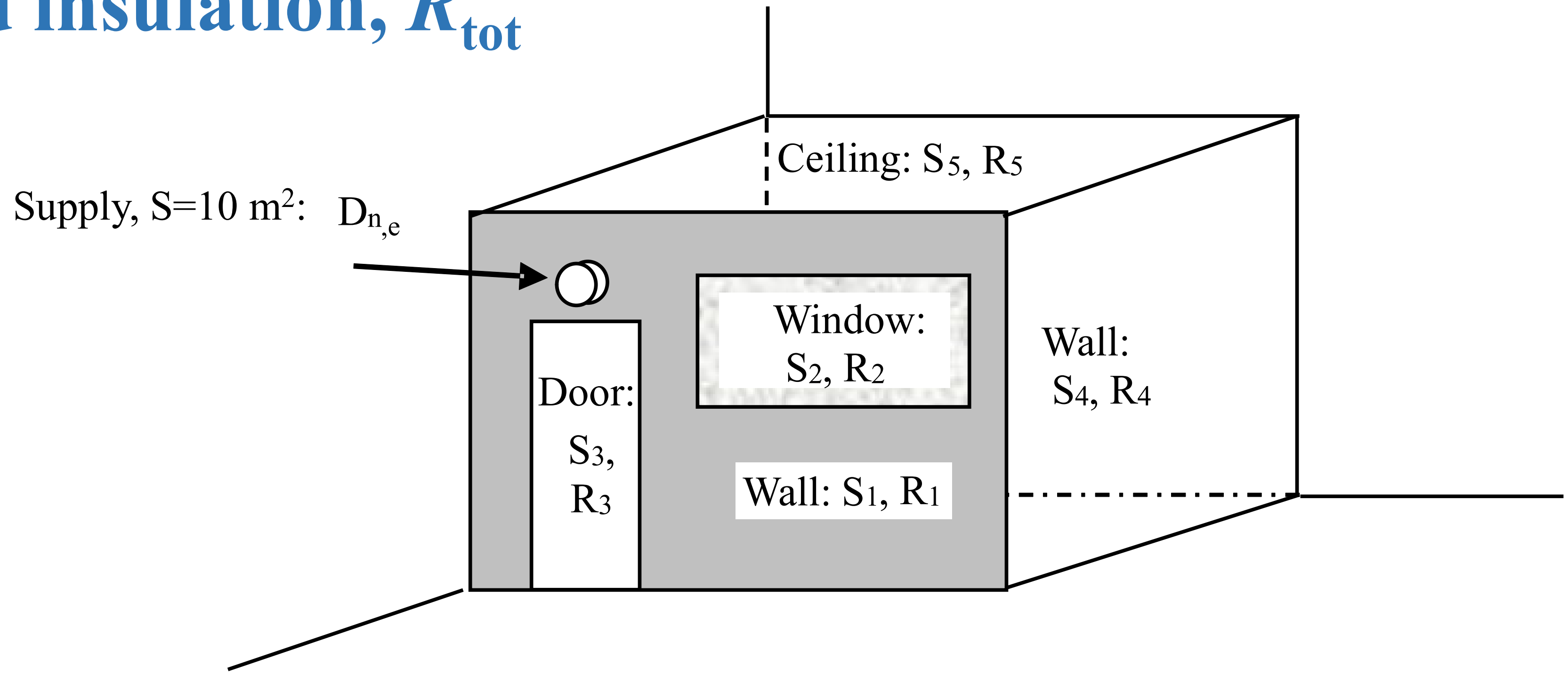
Decree (mandatory)

Room type	**Smallest allowed $D_{nT,w}$ [dB]**
Between residential dwellings and between accommodation rooms	55
From stairway to abovementioned spaces	39

Instruction (mandatory unless otherwise decided)

Room type	**Smallest allowed $D_{nT,w}$ [dB]**		
	To the surrounding spaces in general	To another similar room [b], when they are separated by a door	To the stairway when it is separated by a door
General teaching room [a]	44	42	34
Music teaching room	60	52	44
Teaching room in day-care center	44	42	34
Meeting room	48	42	34
Nursing room such as operation room, reception room, therapy room, rest room [c] [d]	48	42	39
Patient room in hospital or health center [d]	48	42	34
Exercise room	57	48	42
Office room [d]	40	40	30
Between two separate companies in an office buildi	52	-	-
Working room of social worker, psychologist, health nurse or student advisor in a school	48	42	39

Total sound insulation, R_{tot}



- S_i [m²] is the area of component i
- R_i [dB] is the SRI of component i

$$R_{tot} = 10\log_{10} \frac{\sum_i S_i}{\sum S_i 10^{-R_i/10}}$$

8.1

Door 10M x 21M.

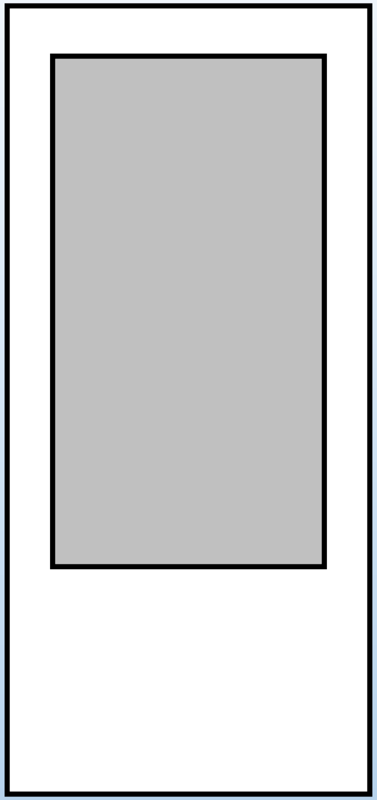
Glazing 7M x 14M.

Door Rw36dB.

Glazing Rw47dB.

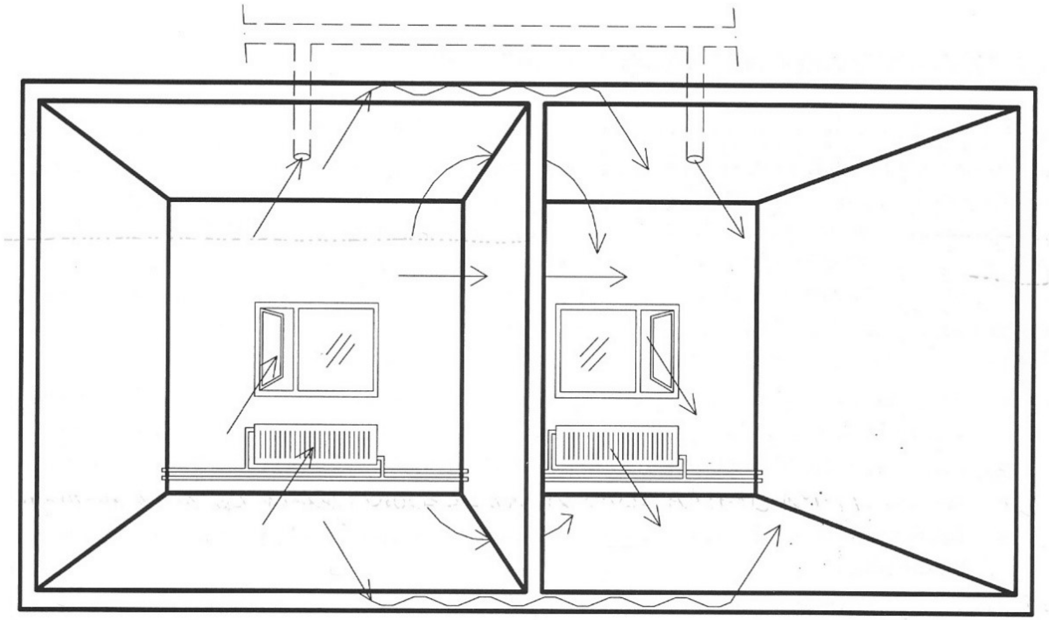
Total sound insulation?

$$R_{tot} = 10 \lg \frac{\sum_i S_i}{\sum S_i 10^{-R_i/10}}$$



Sound insulation inside buildings

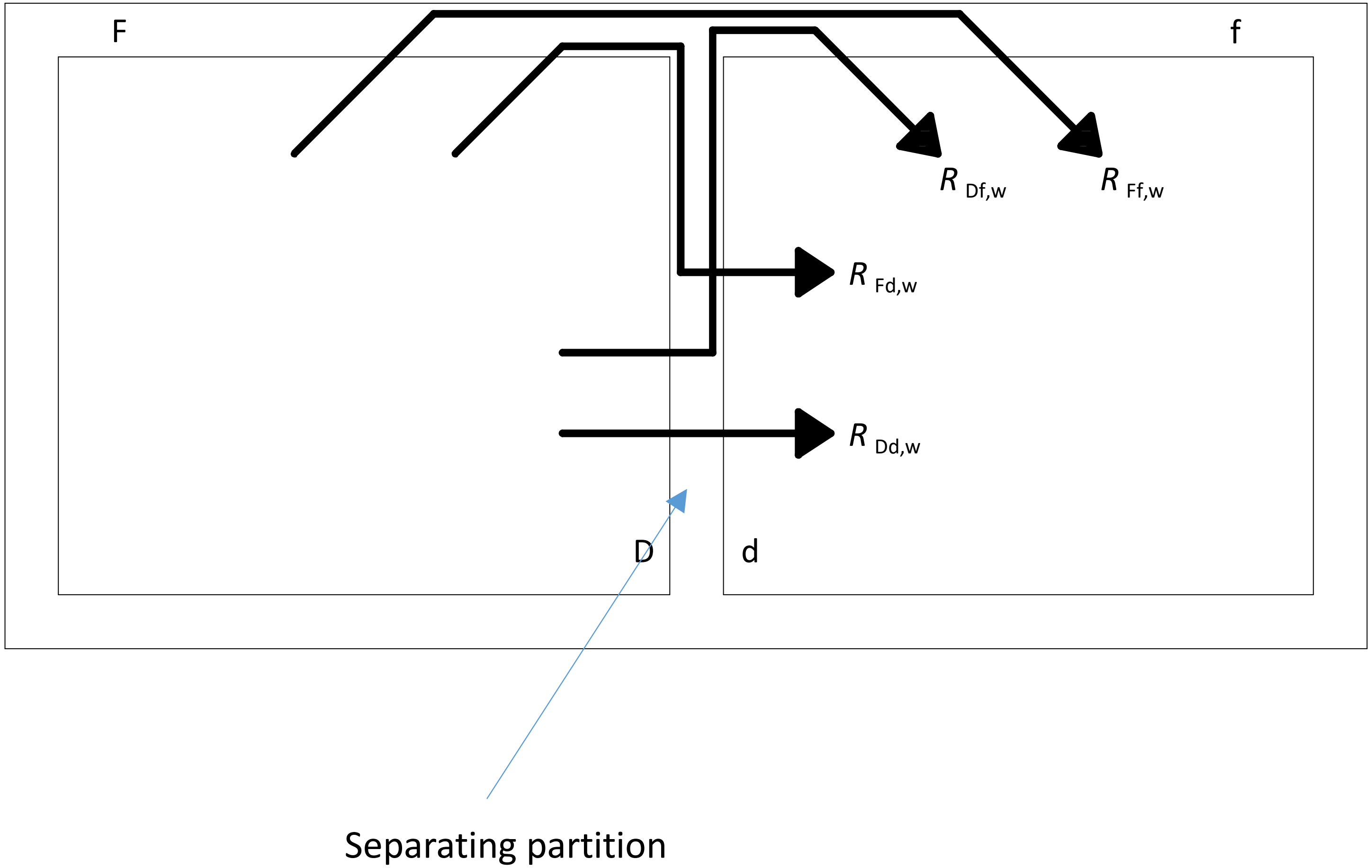
Sound transmission paths:



- **Direct sound** through the separating element
- **Structural transmission** via flanking paths
  - floor, ceiling, walls
  - columns and flues
- **Air paths**
  - via windows or doors
- **HVAC**
  - via duct walls
  - via ducts
- **Slits**

Modeling of airborne flanking transmission – 13 paths

- One direct path (Dd).
- Four first order flanking paths (Ff)
- Four second order flanking paths (Df)
- Four third order flanking paths (Fd)
- The separating partition has an area S_s
- The separating partition has four joints of lenght l – joint is the line connecting the flanking surfaces and the partition



EN 12354-1 simplified method for calculating the apparent weighted airborne sound reduction index R'_w

