Building Acoustics
Flanking Sound Transmission

07

7 Flanking Sound Transmission
by J.J.M. Cauberg, A. Schuur and M.J. Tenpierik

7.1 Introduction

One of the most important assignments of architectural acoustics is to control the sound transmission between two rooms. In the chapter on "Health" the Dutch "Bouwbesluit" puts requirements on the characteristic air-borne sound insulation index, $I_{lu;k}$, between an enclosed room in a dwelling and an enclosed room or a set of enclosed rooms in an adjacent dwelling. From a quality perspective it is quite common to even use more stringent requirements (3 to 5 dB) than specified herein. This characteristic air-borne sound insulation index, $I_{lu;k}$, is defined in Dutch standard NEN 5077 "Geluidwering in woongebouwen-Bepalingsmethoden voor de grootheden voor luchtgeluidisolatie, contactgeluidisolatie, geluidwering van uitwendige scheidingsconstructies en geluidniveaus veroorzaakt door installatie". It uses the normalised air-borne sound reduction index, D_{nT}, as a basis. Since D_{nT} is a measure of the sound pressure level difference between two rooms ($L_{p;r} – L_{p;s}$), it includes via $L_{p;r}$ all sound transmission between two rooms, i.e. direct and flanking transmissions. To check a situation against building codes thus requires knowledge of flanking transmission.

To characterise the sound transmission between two rooms often only the direct transmission through the partition wall is considered:

$$L_{p;r} = L_{p;s} - R_d + 10\log\left(S_d / A_r\right)$$ (7.1),

with
$L_{p;r}$ = sound pressure level inside receiver room [dB]
$L_{p;s}$ = sound pressure level inside sender room [dB]
R_d = air-borne sound insulation of partition wall [dB]
S_d = surface area of partition wall [m²]
A_r = total sound absorption of receiver room [m² sabin]

Although not further specified in the "Bouwbesluit", the influence of flanking walls on sound transmission is limitedly mentioned: "in practise, the predicted sound pressure level in the receiver room (according to equation 7.1) is approximately 1 to 2 dB higher because of flanking transmission and sound leaks provided the construction is well-constructed". NPR 5070 "Geluidwering in woongebouwen. Voorbeelden van wand- en vloerconstructies" (1993; "sound insulation in buildings. Examples of wall and floor constructions") more specifically puts requirements on flanking walls specifically related to their mass.

In this chapter, flanking sound transmission between two rooms via the building construction (flanking walls) will be treated.

7.2 Flanking Sound Transmission: Air-Borne Excitation

7.2.1 Acoustic model
The possible sound transmission paths between two rooms are depicted in Figure 7.1. For the direct path (Dd) equation (7.1) is valid. It is explained in previous chapters. Sound transmission via the flanking paths Ff, Df and Fd will be treated in detail in this chapter using an acoustic model. For computing the sound pressure level in the receiver room, caused by sound energy transmitted from sending to receiver room via a flanking path, a mathematical relationship like equation (7.1) will be derived which allows for the calculation of D_{nT} and $I_{lu;k}$ using an easy computation scheme.
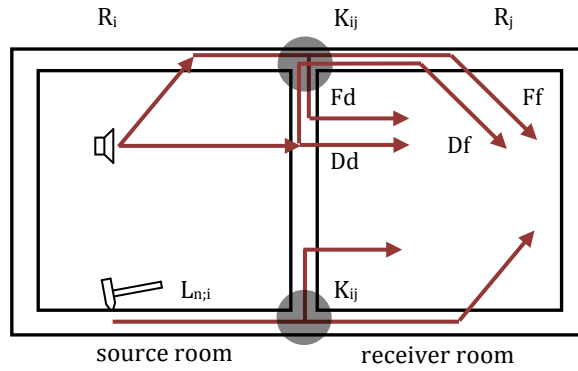
Figure 7.1 – Transmission paths of sound from one room to another.

Concerning the sound pressure level in the receiver room, $L_{p;j}$, resulting from a sound power radiating from surface j, $L_{w;j}$, the following applies:

$$L_{pj} = L_{wj} + 10\log\frac{4}{A_r}$$ (7.2a).

As a result, the following also applies:

$$p^2_{eff;j} = \frac{W_j}{4\rho_{air}c_{air}A_r}$$ (7.2b),

with
$L_{p;j}$ = sound pressure level inside receiver room resulting from surface j [dB]
$p_{eff;j}$ = sound pressure inside receiver room resulting from sound power W_j [N/m²]
$L_{w;j}$ = radiated sound power level by surface j [dB]
W_j = radiated sound power by surface j [W]
ρ_{air} = density of air [kg/m³]
c_{air} = speed of sound in air [m/s].

The sound power which radiates from a vibrating surface j can be calculated as:

$$W_j = \rho_{air}c_{air}\overline{v}_j^2 S_j \sigma_j$$ (7.3),

with
S_j = surface area of surface j [m²]
σ_j = radiation factor of surface j [-].
v_j = the averaged vibration velocity of surface j [m/s]

As p^2_{eff} is a measure of the amplitude of the sound in air, v^2_j defines the amplitude of the vibration in a vibrating construction. The radiation factor is a measure for the amount of acoustic energy that can radiate from a vibrating surface. This factor depends on frequency: above the coincidence frequency of the surface it is 1; below this frequency it is smaller than 1; and at this frequency it is larger than 1. The radiation factor is not only influenced by coincidence frequency but also by the dimensions of the wall.

Because a wave in surface i having a vibration velocity, v_i (Figure 7.1) travels via the junction to surface j, surface j starts to vibrate with a certain velocity, v_j. However, at this junction between surface i, j and the partition wall dampening of the amplitude of the bending wave occurs. As a result
$$\overline{v}_j^2 = d_{ij}\overline{v}_i^2$$ (7.4).

In this equation
d_{ij} = the velocity level difference coefficient between surface i and j [-].

The vibration velocity of surface i, $\bar{v}_i^2$, is determined by the (direct) sound insulation of surface i. The following applies:

$$\tau_i = \frac{W_{i;radiated}}{W_{i;incident}}$$ (7.5),

$$W_{i;radiated} = \rho_{air} c_{air} \bar{v}_i^2 \sigma_i S_i$$ (7.6),

$$W_{i;incident} = \frac{p_{eff;s}^2 S_i}{4 \rho_{air} c_{air}}$$ (7.7),

in which
τ_i = sound transmission coefficient of surface i ($R_i = 10 \log 1/\tau_i$)
$W_{i;radiated}$ = the radiated sound power of surface i [W]
        (assuming that surface i were a direct partition wall between two rooms)
$W_{i;incident}$ = the incident sound power on surface i resulting from a diffuse sound
        field in the sending room [W]
$p_{eff;s}$ = the effective sound pressure in the sending room [Pa].