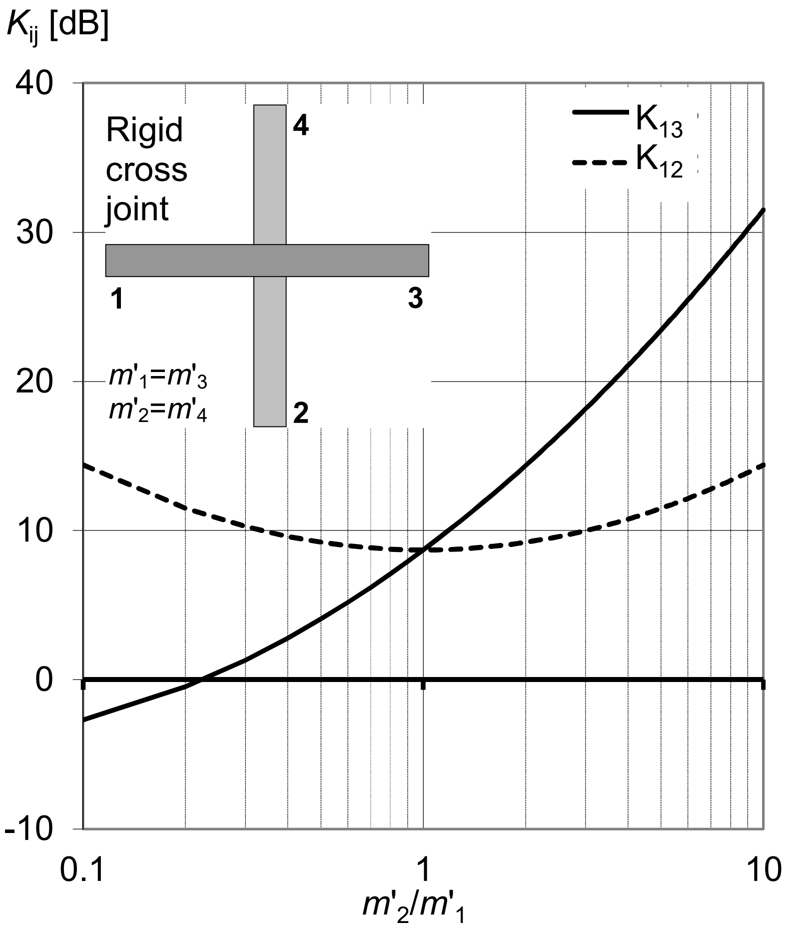
- R_s , R_F and R_f [dB] are the laboratory values of the concrete structures in laboratory
- ΔR_{Dd} [dB] is the improvement of R_w obtained with a lining wall in laboratory conditions.
- S_s [m^2] is the area of the separating wall
- K [dB] is the coupling loss factor
- l_f [m] is the length of the joint under question
  - either the height or the width of separating construction

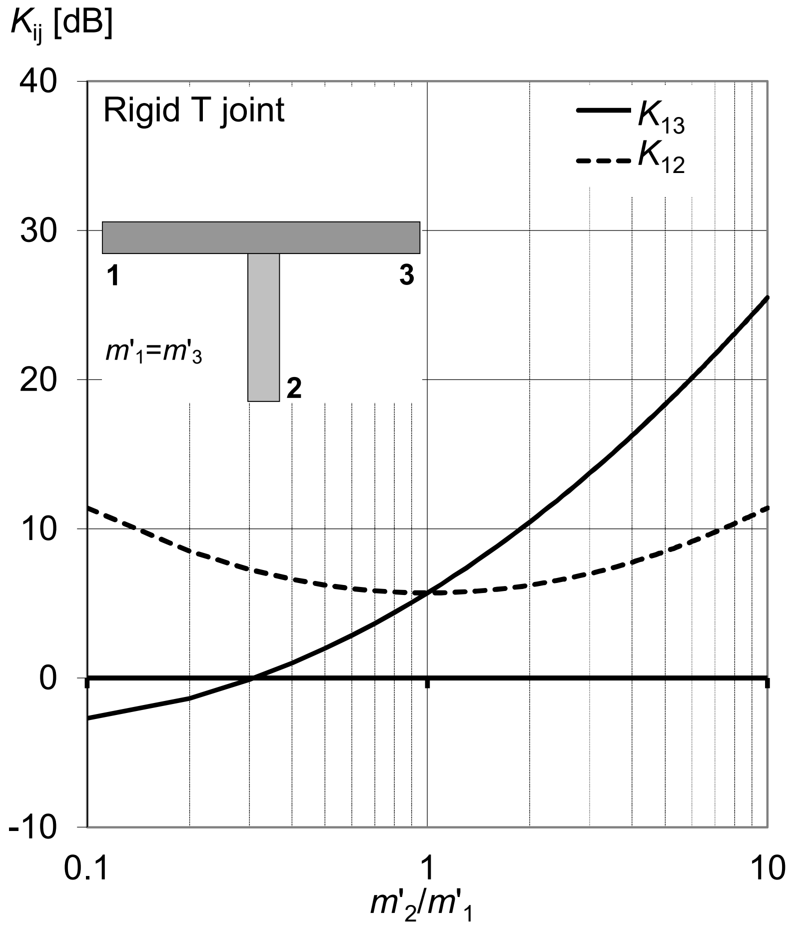
- Direct path: $$R_{Dd,w} = R_{s,w} + \Delta R_{Dd,w}$$

- Flanking paths: $$R_{Ff,w} = \frac{R_{F,w} + R_{f,w}}{2} + \Delta R_{Ff,w} + K_{Ff} + 10\lg\frac{S_s}{l_f}$$
$$R_{Fd,w} = \frac{R_{F,w} + R_{d,w}}{2} + \Delta R_{Fd,w} + K_{Fd} + 10\lg\frac{S_s}{l_f}$$
$$R_{Df,w} = \frac{R_{D,w} + R_{f,w}}{2} + \Delta R_{Df,w} + K_{Df} + 10\lg\frac{S_s}{l_f}$$

- All 13 paths: $$R'_w = -10\lg\left[10^{-R_{Dd,w}/10} + \sum_{F=f=1}^{4} 10^{-R_{Ff,w}/10} + \sum_{f=1}^{4} 10^{-R_{Df,w}/10} + \sum_{F=1}^{4} 10^{-R_{Fd,w}/10}\right]$$

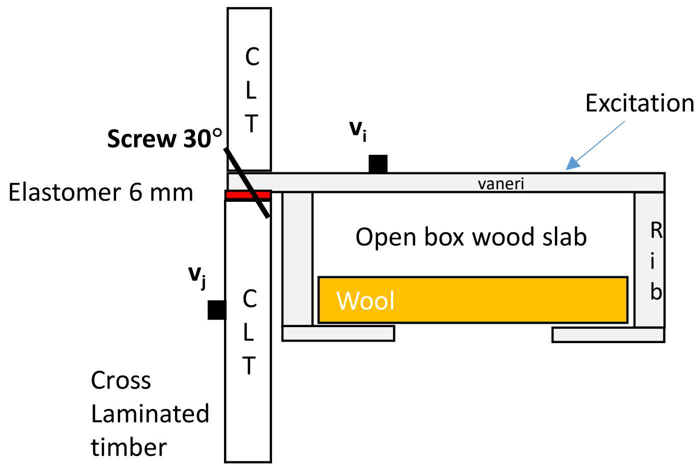
Coupling loss factor *K* of a joint

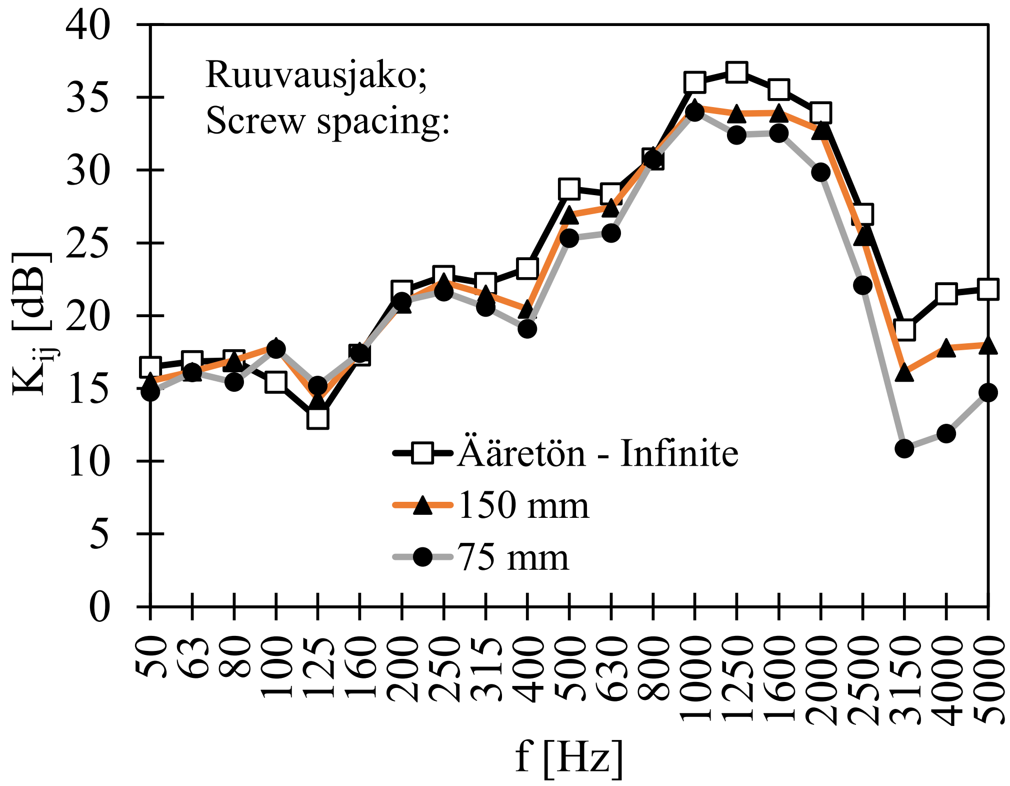




RULE OF THUMB: If $m'_1=m'_2=m'_3=m'_4$, X-joint isolation is 9 dB and T-joint isolation is 6 dB.

Measured K_{ij} for a timber joint





- $K_{i,j}$ measuremen ISO 10848 in three **screw** spacings
- Excitation with tapping machine in structure i
- Velocity **v** measurement in structures i and j
- Reverberation time impulse excitation using hammer

$$K_{ij} = \overline{D_{v,ij}} + 10\lg\left(\frac{l_{ij}}{\sqrt{a_i a_j}}\right)$$

$\overline{D_{v,ij}}$ is the direction-averaged velocity level difference between elements *i* and *j*, in dB;

l_{ij} is the junction length between elements *i* and *j*, in m;

a_i, a_j are the equivalent absorption lengths of elements *i* and *j*, in m.

$$a_j = \frac{2{,}2\pi^2 S_j}{T_{s,j} c_0 \sqrt{\frac{f}{f_{ref}}}}$$

where

$T_{s,j}$ is the *structural reverberation time* (3.8) of the element *j*, in s;

S_j is the surface area of the element *j*, in m^2;

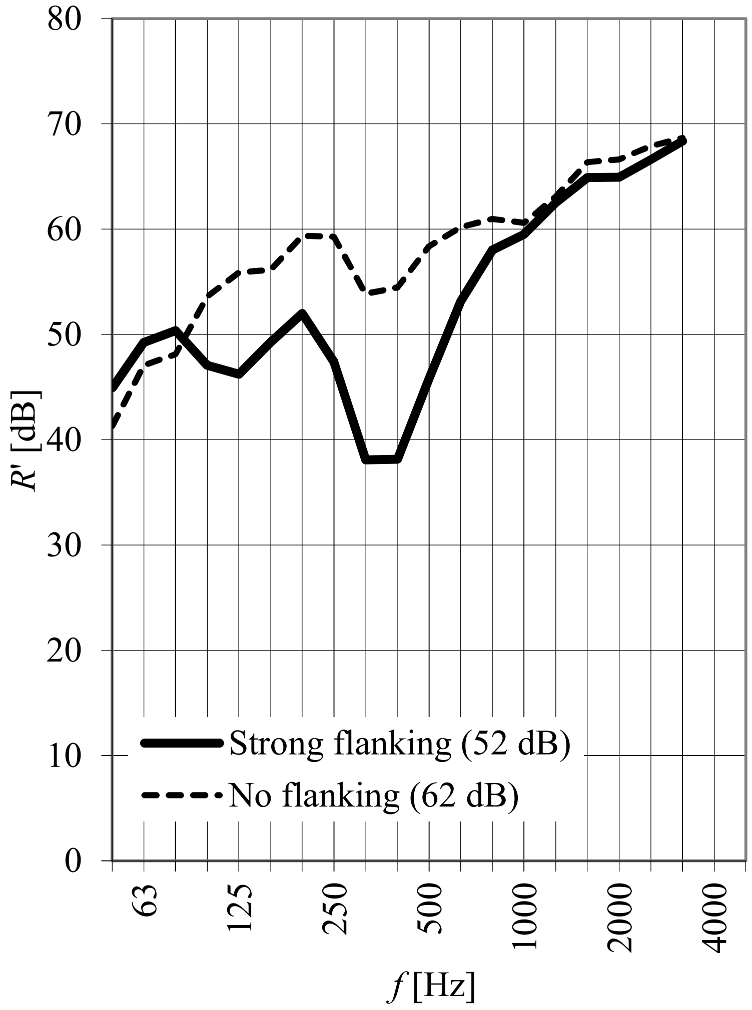
c_0 is the speed of sound in air, in m/s;

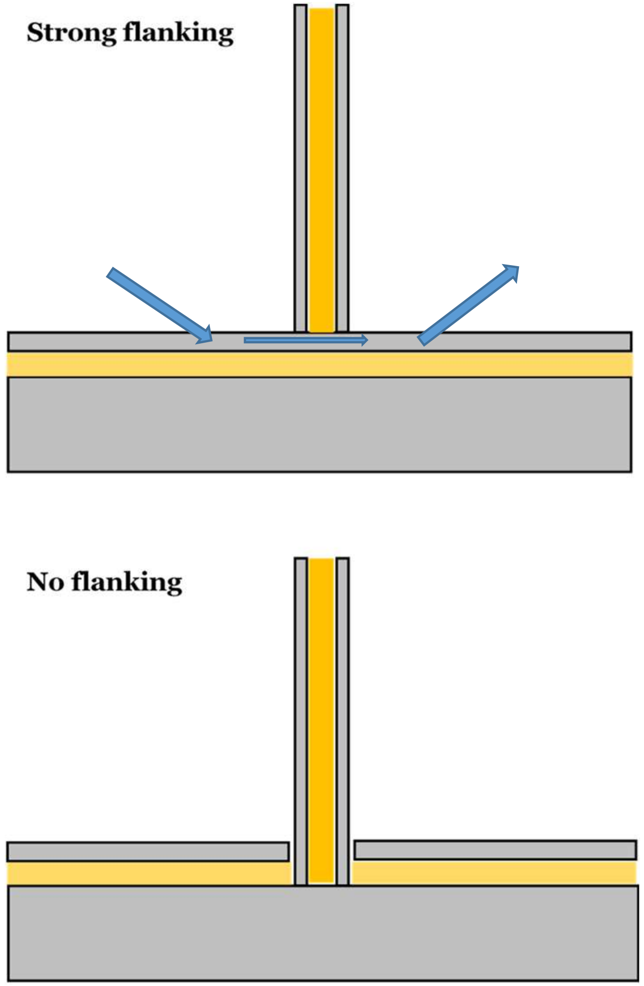
f is the frequency, in Hz;

f_{ref} is the reference frequency, in Hz (f_{ref} = 1 000 Hz).