Combining equations (7.5), (7.6) and (7.7) gives:

$$\bar{v}_i^2 = \frac{p_{eff;s}^2}{4 \rho_{air}^2 c_{air}^2} \cdot \frac{\tau_i}{\sigma_i}$$ (7.8)

The flanking sound transmission coefficient, τ_{ij}, via the surfaces i and j can now be defined as the ratio of the sound power which radiates from surface j in the receiver room and a reference sound power. Since the total sound transmission from the sending towards the receiver room is the sum of all sound transmissions via all surfaces, it is advantageous to use just one reference sound power in the sending room. We have seen in previous chapters that for determining the air-borne sound insulation of wall constructions, the incident sound power on the partition wall between two adjacent rooms, $W_{d;incident}$, is taken. This sound power equals

$$W_{s;ref} = W_{d,incident} = \frac{p_{eff;s}^2}{4 \rho_{air} c_{air}} S_d$$ (7.9),

with
$W_{s;ref}$ = the reference sound power in the sending room [W]
$W_{d;incident}$ = the sound power hitting the direct partition wall in the sending [W]
S_d = the surface area of the direct partition wall [m²].

If no direct partition wall is available, S_d is assumed to be 10 m².

Using equations (7.3), (7.4), (7.8) and (7.9) we can now write for the transmission coefficient τ_{ij}

$$\tau_{ij} = \frac{W_j}{W_{d;incident}} = d_{ij} \tau_i \frac{S_j}{S_d} \cdot \frac{\sigma_j}{\sigma_i}$$ (7.10).

One problem however arises here. In practice, the radiation factors σ_i and σ_j are often not known with sufficient accuracy. A solution to this problem comes from using the principle of force reciprocity. This principle implies that the flanking sound transmission coefficient should remain the same if surfaces i and j are exchanged. Mathematically this implies that

$$\tau_{ij} = \tau_{ji}$$ (7.11).

Applying this principle to equation (7.10) results in

$$d_{ij}\tau_i \frac{S_j}{S_d}\cdot\frac{\sigma_j}{\sigma_i} = d_{ji}\tau_j \frac{S_i}{S_d}\frac{\sigma_i}{\sigma_j}$$ (7.12a),

and thus in

$$\left(\frac{\sigma_j}{\sigma_i}\right)^2 = \frac{\tau_j}{\tau_i}\cdot\frac{d_{ji}}{d_{ij}}\cdot\frac{S_i}{S_j}$$ (7.12b).

Combining equations (7.10) and (7.12) yields

$$\tau_{ij} = \sqrt{\tau_i\tau_j}\sqrt{d_{ij}d_{ji}}\sqrt{\frac{S_iS_j}{S_d^2}}$$ (7.13).

If we finally take the logarithm of both sides and multiply with 10, we can write

$$R_{ij} = \frac{R_i}{2} + \frac{R_j}{2} + \overline{D}_{ij} + 10\log\sqrt{\frac{S_d^2}{S_iS_j}}$$ (7.14),

with
$\overline{D}_{ij}$ $= \left(D_{v;ij} + D_{v;ji}\right)/2$ = the (directional) average junction dampening or velocity level difference [dB]
$D_{v;ij}$ = - 10 log d_{ij} = junction dampening [dB]
R_i = air-borne sound insulation of surface i [dB]
R_j = air-borne sound insulation of surface j [dB]

R_i and R_j are the air-borne sound insulation of these surfaces in the real situation (situ), thus including dampening caused by the edge of the surfaces. As a reasonable approach the measured values from a laboratory (lab) can be taken for R_i and R_j. So,

$$R_{i;situ} = R_{i;lab} - 10\log\frac{T_{s;situ}}{T_{s;lab}} \approx R_{i;lab}$$ (7.15),

in which
T_s = the structural reverberation time of the surface [s]

As the sound pressure level difference between sender and receiver room can be calculated according to equation (7.1) using the situation-independent parameter R_d and the situation-dependent parameters S_d and A_r, the vibration level differences between surface i and j can also be determined from context-independent and context-dependent parameters. This is done as follows

$$\overline{D}_{ij} = K_{ij} - 10\log\frac{l_{ij}}{\sqrt{a_ia_j}}$$ (7.16),

with
K_{ij} = the normalised situation-independent vibration reduction index [dB]
l_{ij} = the length of the contact line between surface i and j [m]
$a_{i,j}$ = a geometric correction factor for surface i and j respectively, i.e. the absorption length [m]

These geometric correction factors, a_i and a_j, are defined as

$$a_i = \frac{2.2\pi^2 S_i}{c_{air} T_{s;i}} \sqrt{\frac{f_{ref}}{f}}$$ (7.17),

with
f = frequency [Hz]
f_{ref} = reference frequency (=1000 Hz).

As a reasonable global estimation, we can say that the value of a practical equals the value of S ($a \approx S$ number-wise), as a consequence of which equation (7.16) changes to

$$\overline{D_{ij}} = K_{ij} - 10\log\frac{l_{ij}}{\sqrt{S_i S_j}}$$ (7.18).

K_{ij} characterises the vibration transmission from surface i to j in a normalised way and independent of the situation. Or in other words, using K_{ij} allows a calculation of the actual junction dampening $\overline{D}_{ij}$ if the parameters l_{ij}, S_j and S_i of the actual situation are known.

Equation (7.14) can now finally be re-written to the fundamental equation for calculating flanking sound transmission

$$R_{ij} = \frac{R_i + R_j}{2} + \Delta R_i + \Delta R_j + \overline{D}_{ij} + 10\log\frac{S_d}{\sqrt{S_i S_j}}$$

$$= \frac{R_i + R_j}{2} + \Delta R_i + \Delta R_j + K_{ij} - 10\log\frac{l_{ij}}{\sqrt{a_i a_j}} + 10\log\frac{S_d}{\sqrt{S_i S_j}}$$

$$\approx \frac{R_i + R_j}{2} + K_{ij} - 10\log\frac{l_{ij}}{\sqrt{S_i S_j}} + 10\log\frac{S_d}{\sqrt{S_i S_j}}$$

$$R_{ij} \approx \frac{R_i + R_j}{2} + K_{ij} + 10\log\frac{S_d}{l_{ij}}$$ (7.19).

In this equation ΔR_i and ΔR_j reflect additional sound reduction resulting from floating screeds, suspended ceilings or a lightweight wall in front of a massive wall. In case of lightweight ceilings, front walls or screeds in front of massive basic constructions, the additional sound insulation of these elements in a direction perpendicular to this element may be taken. In case of lightweight ceilings, screeds and front walls in front of lightweight basic constructions approximately half of their additional sound insulation in perpendicular direction may be taken (Bron-van der Jagt et al., 2010). If no such elements exist, these two terms can be neglected.

7.2.2 Junction dampening and the vibration reduction index
The dampening of acoustic waves inside building constructions occurring at their interface has primarily been experimentally determined. The currently available data mostly only concerns the parameter D_{ij} as expressed in equation (7.14). Concerning the situation-independent vibration reduction index, K_{ij}, hardly any directly measured data is available. The available data mostly derives from measurements of D_{ij} corrected with a global average value derived from practice as

$$K_{ij} \approx \overline{D}_{ij} - 5$$ (7.20).

As can be derived from Figure 7.1, junctions can have the following configurations:
- +-shape:
  - with a straight transmission path
  - with a transmission path at right angles
  - with rigid connections
  - with flexible connections
  - with a lightweight double construction
- T-shape:
  - with a straight transmission path
  - with a transmission path at right angles
  - with rigid connections
  - with flexible connections
  - with a lightweight double construction
  - with a lightweight façade system
- corner
- a change in construction thickness or materialization

A good overview of the vibration reduction index, K_{ij}, with practical examples can be found in Gerretsen (2001). These examples are depicted here as Figure 7.2 to 7.8. In these figures, K_{ij} is expressed as function of the ratio of masses of the construction elements coming together in the node. These K_{ij}-values can only be used in case the construction elements continue from one side of the node to the other and their masses remain the same. In the European standard EN 12354-1 K_{ij} is expressed as function of M defined as

$$M = \log (m_{\perp i} / m_i) \qquad\qquad (7.21a),$$

with
m_i = the mass (per square meter) of construction i as part of transmission from i to j [kg/m^3]
$m_{\perp i}$ = the mass (per square meter) of the construction perpendicular to construction i [kg/m^3]

In agreement with this standard, the variable M in the equations below the following figures is as

$$M = \log (m_2 / m_1) \qquad\qquad (7.21b),$$

with
m_1 = the mass (per square meter) of the flanking construction in the sending room [kg/m^3]
m_2 = the mass (per square meter) of the partition wall perpendicular to construction 1 [kg/m^3]

The choice for the mass ratio m_2 / m_1 is somewhat arbitrary for flanking transmission 'around the corner' since the vibration reduction index, K_{ij}, for, e.g., the transmission from surface 2 to surface 3 is identical to the one for transmission from surface 1 to surface 2. In case of flanking transmission 'around the corner' M could have been defined as $\log (m_1 / m_2)$ instead, producing the same result.

From Figures 7.2 to 7.8 we can derive that, if the partition wall with mass m_2 is very heavy relative to the flanking wall with mass m_1, thus if $m_2 \gg m_1$, the vibration reduction index K_{ij} will be high. The values of R_i and R_j of a lightweight flanking wall as used in equation (7.19) however will be small. The resulting flanking sound reduction index of transmission path Ff via the lightweight flanking wall, R_{Ff}, will in that case also be relatively small particularly at the higher frequencies.

As a final remark, the vibration reduction index, K_{ij}, in many cases does not depend on frequency (expressed with 0 dB/octave); in some other cases a frequency-dependency does exist. Such a dependency is then formulated below the figure.
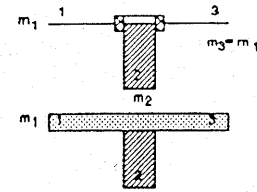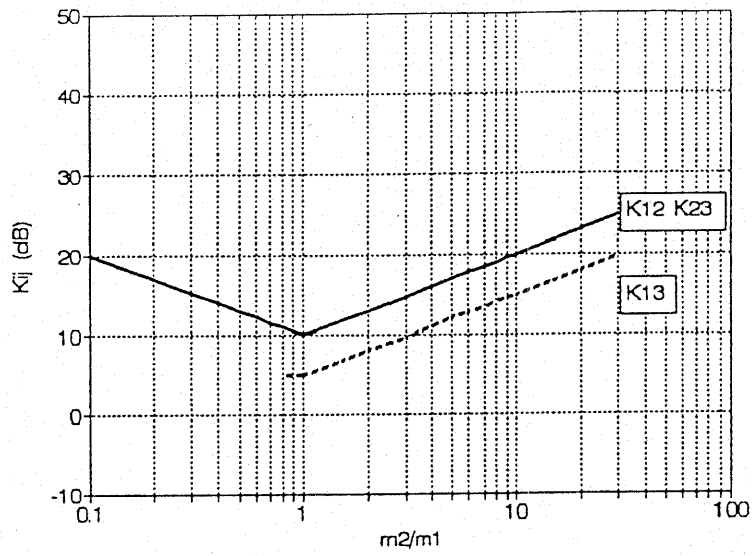
$K_{13} = 5 + 10\,M$ with a minimum of 5 dB;   0 dB/oct.

$K_{12} = K_{23} = 10 + 10\,|M|$;   0 dB/oct.