Example of strong flanking via floating floor

- A double wall was built above a 60-mm-thick floating floor plate
- The laboratory value of the double wall was 65 dB R_w .
- Measured value was 52dB R'_w . The target was 60 dB. Coincidence frequency of the floor plate was 400 Hz. Strong flanking both below and above 400 Hz.
- Cutting the plate resulted in 62 dB.

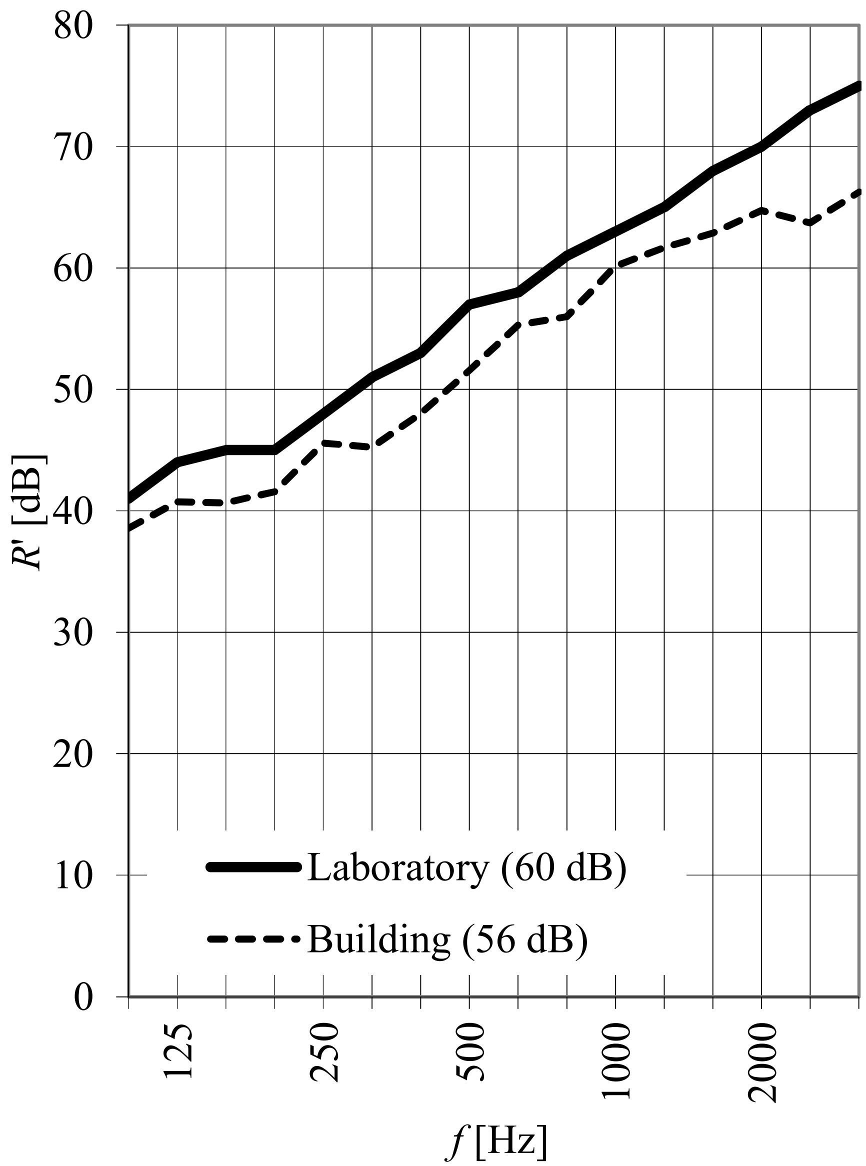




RIL 243-1-2007

Steel reinforced concrete slab 180 mm

- It is typical that the field value is 3-5 dB lower than the laboratory value due to structural flanking.

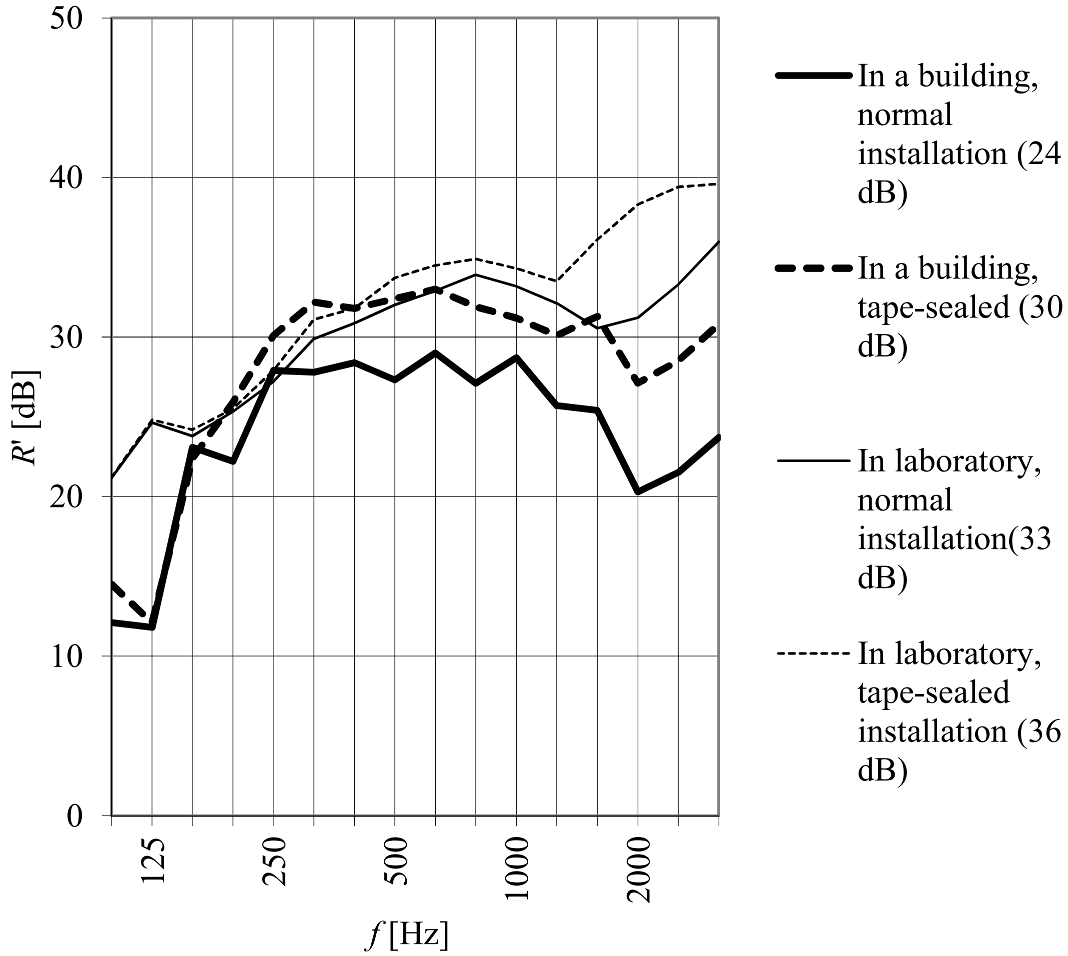


Effect of slits on SRI – office door

- Measured values of a typical office door
  - sound insulation class 25 dB
  - 33 dB R_w
- Small slits are usual due to improper workmanship.
- Therefore, the classification for doors and mobile walls (SFS 5907:2004) involve a 5 to 8 dB safety margin.

Table A.1 Door sound insulation classes and their requirements

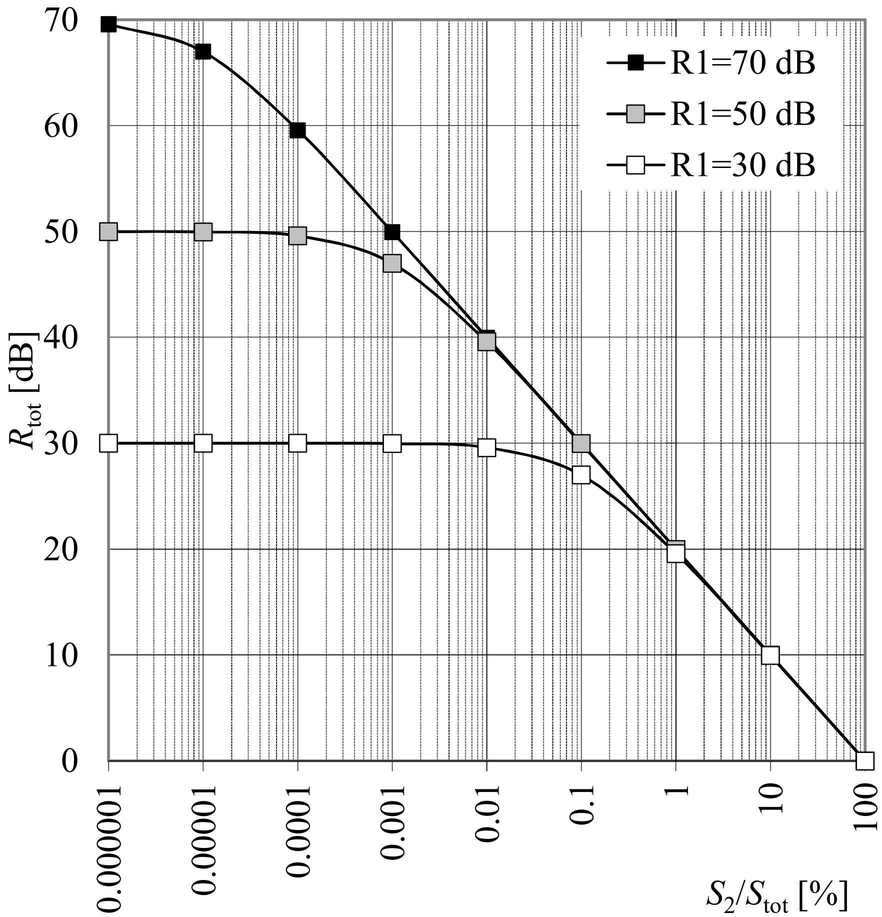
Sound insulation class	Required minimum values achieved in laboratory measurements, R_w
25	30
30	37
35	42
40	48
45	53



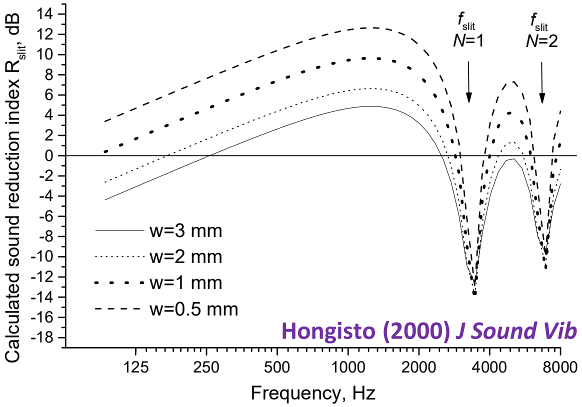
Effect of slits on SRI

$$R_{tot} = 10 \lg \frac{S_1 + S_2}{S_1 \cdot 10^{-R_1/10} + S_2 \cdot 10^{-R_2/10}}$$

- S_1 [m^2] is the area of structural component
- R_1 [dB] is the SRI of structural component
- S_2 [m^2] is the area of slits and holes
- $S_{tot}=S_1+S_2$
- R_2 [dB] is the SRI of slits and holes
- First approximation: R_2=0 dB (independent on frequency) is applied in the exercise.
- Frequency dependent models include the dimensions of the slit: SRI of the slit is negative at frequencies where the slit depth is the multiple of half wavelength