Examples
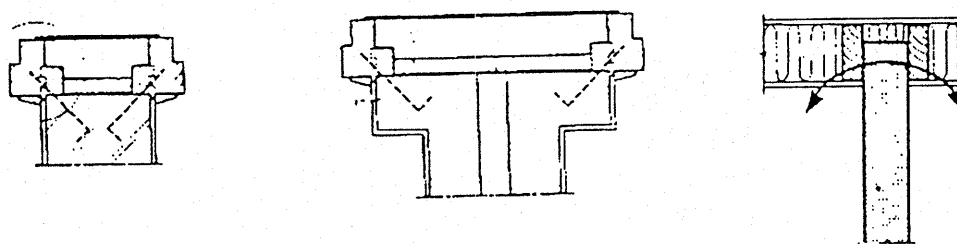

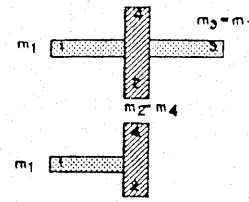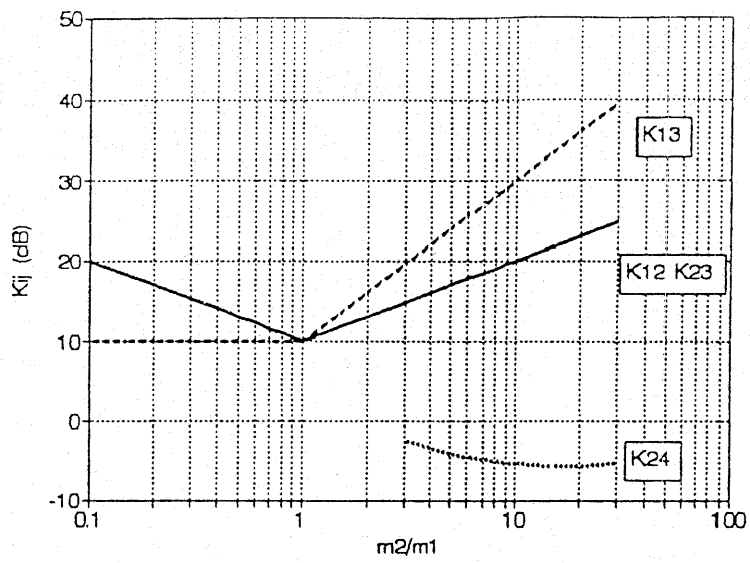Figure 7.2 – Vibration reduction index of lightweight facade systems.

$K_{13} = 10 + 20\ M - 3.3 \log (f / f_0)$ with a minimum of 10 dB;
$K_{12} = K_{23} = 10 + 10\ |M| + 3.3 \log (f / f_0)$;
$K_{24} = 3.0 + 14.1\ M + 5.7\ M^2$; $m_2/m_1 > 3$;   0 dB/oct.

$f_0 = 500$ Hz

Examples
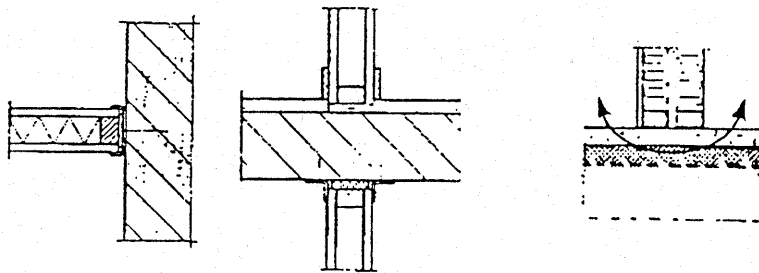
Figure 7.3 - Vibration reduction index of lightweight double consruction with a homogeneous construction.
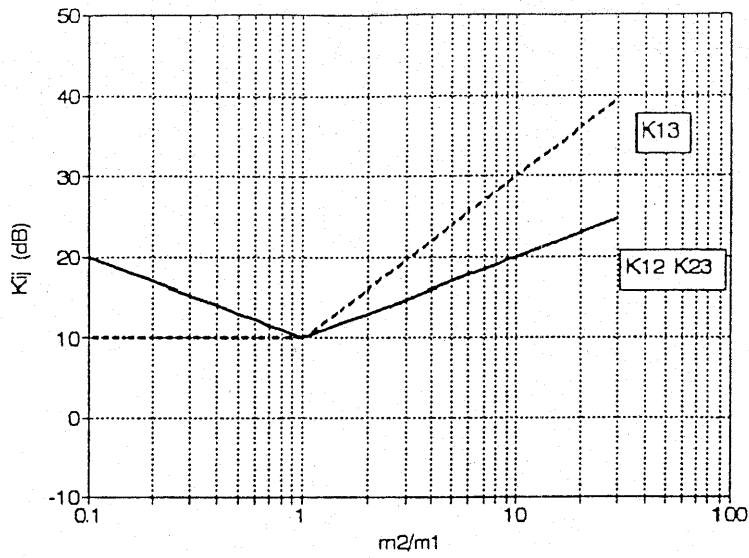
$K_{13} = 10 + 20\,M – 3.3\log(f/f_0)$ with a minimum of 10 dB;

$K_{12} = K_{23} = 10 + 10\,|M| - 3.3\log(f/f_0)$;

$f_0 = 500$ Hz

Examples
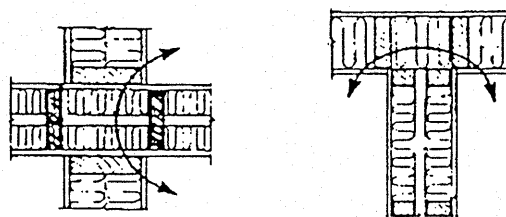
Figure 7.4 - Vibration reduction index of a node with lightweight double constructions.
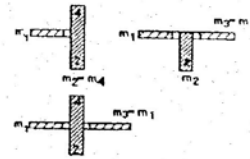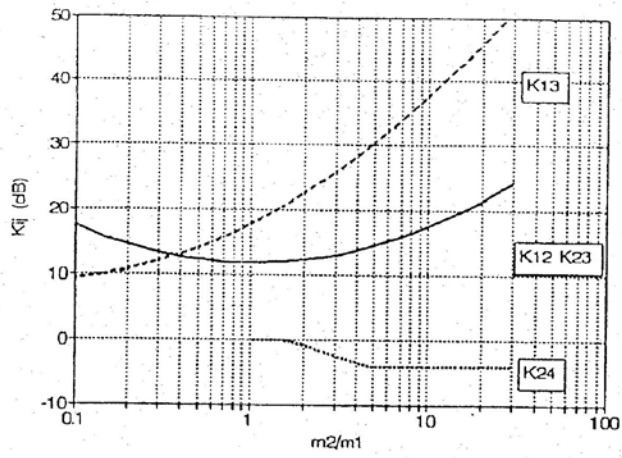
$K_{13} = 5.7 + 14.1\,M + 5.7\,M^2 + 2\,\Delta_1;$
$K_{12} = K_{23} = 5.7 + 5.7\,M^2 + \Delta_1;$
$K_{24} = 3.7 + 14.1\,M + 5.7\,M^2; \qquad 0 \le K_{24} \le -4\ \mathrm{dB}; \qquad 0\ \mathrm{dB/oct.}$

$\Delta_1 = 10 \log (f / f_1) \qquad$ provided that $f > f_1$
$f_1 = 125\ \mathrm{Hz} \qquad$ if $E_1 / t_1 \approx 100\ \mathrm{MN/m^3}$
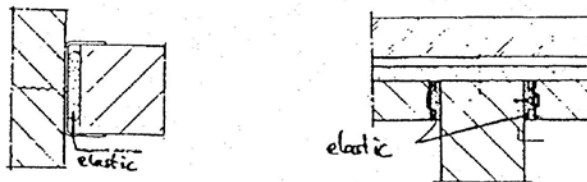
Examples