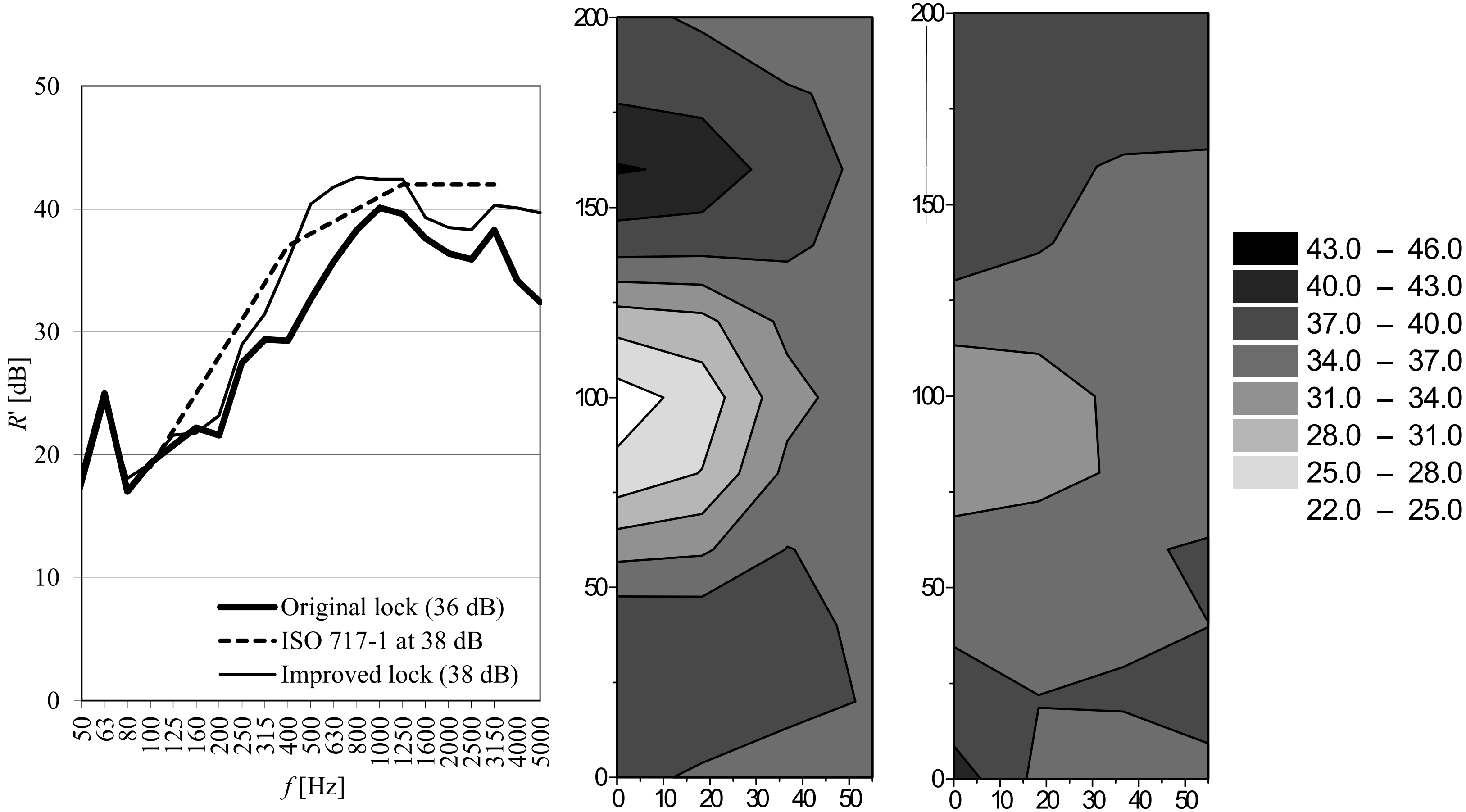


The SRI of a slit of depth 45 mm with varying widths W.



Localization of sound leak using intensity method

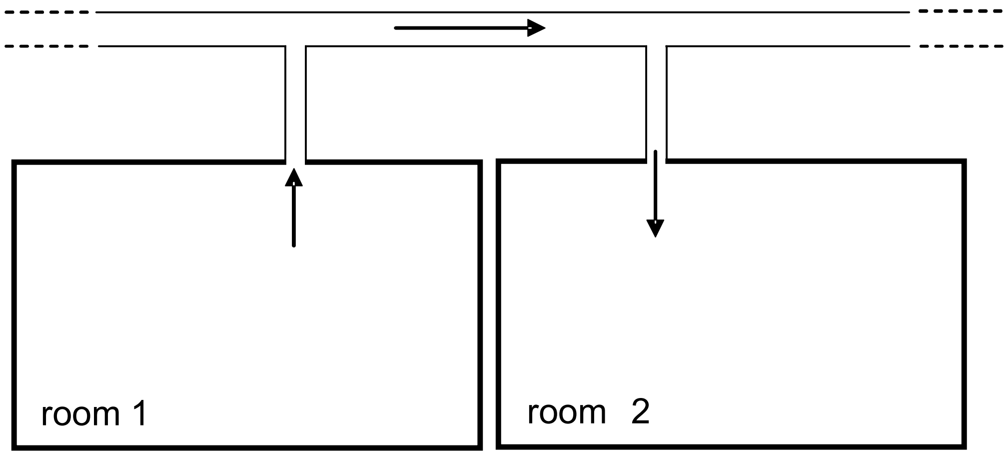
- Sound intensity level was measured at a distance of 15 cm from the door surface at a grid of 5x20 points
- Strong radiation of the lock around 500 Hz
- Lock was improved by a ”sound trap”



Hongisto et al. (1997) **Noise Con Eng J**

Airborne flanking via ducts

- Flanking is noticeable when the partition is better than 35…45 dB R'_w
- Flanking is prevented by a silencer
- Flanking increases with increasing duct size because the impedance of the hole increases with decreasing size



- SRI through the duct path, R_d [dB] can be roughly estimated by

$$R_d = D_1 + D_s + D_d + D_2$$

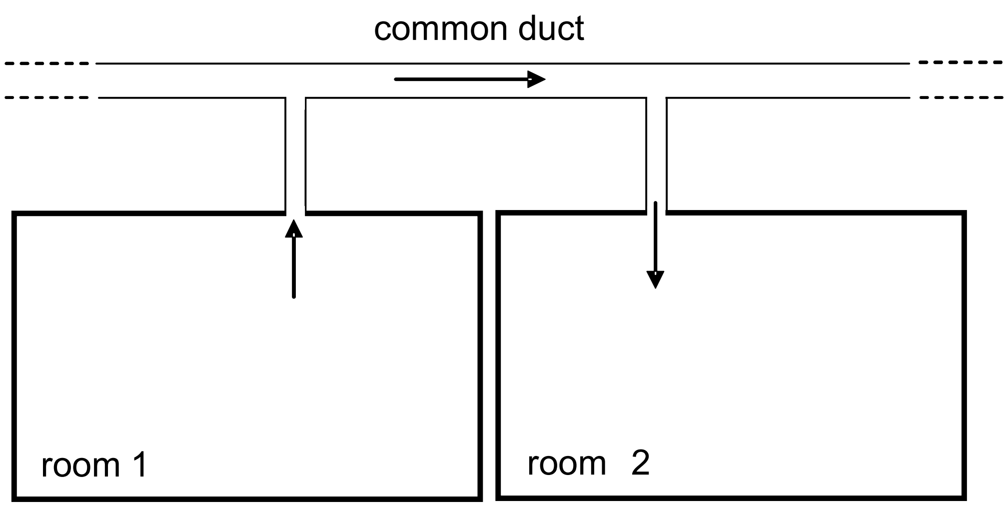
  - D_1 [dB] is attenuation of the terminal in room 1
    - Product values are not available in terminal speficications so one needs to use D_1=D_2.
  - D_s [dB] is the total attenuation of silencers in the duct
  - D_d [dB] is the attenuation caused by the duct divisions (branches)
  - D_2 [dB] is the terminal attenuation towards room 2
    - Product values D_t are applied from product specifications
- Aggregate SRI between two rooms separated by a partition and flanking duct is

$$R_{tot} = 10 \cdot \log_{10}\left[\frac{S_d + S_p}{S_d 10^{-R_D/10} + S_p \cdot 10^{-R_p/10}}\right]$$

  - S_S [m^2] is the physical area of the duct towards room 1
  - S_p [m^2] is the physical area of the partition
  - R_p [dB] is the sound reduction index of the partition

Airborne flanking via ducts – Laboratory testing

- terminal (such as range hood) is installed to both rooms
- terminals are connected by a duct
- common duct is terminated by a silencer in both ends to avoid reflections

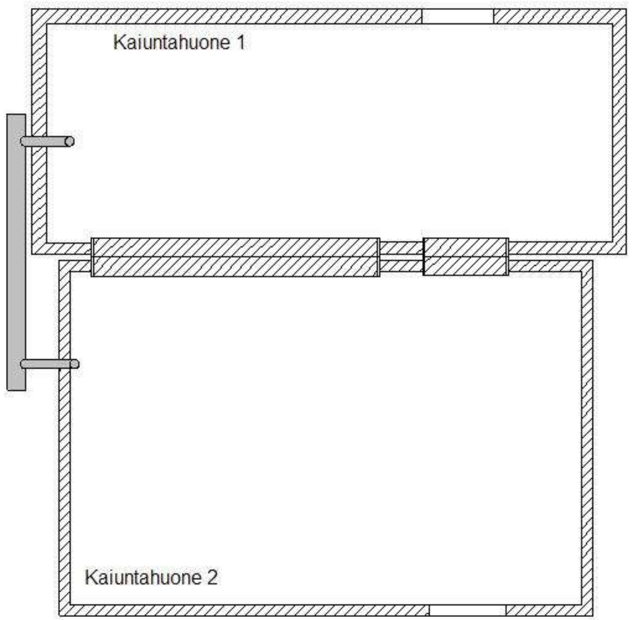


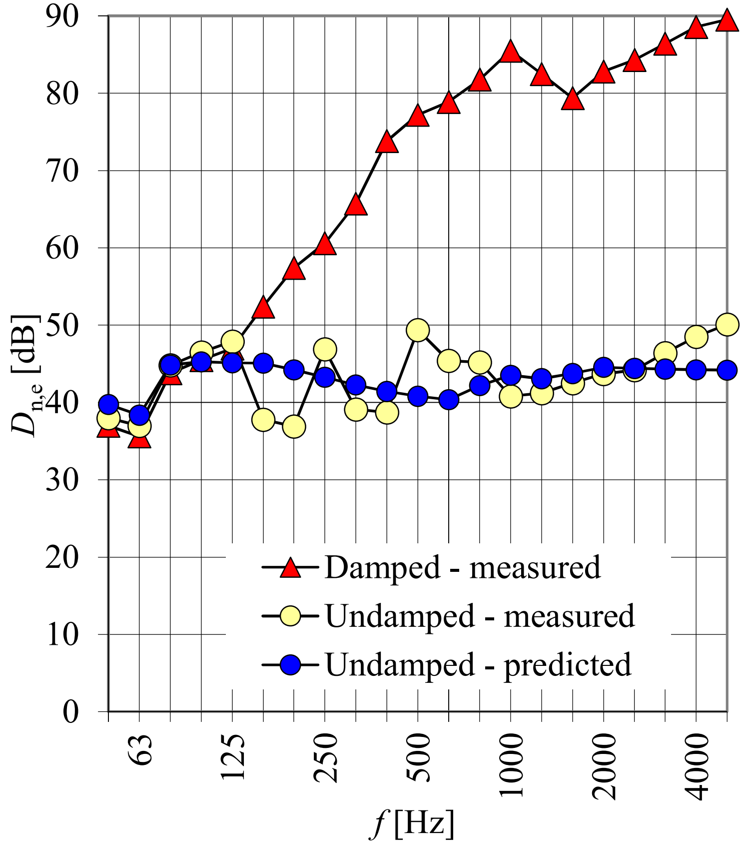
Airborne flanking via ducts – A measurement result

Duct components from room 1 to room 2:

- room 1
- 90° bend in 125 mm duct
- 125 mm duct 600 mm
- 125 to 160 mm transformer
- T-branch from 160 to 250 mm
- 250 mm duct 3000 mm
- T-branch from 250 to 160 mm
- 125 mm duct 600 mm
- 90° bend in 125 mm duct
- room 2

- Undamped - open duct ends, no terminal
- Damped – duct ends are covered with steel plug



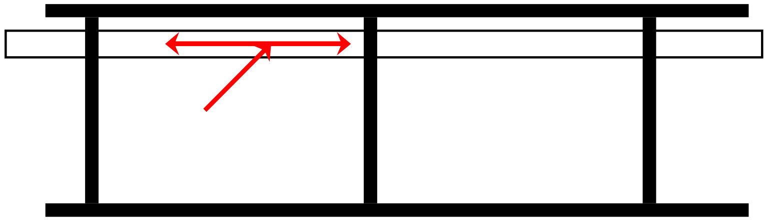


- Hongisto V, Häggblom H, Työterveyslaitos, 2009. p. 29

Transmission of airborne sound to and from the duct

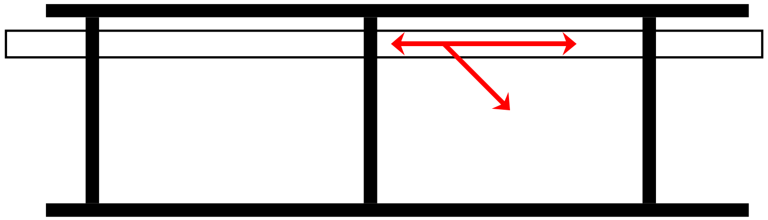
- L_{W2} [dB] is the sound power level inside the duct
- $L_{p,1}$ [dB] is the SPL in the room outside the duct
- R [dB] is the sound reduction index of the duct wall
- S_k [dB] is the surface area of the duct in the room

$$L_{W,2} = L_{p,1} - R + 10\lg S_k - 6$$



- $L_{p,2}$ [dB] is the SPL in the room [dB]
- L_{W1} [dB] is the sound power level inside the duct
- A [m²] is the absorption area of the room