Figure 7.5 - Vibration reduction index of a node with flexible layers.
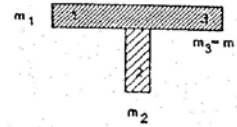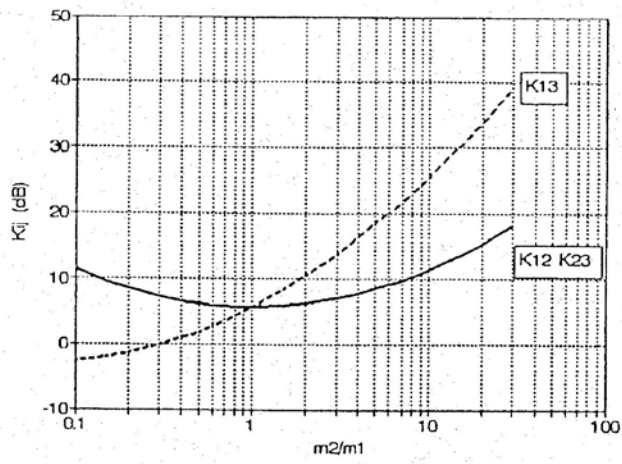
$K_{13} = 5.7 + 14.1\,M + 5.7\,M^2$;   0 dB/oct.
$K_{12} = K_{23} = 5.7 + 5.7\,M^2$;   0 dB/oct.
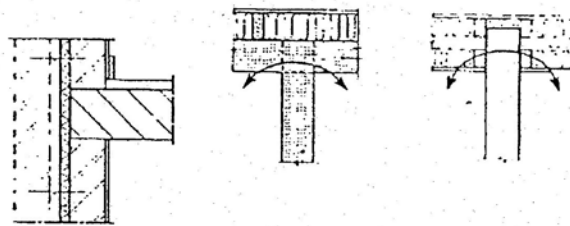
Examples

Figure 7.6 - Vibration reduction index of a rigid T-junction.
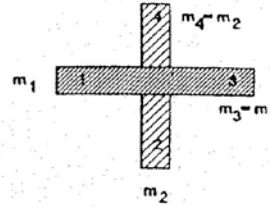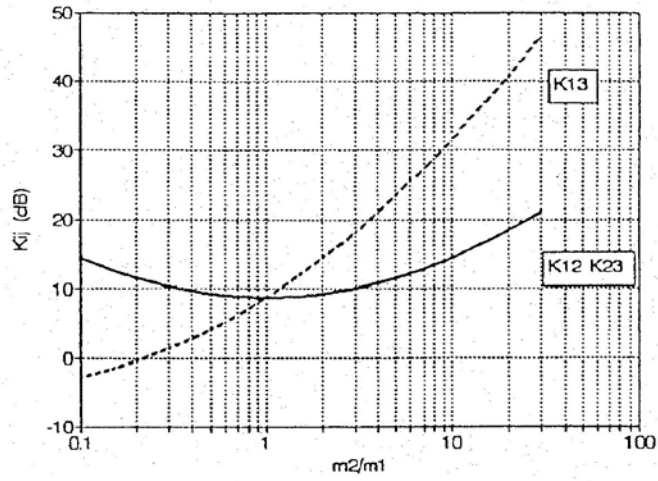
$K_{13} = 8.7 + 17.1\,M + 5.7\,M^2;$ 0 dB/oct.

$K_{12} = K_{23} = 8.7 + 5.7\,M^2;$ 0 dB/oct.

Examples
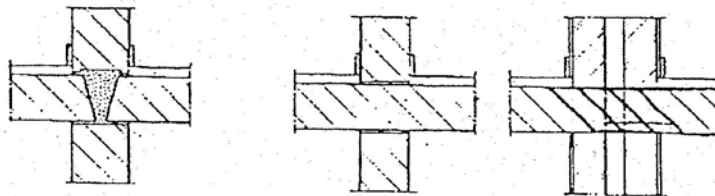
Figure 7.7 - Vibration reduction index of a rigid +-junction.
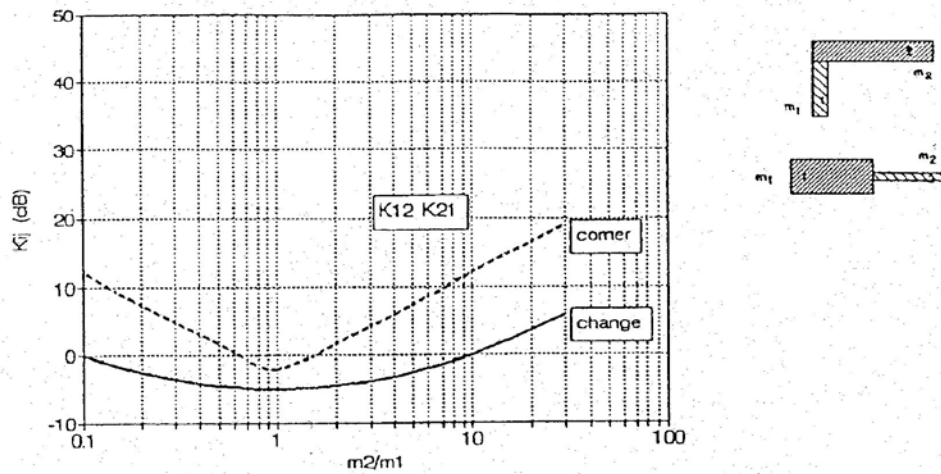
Corner:
$K_{12} = K_{21} = 15\ |M| - 3$;   with a minimum of -2 dB;   0 dB/oct.

Constructional change:
$K_{12} = K_{21} = 5\ M^2 - 5$;   0 dB/oct.

Figure 7.8 - Vibration reduction index of a corner or a constructional change.

7.2.3   Calculation scheme for obtaining total sound insulation between two rooms
The equations derived in the previous sections allow us to calculate the entire direct and flanking sound transmission from one room to another. For such a computation we distinguish several steps:
- Step 1: get acoustic data for all relevant construction elements and junctions by doing measurements, obtaining data from manufacturers or by making estimations;
- Step 2: fit the actual situation into the computation scheme using equations (7.15) and (7.16) (or (7.18)) and make simplifications (concerning the use or not of dampening) if necessary;
- Step 3: calculate R_d for the direct path through the partition wall and R_{ij} for each flanking transmission path using equation (7.19);
- Step 4: Add all transmission paths to obtain the sound insulation between both rooms, R', which is calculated as

$$R' = -10\log\left[10^{-R_d/10} + \sum 10^{-R_{ij}/10} \right]$$ (7.22);

- Step 5: Calculate the normalised sound reduction index, D_{nT}, used by building codes and standards to set limits to the sound transmission in buildings as

$$D_{nT} = R' + 10\log\left[\frac{V}{6S_d T_0} \right]$$ (7.23),

with
V = the volume of the receiving room [m^3]
S_d = the surface area of the partition wall [m^2]
R_d = the air-borne sound insulation of the direct partition wall/floor including front walls, etc.
T_0 = a reference reverberation time (=0.5 s for dwellings and 0.8 s for offices).

As a calculation example, we look at two adjacent and identical cubic rooms of 4 x 4 x 4 m³. The walls and floors have identical mass, identical air-borne sound insulation values (R_d) and identical surface areas. The junction between walls and floors are fixed +-junctions. This implies that R_{ij} is identical for each flanking transmission path, that $m_2 / m_1 = 1$ and thus $M = 0$ and that according to Figure 7.7 the vibration reduction index, K_{ij}, for each flanking transmission path is 8.7 dB ($K_{13} = K_{12} = K_{23}$). For step 2, we neglect dampening, as a result of which the air-borne sound insulation measured in a laboratory equals the one in practice (eq. (7.15)) and the value of the geometric correction factor a equals the value of the surface area of the respective construction wall (eq. (7.15) equals eq. (7.18)). For step 3, we can now use equation (7.19) to calculate the flanking sound reduction index for each transmission path. Since all transmission paths are identical in this simple example we only do this once:

$$R_{ij} \approx \frac{R_i + R_j}{2} + K_{ij} + 10\log\frac{S_d}{I_{ij}} = \frac{R_d + R_d}{2} + 8.7 + 10\log\frac{4\times 4}{4} = R_d + 14.7$$

For step 4, we first have to determine the number of (identical) transmission paths. Via each junction there can be 3 transmission paths and in total there are 4 junctions between both rooms. We thus have 12 identical transmission paths. All flanking and direct transmission paths can now be combines into one value using equation (7.22) as

$$R' = -10\log\left[10^{-R_d/10} + 12\cdot\left(10^{-(R_d+14.7)/10}\right)\right] = -10\log\left[10^{-R_d/10} + 12\cdot\left(10^{-R_d/10}\cdot 10^{-14.7/10}\right)\right]$$

$$= -10\log\left[10^{-R_d/10}\cdot\left(1+12\cdot 10^{-14.7/10}\right)\right] = -10\log\left[10^{-R_d/10}\right] - 10\log\left[1+12\cdot 10^{-14.7/10}\right] = R_d - 1.5$$

As a result in this particular case, the air-borne sound insulation between both rooms is only 1.5 dB worse due to flanking sound transmissions. In many other situations however the influence of flanking transmissions can be much higher. Using the value for R', finally, the normalised sound reduction index, D_{nT}, can be calculated. This final step will be omitted here.

7.2.4 Extended calculation example

As an extended example, the computation scheme for determining the total sound transmission between two rooms will be demonstrated using an example from Braat-Eggen and Luxemburg (1993). This example deals with the sound insulation between two bed rooms on two sides of a wall which separates between two houses (Figure 7.9). The symbols and junction dampening are derived from section 7.2.2.

To be able to calculate the sound reduction between the two bed rooms, the following data is needed:
- The air-borne sound insulation, R_d, and surface area, S_d, of the partition wall between both rooms;
- The air-borne sound insulation, R_i and R_j, and surface area, S_i and S_j, of all adjoining walls/floors;
- The vibration dampening, D_{ij}, of vibration reduction index, K_{ij}, of all relevant junctions;
- The net volume of the rooms, V.

In this example both rooms are identical and have a volume of 30 m³.

Sound insulation and surface area of the partition wall
The partition wall consists of 200 mm concrete, has a surface area of 10 m² and a mass of 460 kg/m². The sound insulation of a 200 mm thick concrete wall equals

f [Hz]	125	250	500	1000	2000
R_d [dB]	38	45	54	62	69
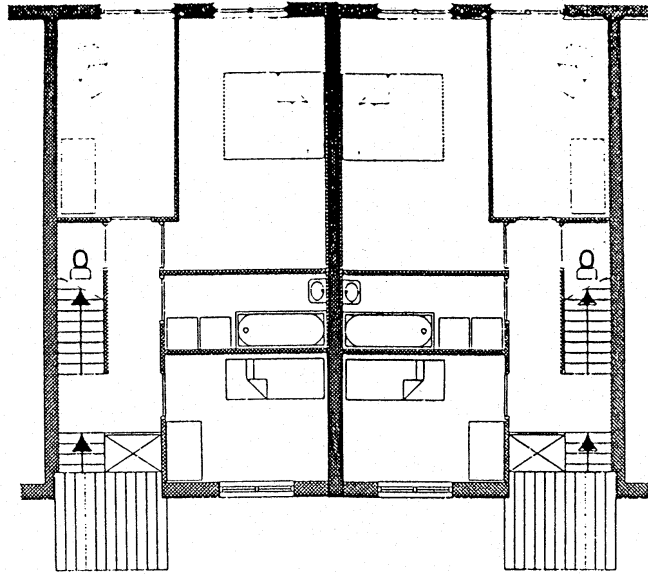
Figure 7.9 - Plans of two adjoining row houses.