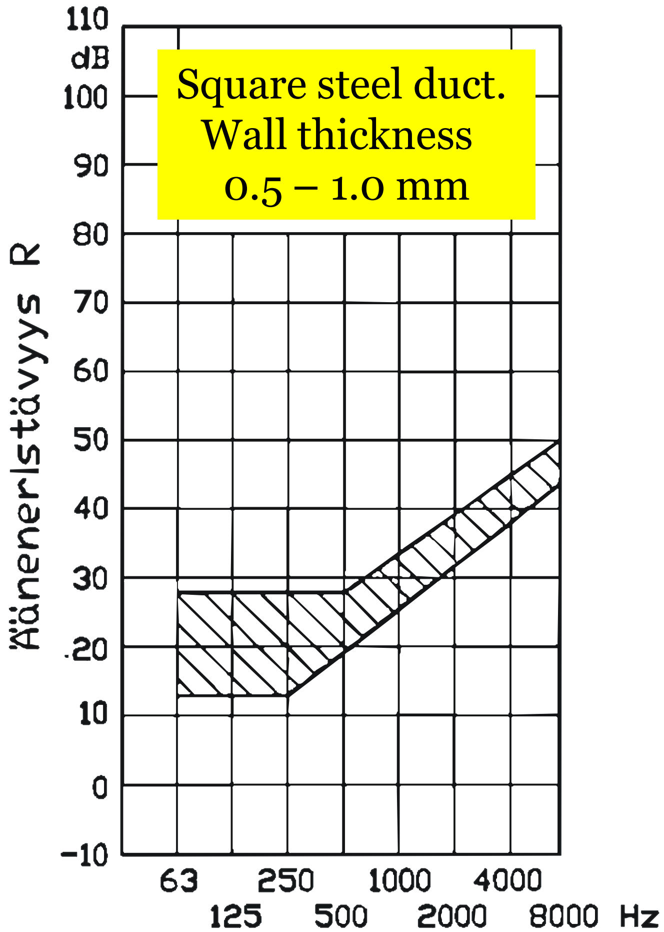
$$L_{p,2} = L_{W,1} - R + 10\lg \frac{S_k}{A_2 S_1} + 3$$

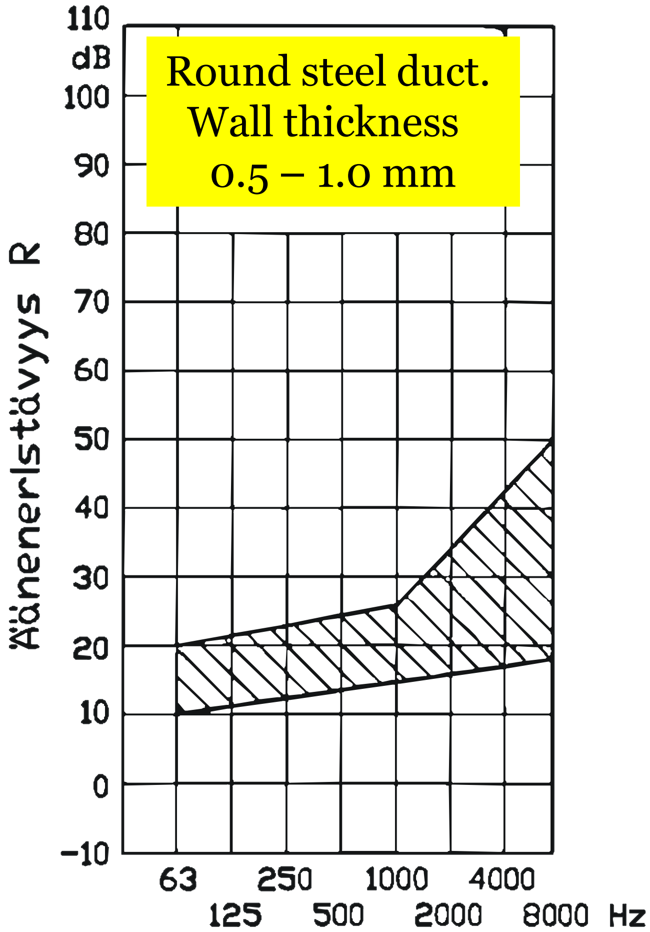


VDI 2081

Sound reduction index R of duct walls

- The values can be used to estimate the transmission through the duct walls.





Laine, Suomen LVI-Liitto r.y.

Flanking 1 in a row house - identification

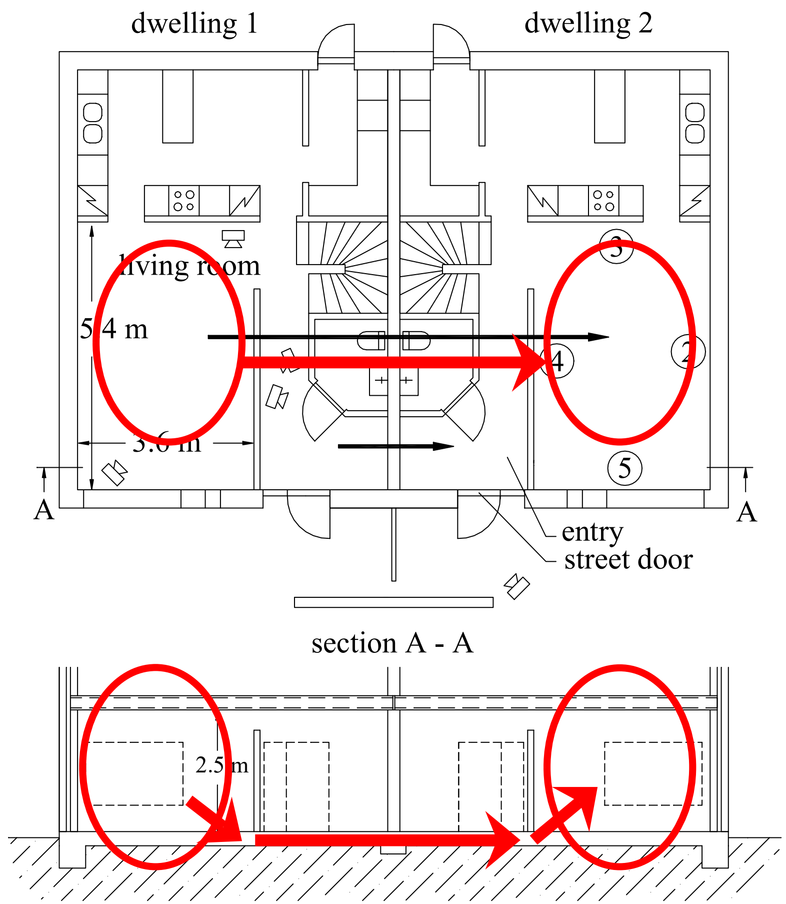
- Living sounds could be heard between living rooms although they were far from the partition wall
- Requirement 55 dB R'_w. Measured result 53 dB.
- Sound path could not be identified by ears.
- Sound power level radiated by each surface was determined using sound intensity method.
- Bolded value means reliable data
- Floor was the main sound radiator at 125 – 1000 Hz.

The original situation

Surface	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
1. Floor	**52.8**	**56.4**	**68.5**	**50.9**	16.0	21.0
2. Back wall	45.7	47.9	-58.1	-42.2	-27.9	17.3
3. Kitchen wall	-49.8	-52.6	-62.1	-45.8	-24.4	5.7
4. Entry wall	-51.4	-54.1	-62.9	-45.8	25.7	19.6
5. Façade	-46.3	-50.3	-59.7	-42.1	-22.5	-7.1
6. Ceiling	49.2	43.7	-58.7	-38.9	**32.6**	**23.2**

The final situation

Surface	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
1. Floor	**52.7**	50.8	52.4	-31.4	-26.2	15.9
2. Back wall	**50.8**	48.9	53.0	40.2	29.0	19.8
6. Ceiling	-43.8	44.5	53.4	**42.2**	**37.0**	**27.3**

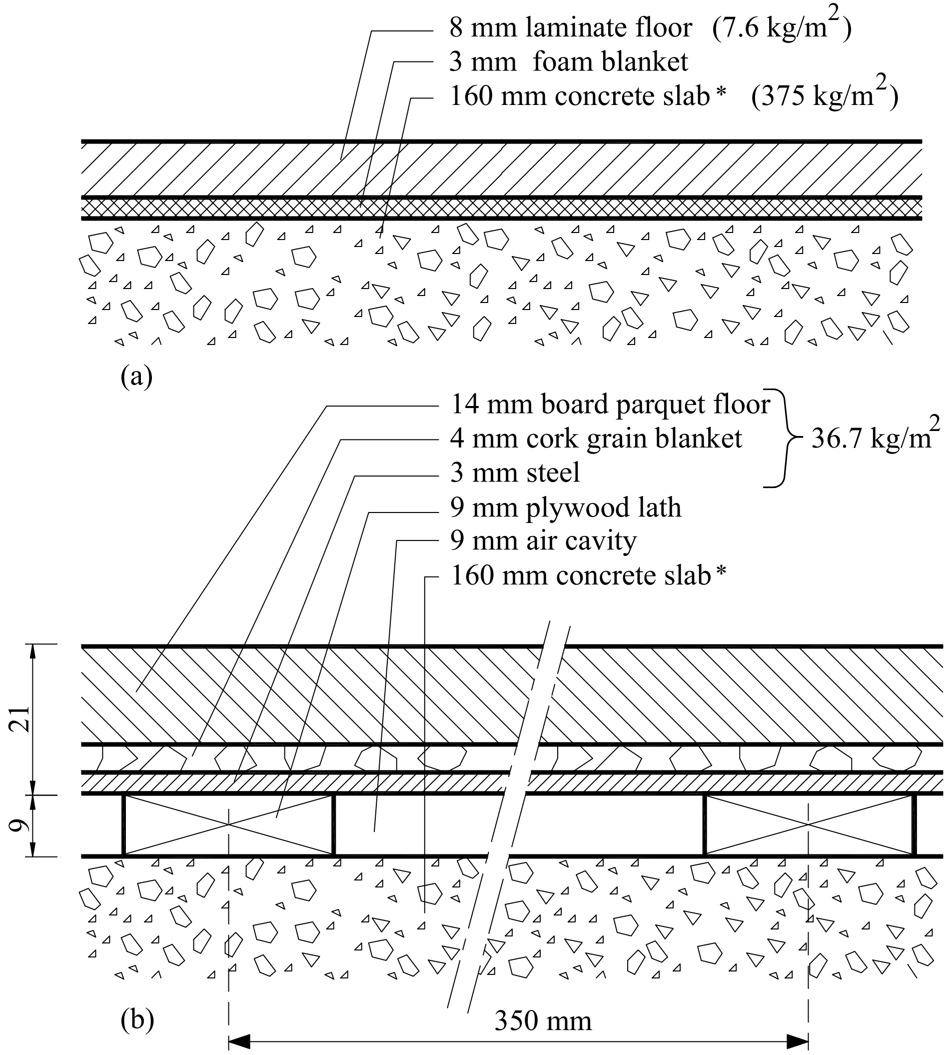


Hongisto (2001) **Appl Acoust**

Flanking 1 in a row house - solution

(a) Original floor. f_0=500 Hz.

(b) New floor in another dwelling. f_0=175 Hz.



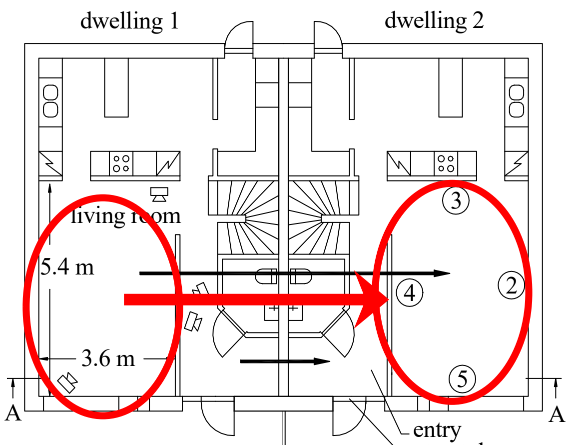
$$f_0 = \frac{1}{2\pi}\sqrt{\frac{s'}{m'}}$$