Sound insulation and surface area of the adjoining walls and floors
The floor and the ceiling consist of a 180 mm thick concrete slab including 30 mm surface layer. They have a surface area of 12 m^2 and a mass of 471 kg/m^2. The sound insulation of these concrete slabs equals

f [Hz]	125	250	500	1000	2000
R [dB]	41	46	55	63	70

The internal wall that perpendicularly connects to the partition wall consists of 70 mm thick gypsum blocks, has a surface area of 7.5 m^2 and a mass of 67 kg/m^2. The sound insulation of 70 mm thick gypsum blocks equals

f [Hz]	125	250	500	1000	2000
R [dB]	29	29	26	32	41

The façade that connects to the partition wall consists of glass and a masonry cavity wall. It has a surface area of 5 m^2 and a mass of 320 kg/m^2. Since from a perspective of flanking transmission a cavity wall does not act like such a wall, a fictive homogeneous wall is used with a mass equal to the mass of the inner leaf plus half of the mass of the outer leaf. The sound insulation of this modelled façade equals

f [Hz]	125	250	500	1000	2000
R [dB]	36	40	44	53	61

Junction dampening of the adjoining walls and floors
The junction dampening is determined using the mass ratios of the construction walls. In agreement with Figures 7.2 and 7.7 we get

	m_2/m_1	M	K_{ij}	$D_{ij} \approx K_{ij} + 5$
Floor: fixed +-junction (Fig.7.7)				
partition wall - floor (K_{23})	460/471=0.98	-0.01	8.7	14
floor - partition wall (K_{12})	460/471=0.98	-0.01	8.7	14
floor - floor (K_{13})	460/471=0.98	-0.01	8.7	14

Ceiling: fixed +-junction (Fig.7.7)				
partition wall - ceiling (K_{23})	460/471=0.98	-0.01	8.7	14
ceiling - partition wall (K_{12})	460/471=0.98	-0.01	8.7	14
ceiling - ceiling (K_{13})	460/471=0.98	-0.01	8.7	14
Interior walls: fixed +-junction (Fig.7.7)				
partition wall - interior wall (K_{23})	460/67=6.87	0.837	12.7	18
interior wall - partition wall (K_{12})	460/67=6.87	0.837	12.7	18
interior wall - interior wall (K_{13})	460/67=6.87	0.837	27.0	32
Facade: T-junction (Fig.7.2)				
partition wall - façade (K_{23})	460/320=1.44	0.158	11.6	17
façade - partition wall (K_{12})	460/320=1.44	0.158	11.6	17
façade - façade (K_{13})	460/320=1.44	0.158	6.6	12

Now that all relevant acoustic properties have been specified, we can proceed with the calculation. For the direct sound insulation between both rooms, we can immediately use the values of the concrete partition wall. It was specified as

f [Hz]	125	250	500	1000	2000
R_d [dB]	38	45	54	62	69

For the flanking sound transmission paths, we must calculate R_{ij} for instance using equation

$$R_{ij} = \frac{R_i + R_j}{2} + \overline{D}_{ij} + 10\log\frac{S_d}{\sqrt{S_i S_j}} .$$

Please observe that, since we use the simplified calculation of D_{ij} from K_{ij} ($D_{ij} \approx K_{ij} + 5$), a small difference occurs compared to the situation in which we would have used $D_{ij} \approx K_{ij} - 10\log(l_{ij} / \sqrt{(S_i S_j)})$. Using previous equation we calculate for each flanking transmission path the following values

ceiling - partition wall / floor - partition wall

f [Hz]	125	250	500	1000	2000
$R_d / 2$ [dB]	19.0	22.5	27.0	31.0	34.5
$R_{fl} / 2$ [dB]	20.5	23.0	27.5	31.5	35.0
D_{ij} [dB]	14.0	14.0	14.0	14.0	14.0
$10\log(S_d / \sqrt{(S_i S_j)})$ [dB]	-0.4	-0.4	-0.4	-0.4	-0.4
$R_{fl\text{-}d}$ [dB]	53.1	59.1	68.1	76.1	83.1

interior wall - partition wall

f [Hz]	125	250	500	1000	2000
$R_d / 2$ [dB]	19.0	22.5	27.0	31.0	34.5
$R_{int} / 2$ [dB]	14.5	14.5	13.0	16.0	20.5
D_{ij} [dB]	18.0	18.0	18.0	18.0	18.0
$10\log(S_d / \sqrt{(S_i S_j)})$ [dB]	+0.6	+0.6	+0.6	+0.6	+0.6
$R_{int\text{-}d}$ [dB]	52.1	55.6	58.6	65.6	73.6

façade - partition wall

f [Hz]	125	250	500	1000	2000
R_d / 2 [dB]	19.0	22.5	27.0	31.0	34.5
R_{fac} / 2 [dB]	18.0	20.0	22.0	26.5	30.5
D_{ij} [dB]	17.0	17.0	17.0	17.0	17.0
$10 \log (S_d / \sqrt{(S_i S_j)})$ [dB]	+1.5	+1.5	+1.5	+1.5	+1.5
R_{fac-d} [dB]	55.5	61.0	67.5	76.0	83.5

partition wall - ceiling / partition wall - floor

f [Hz]	125	250	500	1000	2000
R_d / 2 [dB]	19.0	22.5	27.0	31.0	34.5
R_{fl} / 2 [dB]	20.5	23.0	27.5	31.5	35.0
D_{ij} [dB]	14.0	14.0	14.0	14.0	14.0
$10 \log (S_d / \sqrt{(S_i S_j)})$ [dB]	-0.4	-0.4	-0.4	-0.4	-0.4
R_{d-fl} [dB]	53.1	59.1	68.1	76.1	83.1

partition wall - interior wall

f [Hz]	125	250	500	1000	2000
R_d / 2 [dB]	19.0	22.5	27.0	31.0	34.5
R_{int} / 2 [dB]	14.5	14.5	13.0	16.0	20.5
D_{ij} [dB]	18.0	18.0	18.0	18.0	18.0
$10 \log (S_d / \sqrt{(S_i S_j)})$ [dB]	+0.6	+0.6	+0.6	+0.6	+0.6
R_{d-int} [dB]	52.1	55.6	58.6	65.6	73.6

partition wall - façade

f [Hz]	125	250	500	1000	2000
R_d / 2 [dB]	19.0	22.5	27.0	31.0	34.5
R_{fac} / 2 [dB]	18.0	20.0	22.0	26.5	30.5
D_{ij} [dB]	17.0	17.0	17.0	17.0	17.0
$10 \log (S_d / \sqrt{(S_i S_j)})$ [dB]	+1.5	+1.5	+1.5	+1.5	+1.5
R_{d-fac} [dB]	55.5	61.0	67.5	76.0	83.5

ceiling - ceiling / floor - floor

f [Hz]	125	250	500	1000	2000
R_{fl} [dB]	41.0	46.0	55.0	63.0	70.0
D_{ij} [dB]	14.0	14.0	14.0	14.0	14.0
$10 \log (S_d / \sqrt{(S_i S_j)})$ [dB]	-0.8	-0.8	-0.8	-0.8	-0.8
R_{fl-fl} [dB]	54.2	59.2	68.2	76.2	83.2

interior wall - interior wall

f [Hz]	125	250	500	1000	2000
R_{int} [dB]	29.0	29.0	26.0	32.0	41.0
D_{ij} [dB]	32.0	32.0	32.0	32.0	32.0
$10 \log (S_d / \sqrt{(S_i S_j)})$ [dB]	+1.2	+1.2	+1.2	+1.2	+1.2
$R_{int-int}$ [dB]	62.2	62.2	59.2	65.2	74.2

façade - façade

f [Hz]	125	250	500	1000	2000
R_f [dB]	36.0	40.0	44.0	53.0	61.0
D_{ij} [dB]	12.0	12.0	12.0	12.0	12.0
$10 \log (S_d / \sqrt{(S_i S_j)})$ [dB]	+3.0	+3.0	+3.0	+3.0	+3.0
R_{f-f} [dB]	51.0	55.0	59.0	68.0	76.0

Combining all 13 (1 direct and 12 flanking) transmission paths according to equation (7.22) then results in the total sound insulation between both rooms. The results are presented below.