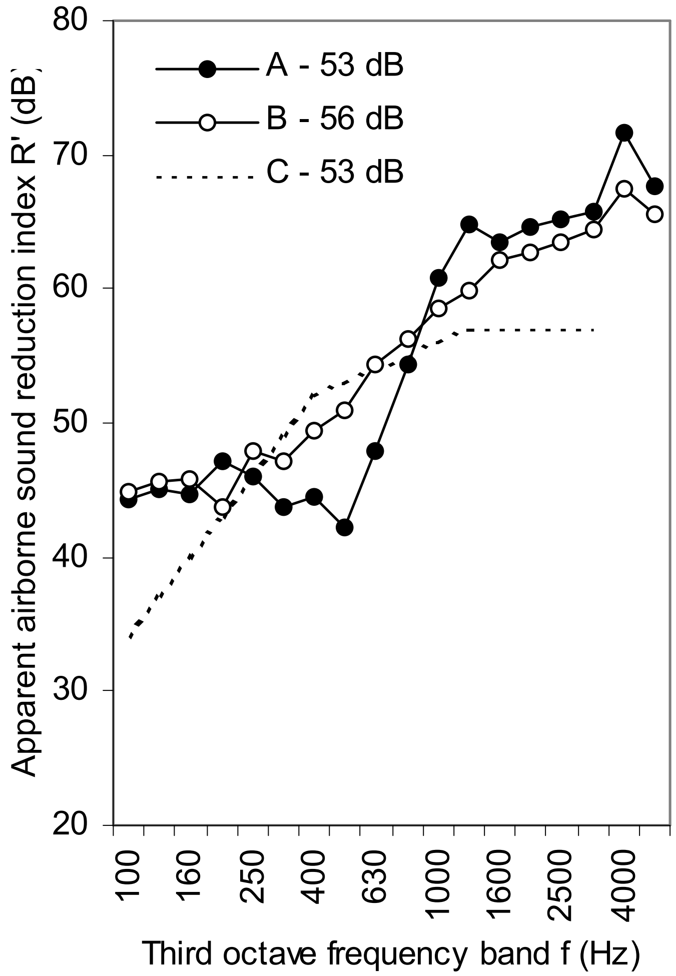
Hongisto, Appl Acoust 2001

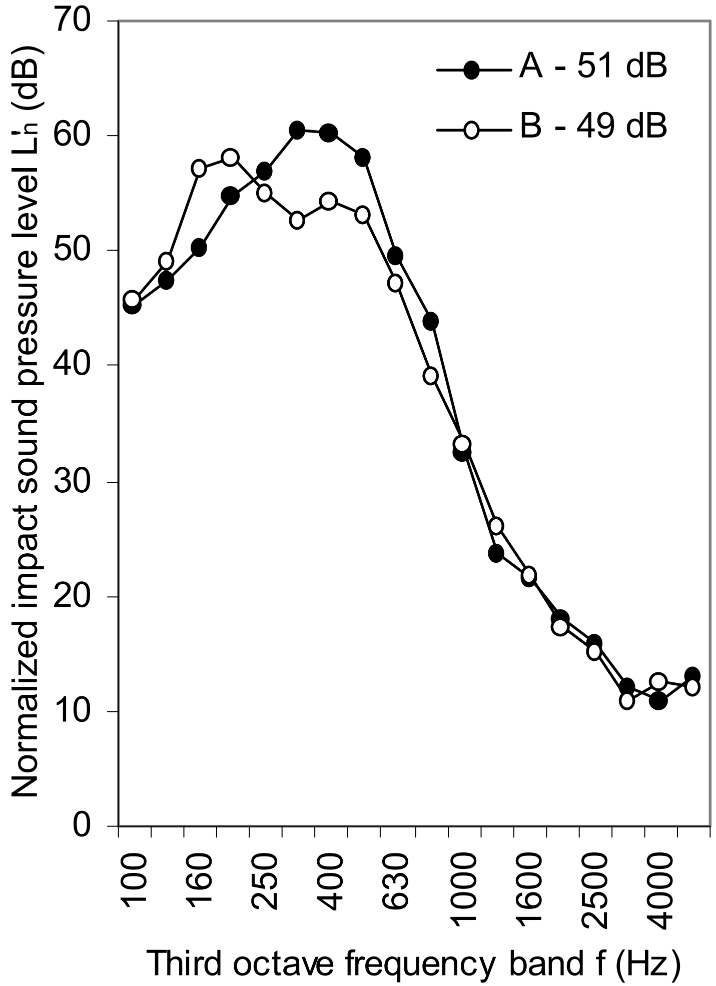
Flanking 1 in a row house - Results

Hongisto, Appl Acoust 2001

- A – Original, 53 dB R'_w
- B – Renovated floor in dw. 2, 56 dB R'_w
- C – ISO 717-1 reference curve at 53 dB
- Dip at 500 Hz disappeared

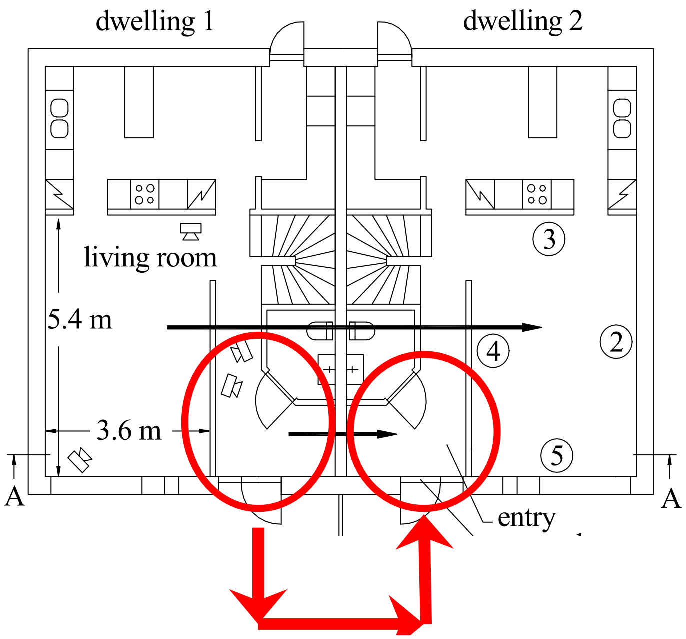




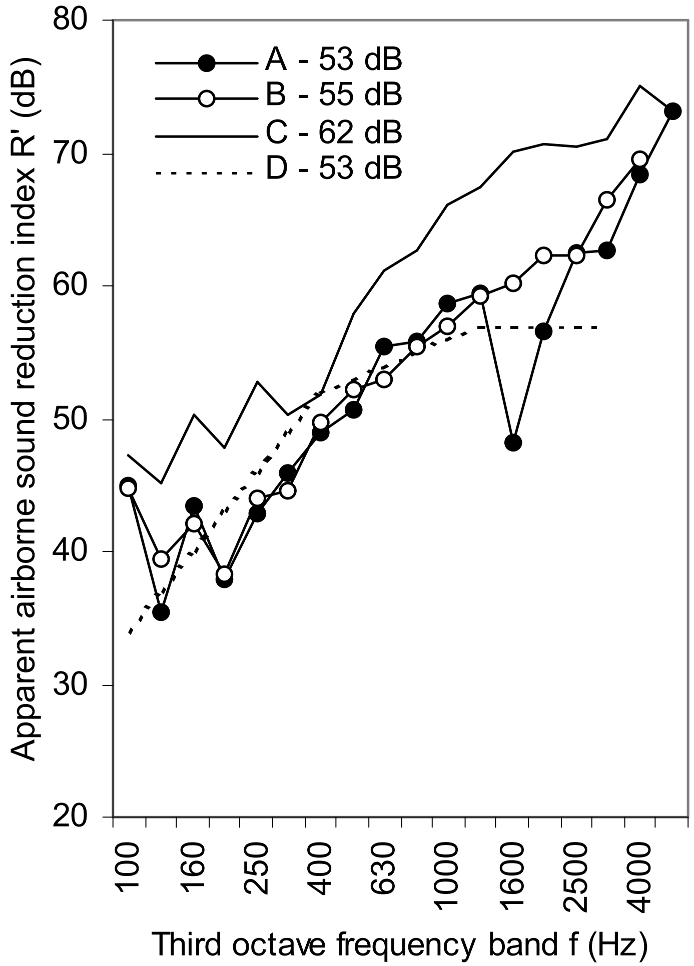


Flanking 2 in a row house – identification

- A – Original situation. Requirement 55 dB was not achieved.
- B – Improved situation
- C – Like A but the door was covered by 50 mm mineral wool and 22 mm chipboard to identify the sound path
- D – ISO 717-1 reference curve at 53 dB



Hongisto, Appl Acoust 2001

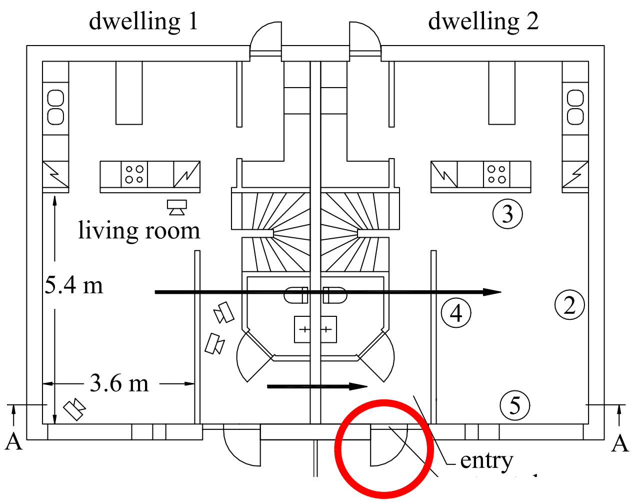


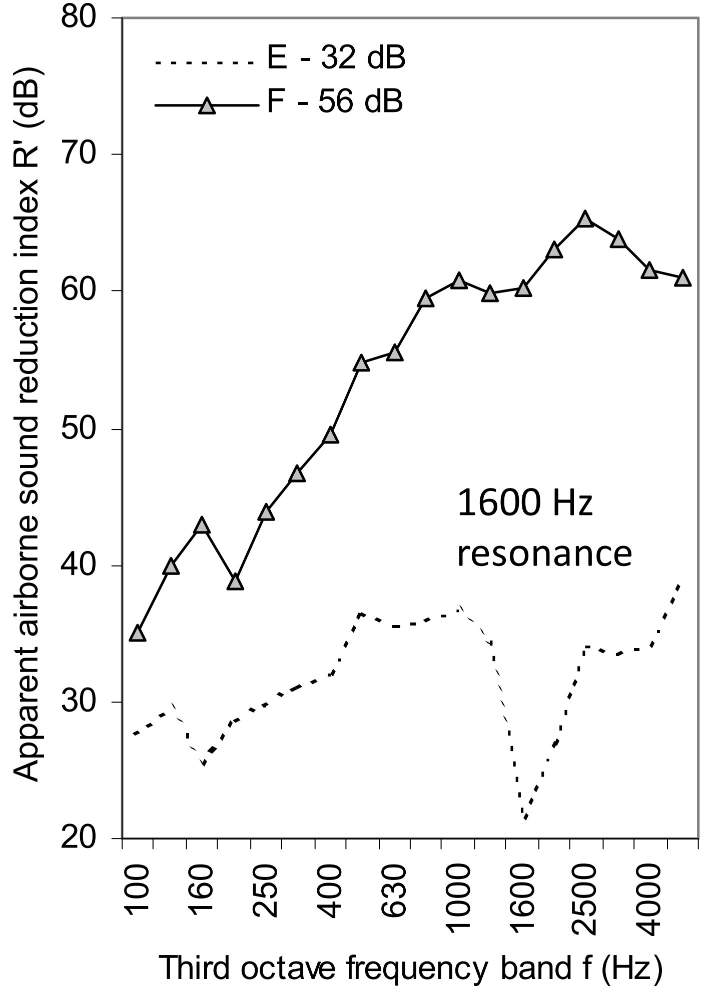
Flanking 2 in a row house – solution

Hongisto, Appl Acoust 2001

Additional measurements

- E – Door alone
- F – Like E but the door was covered by 50 mm mineral wool and 22 mm chipboard to identify the sound path



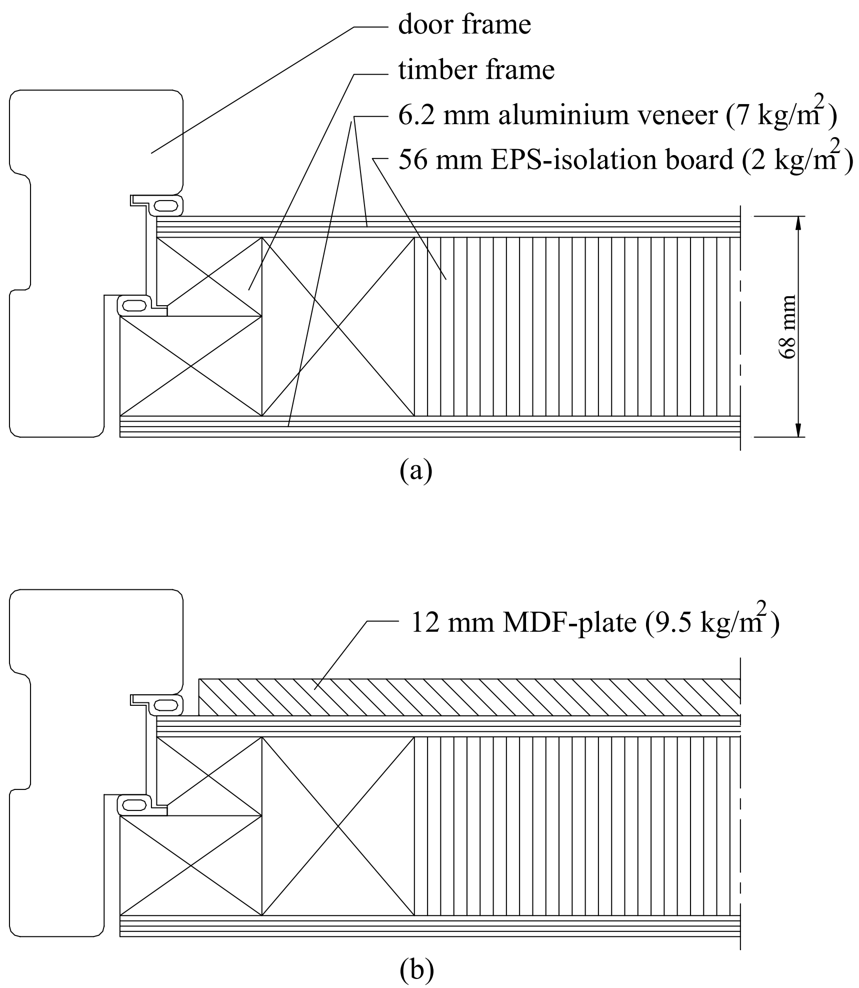


Flanking 2 in a row house – solution

Hongisto, Appl Acoust 2001

(a) Original door structure. Dilatation resonance at 1600 Hz.

(b) Improved door structure.



Impact sound flanking in a row house – Kitchen flooring

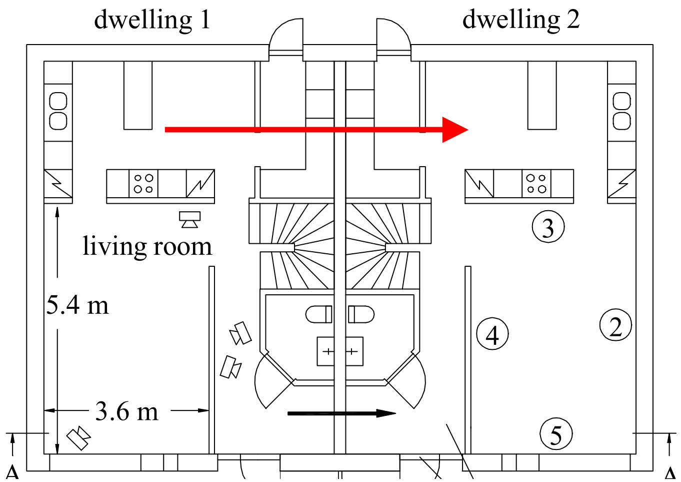
Impact sounds produced in the kitchen could be heard in the neighboring dwelling.

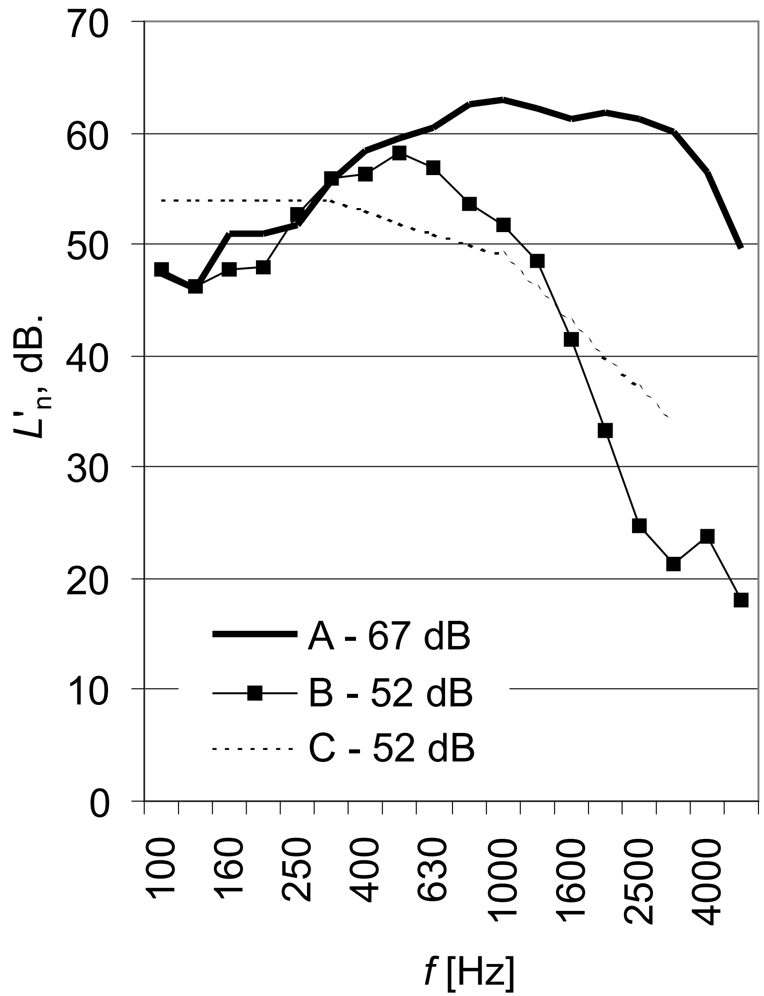
Both dwellings were on the same concrete slab 160 mm, which was not cut between the dwellings.

A – Original floor. Tiles glued directly to the concrete slab.

B – Improved floor. Flexible underlayment between the tiles and concrete slab.

C – ISO 717-2 reference curve





Hongisto, Appl Acoust 2001

Sound insulation demand of facades against road noise

- Facades shall be dimensioned so that the regulated values for **indoor noise level,** $\boldsymbol{L}_{\mathbf{A,eq,s}}$, are not exceeded
- Outdoor noise level $\boldsymbol{L}_{\mathbf{A,eq,u}}$ is estimated, measured or predicted
  - the level without the reflecting effect of the house under question
  - If the level is measured within 10 mm distance from the facade, 6 dB is reduced from the measured value to obtain the value without the effect of standing wave
- Level difference that the facade must produce:
  - $\Delta L = L_{A,eq,u} - L_{A,eq,s}$
    - when the use of the building is known
    - $L_{A,eq,s}$ is the regulated indoor noise level

Decision of government 993/92

	Day time 07-22 T=15 h	Night time 22-07 T=9 h
Regulated values outdoors	$L_{A,eq,T}$ [dB]	$L_{A,eq,T}$ [dB]
Residential areas, recreational areas, health care accommodations	55	50
New areas	55	45
Educational areas	55	-
Residential areas for holiday seasons, camping areas, protected natural areas	45	40
Regulated values indoors	$L_{A,eq,T}$ [dB]	$L_{A,eq,T}$ [dB]
Living, patient and accommodation rooms	35	30
Education and meeting spaces	35	-
Service and office rooms	45	-

NOTE. If the noise includes impulsive or narrow-band character, 5 dB is added to the measured or predicted value before comparing to the tabulated values.

Dimensioning of facade and its components
(Ministry method)

$R_{A,tr} = R_w + C_{tr}$

1. Required level difference ΔL [dB] i.e. demand: $$\Delta L = L_{A,eq,u} - L_{A,eq,s}$$
2. Required total sound insulation $R_{tr,vaad}$ [dB]: $$R_{tr,vaad} = \Delta L + K_1 + 7$$
3. Required total sound insulation $R_{A,tr,kok}$ [dB]: $$R_{A,tr,kok} \geq R_{tr,vaad}$$
   - Requirements concern the single-number quantity $\boldsymbol{R_w + C_{tr}}$
4. Requirement for windows and doors, $R_{A,tr,ikk}$ [dB]: $$R_{A,tr,ikk} \geq R_{tr,vaad} + K_2$$
5. Requirement for the wall $R_{A,tr,seinä}$ [dB]: $$R_{A,tr,seinä} \geq R_{tr,vaad} + 3$$
6. Requirement for small element $D_{n,e,A,tr}$ [dB]: $$D_{n,e,A,tr} \geq R_{tr,vaad} + 5$$

Correction factors:

S/S_H	2.5	2.0	1.6	1.3	1.0	0.8	0.6	0.5	0.4
K_1 (dB)	5	4	3	2	1	0	-1	-2	-3

$(\Sigma S_i)/S$	0.10	0.13	0.15	0.20	0.25	0.30	0.40	0.50
K_2 (dB)	-6	-5	-4	-3	-3	-2	-1	0

S [m^2] area of the facade in the room

S_H [m^2] is the floor area of the room

ΣS_i [m^2] is the total area of windows and doors in the facade

Event-based environmental noises such as railway or airport noise: mean of the maximum levels L_{AFmax} should not exceed the requirement for $L_{A,eq,s}$ more than 10 dB.

Alternative method, RT 084.30 (1975)

- Facade elements are not always available with precisely desired values given by the Ministry method
- RT method is applied to check the outcome with the true values.
- The level difference $\Delta L_{A,i}$ caused by component i is:

$$\Delta L_{A,i} = R_{w,i} + C_{tr,i} - 7 - 10 \cdot \log_{10}\left(\frac{S_i}{S_H}\right)$$

  - S_i [m^2] is the area of component
  - S_H [m^2] is the room's floor area
- Level difference produced by all N components of the facade, $\Delta L_{A,tot}$, is

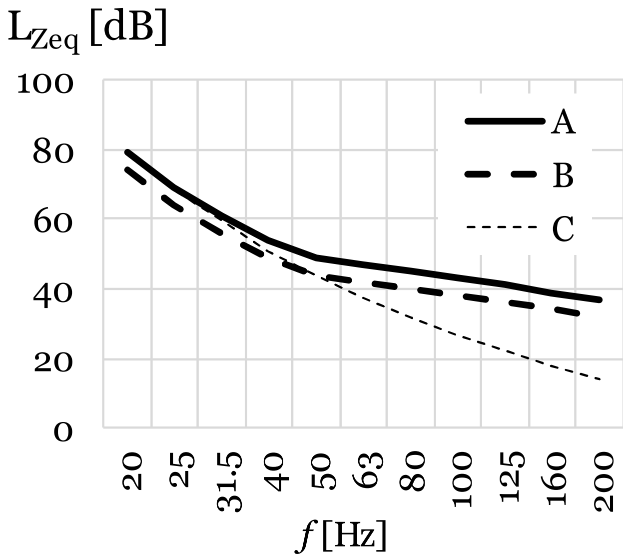
$$\Delta L_{A,tot} = -10 \cdot \log_{10}\left(\sum_{i=1}^{N} 10^{-\Delta L_{A,i}/10}\right)$$

- The value shall exceed ΔL of the facade stated in previous slide

Facade study - Purpose

- In Finland, the sound pressure level (SPL) of low-frequency environmental noise indoors shall not exceed the **regulated values** of the Table
- The SPL caused by environmental noise inside a dwelling at low frequencies is calculated by subtracting the outdoor-indoor level difference (DL) of the façade from the outdoor SPL. During area planning stage, it is usually not possible to measure the façade DL of every dwelling of the inspected area.
- Therefore, politically accepted estimations of DL need to be used, that are most probably exceeded in most façade constructions.
- There is very little data available of the DL of façade constructions during the last decades as reviewed in Ref. [2].

Band f [Hz]	Day 07-22 $L_{Zeq,1h}$ A	Night 22-07 $L_{Zeq,1h}$ B	Hearing threshold C
20	79	74	78.5
25	69	64	68.7
31.5	61	56	59.5
40	54	49	51
50	49	44	44
63	47	42	37.3
80	45	40	31.5
100	43	38	26.6
125	41	36	22
160	39	34	18
200	37	32	14.3



- **Our purpose** was to provide experimental information on the DL of typical façade constructions in Finland and to present feasible estimation of DL that can be used to assess the indoor SPL.
- This is a summary of Keränen et al. (2019).

Keränen, J., Hongisto, V., Hakala, J. (2019). **Building and Environment** 156 12–20.

Facade study – Methods

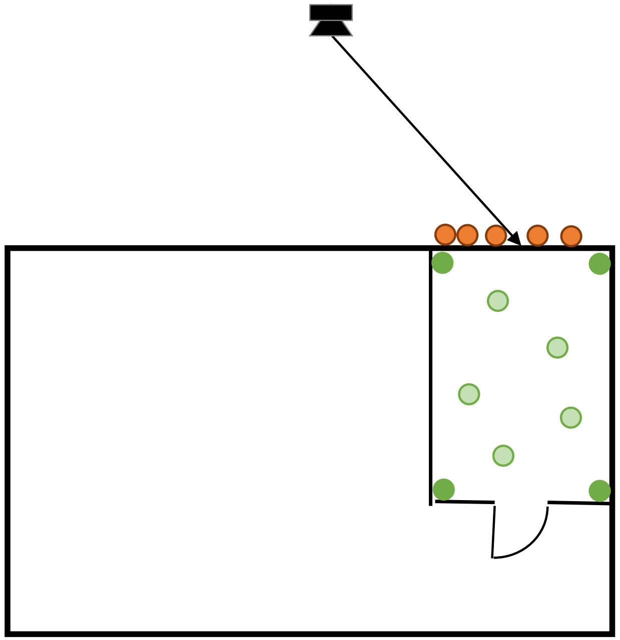
- 26 facades were measured in 13 buildings, within 5 – 5000 Hz
- The buildings were versatile (old/new, heavy/light, w/wo windows)
- Within 50 – 5000 Hz, R'_{45} was determined by ISO 16283-3

$$R'_{45} = L_{1,s} - L_2 + 10 \cdot log_{10}\left(\frac{S}{A}\right) - 1.5$$

  - $L_{1,s}$ [dB] is SPL at 10 mm distance from the facade
- Within 5 – 200 Hz, level difference was separately measured to corners (C) and middle areas (M). Reverberation time was not measured

$$DL_{\mathrm{Cn,f}} = L_{1,s} - L_{2,\mathrm{Cn,f}} - 6$$

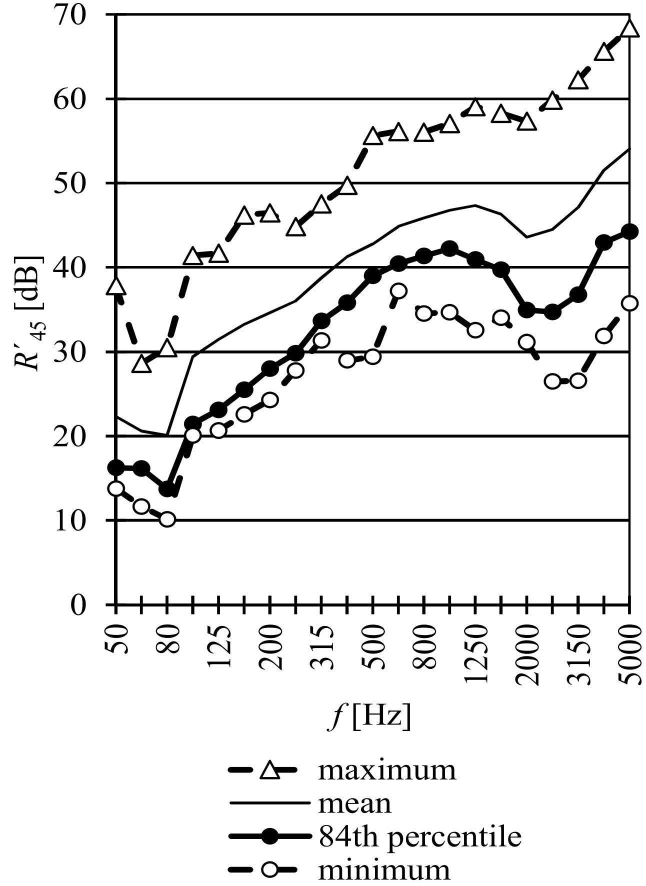
$$DL_{\mathrm{Mn,f}} = L_{1,s} - L_{2,\mathrm{Mn,f}} - 6$$



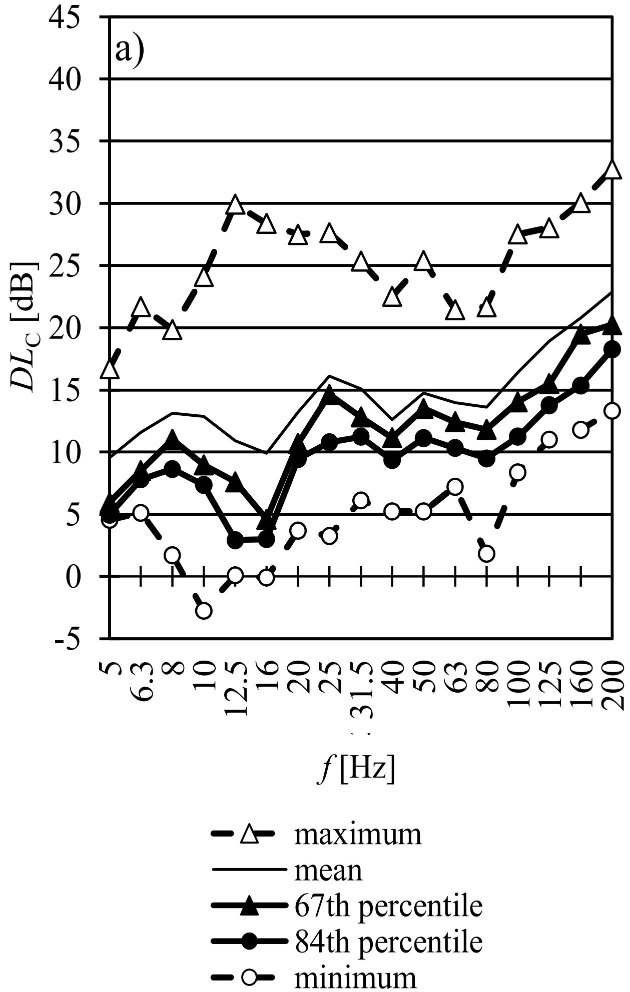
Keränen ym. 2017 Akustiikkapäivät
Keränen et al. 2019 Build Environ

Facade study – Main results

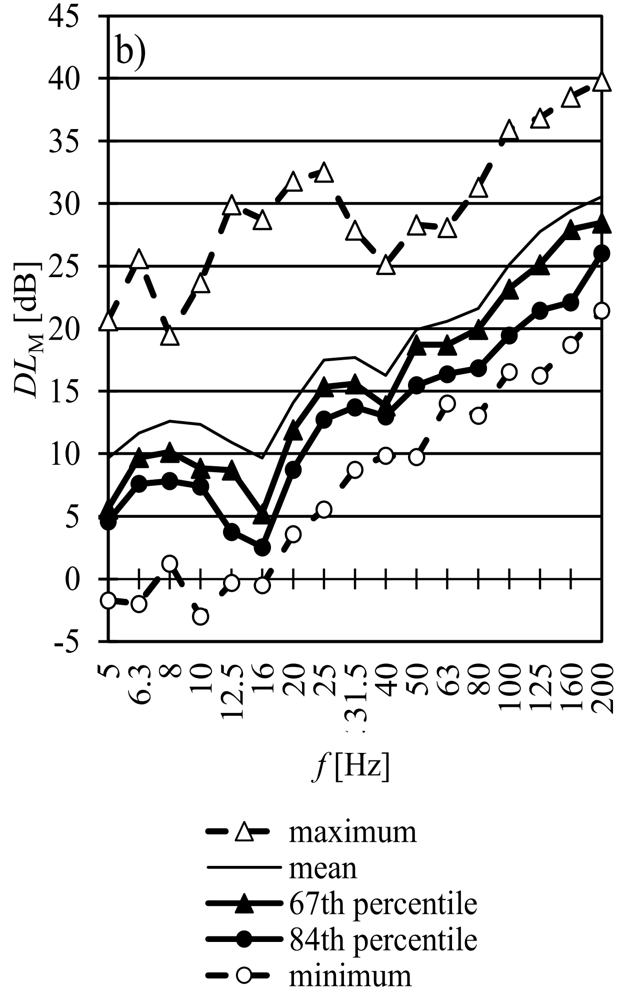
Airborne sound insulation
ISO 16283-3



Sound level difference
Corners of the room



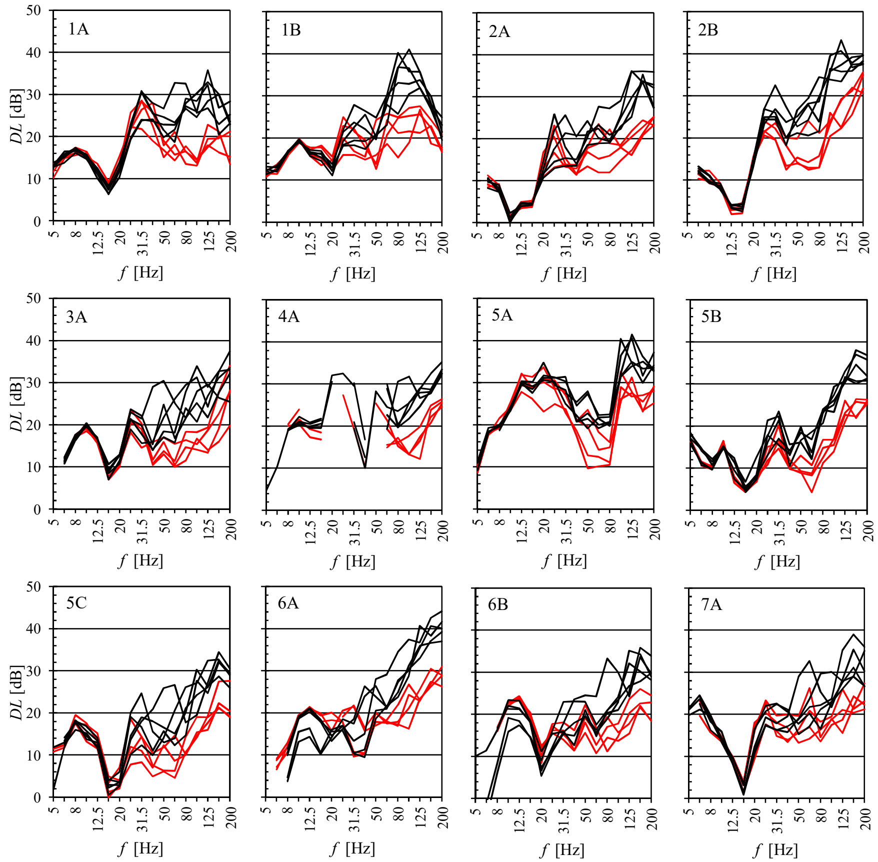
Sound level difference
Middle area of room

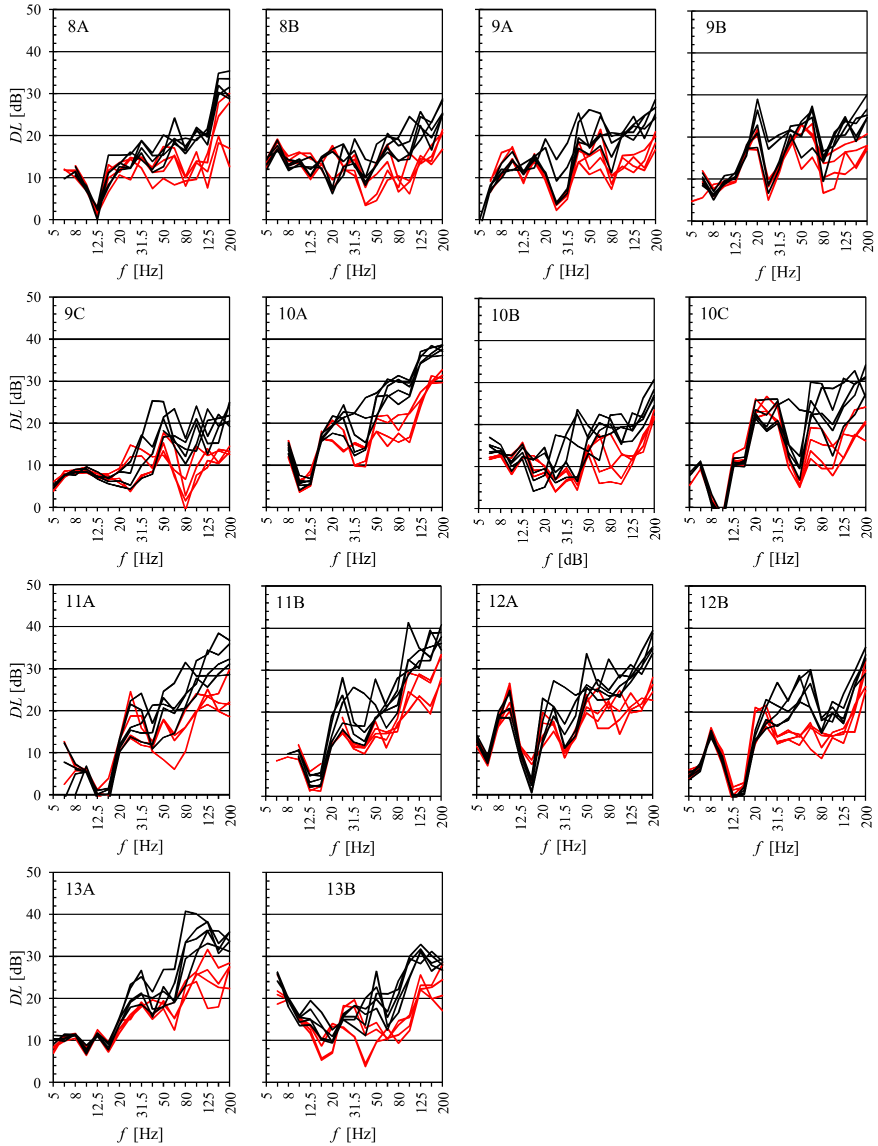


Keränen et al. (2019)

Facade study – Results of DL

- DL_C values (corners) in red, DL_M values (central zone) in black
- No room modes below 20 Hz (values overlap)
- DL_C and DL_C differ a lot within 20-200 Hz, not only within 50-80, where LF procedure is suggested in ISO 16283-3





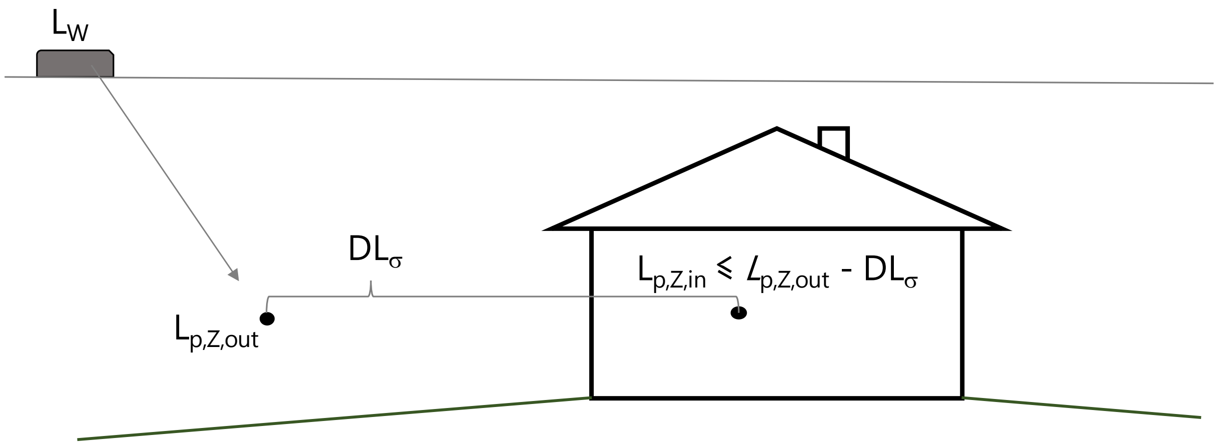
Keränen et al. (2019)

Facade study - Application

- The statistical estimate can be used to estimate indoor SPL of environmental noise when the façade sound insulation is unknown
- SPL of environmental noise $L_{\mathrm{p,Z,out}}$ [dB] on the yard is predicted or measured in 1/3-octaves.
- SPL indoors $L_{\mathrm{p,Z,in}}$ [dB] is obtained by

$$L_{p,Z,in} = L_{p,Z,out} - DL_{\sigma}$$

  - DL_{σ} [dB] represents the level difference that is exceeded in 84 % of Finnish facades (Table).
- $L_{\mathrm{p,Z,in}}$ is compared to **regulated values**



f [Hz]	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
DL_{σ} [dB]	6	6	6	6	7	7	8	8	9	10	12	13	15	17	19	21	23

Keränen et al. (2019)

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