Summary of all transmission paths and combination into one total value

f [Hz]	125	250	500	1000	2000
R_d [dB]	38	45	54	62	69
$R_{\text{floor - d}}$ [dB]	53.1	59.1	68.1	76.1	83.1
$R_{\text{ceiling - d}}$ [dB]	53.1	59.1	68.1	76.1	83.1
$R_{\text{interior wall - d}}$ [dB]	52.1	55.6	58.6	65.6	73.6
$R_{\text{facade - d}}$ [dB]	55.5	61.0	67.5	76.0	83.5
$R_{\text{d - floor}}$ [dB]	53.1	59.1	68.1	76.1	83.1
$R_{\text{d - ceiling}}$ [dB]	53.1	59.1	68.1	76.1	83.1
$R_{\text{d - interior wall}}$ [dB]	52.1	55.6	58.6	65.6	73.6
$R_{\text{d - facade}}$ [dB]	55.5	61.0	67.5	76.0	83.5
$R_{\text{floor - floor}}$ [dB]	54.2	59.2	68.2	76.2	83.2
$R_{\text{ceiling - ceiling}}$ [dB]	54.2	59.2	68.2	76.2	83.2
$R_{\text{interior wall - interior wall}}$ [dB]	62.2	62.2	59.2	65.2	74.2
$R_{\text{facade - facade}}$ [dB]	51.0	55.0	59.0	68.0	76.0
R' [dB]	36.8	43.0	49.8	57.4	65.0
R_d - R' [dB]	1.2	2.0	4.2	4.6	4.0

With a volume of 30 m³ and a surface area of the partition wall of 10 m², the normalised sound reduction index, D_{nT}, between both rooms can now be calculated according to equation (7.23). The results are presented in the table below

normalized sound reduction index and standardised values

f [Hz]	125	250	500	1000	2000
D_{nT} [dB]	36.8	43.0	49.8	57.4	65.0
standardised values [dB]	34.0	43.0	50.0	53.0	54.0
difference [dB]	+2.8	0.0	- 0.2	+4.4	+11.0

The air-borne sound insulation index, I_{lu}, can now be calculated using the difference between D_{nT} and the standardised values. It is the smallest value of the following three situations:
  a.) the average value of the five differences in sound insulation (125 Hz to 2000 Hz), rounded to the closest integer; here: (+2.8+0.0-0.2+4.4+11.0)/5 = 3.6 dB = +4 dB;
  b.) the average value of the two algebraically smallest differences in sound insulation added with 2 dB, rounded to the closest integer; here: (+0.0-0.2)/5 + 2.0 = 2.0 dB = +2 dB;
  c.) the algebraically smallest difference in sound insulation added with 4 dB, rounded to the closest integer; here: -0.2 + 4.0 = 3.8 dB = +4 dB;
I_{lu} here thus equals +2 dB.

The characteristic air-borne sound insulation index, $I_{\text{lu;k}}$, can finally be computed from

$$I_{lu;k} = I_{lu} - 10\log\left[\frac{V}{6 T_o S_d}\right] - 1 = 2 - 10\log\left[\frac{30}{6 \cdot 0.5 \cdot 10}\right] - 1 = 1\, dB\ (T_0 = 0.5\, s)$$

7.3 Flanking Sound Transmission: Structure-Borne Excitation

In the previous sections only air-borne excitation of construction elements was considered. Such air-borne excitation might be caused by a radio, a television, a human voice, etc. In practice however structure-borne excitation, for instance caused by a washing machine, other equipment or women walking on high heels, must sometimes be considered as well. In this section the equation describing flanking sound transmission caused by structure-borne excitation or impact sound will be presented. Since in both cases we deal with

flanking transmission, the transmission of waves from one room to the other is identical. The only difference lies in the way the construction is caused to vibrate.

Using a similar procedure as in section 7.2.1 and again using the principle of force reciprocity, the governing equations for flanking transmission caused by impact noise can be derived. The sound pressure level in the receiver room, $L_{n;ij}$, caused by element i in the receiver room with $L_{n;ii}$ equals

$$L_{n;ij} = L_{n;ii} - \Delta L_{n;ii} - \Delta R_j + \frac{R_i - R_j}{2} - \overline{D}_{ij} - 10\log\sqrt{\frac{S_j}{S_i}} \qquad (7.24a).$$

As an estimate, neglecting dampening, we can also simplify this equation as

$$L_{n;ij} = L_{n;ii} - \Delta L_{n;ii} - \Delta R_j + \frac{R_i - R_j}{2} - K_{ij} - 10\log\frac{S_i}{l_{ij}} \qquad (7.24b).$$

It is important finally to realise that due to the way the structure is excited, usually only two flanking transmission paths exist: Ff and Fd in case a floor, ceiling or parallel wall is excited. Based upon these paths, the total sound pressure level in the receiver room can be calculated from

$$L_{p;r} = 10\log\left(\sum 10^{L_{n;ij}/10}\right) \qquad (7.25).$$

7.4   Flanking Sound in Practice

7.4.1   Building constructions that separate between dwellings

Flanking sound transmission is particularly important for the sound proofing between two dwellings. Flanking transmissions lead to a reduction of the total sound insulation of 1 to 2 dB. This reduction in fact needs to be compensated with a better acoustic performance of the direct partition wall because performance requirements are set for $I_{lu;k}$ which includes both direct and flanking transmissions. The calculation example of section 7.2.4 shows us that this indeed is the case. The sound insulation of the 12 flanking transmission paths combined was calculated as

f [Hz]	125	250	500	1000	2000
R [dB]	43.0	47.3	51.9	59.2	67.2

This sound insulation must be seen against the sound insulation of the direct partition wall which was given as

f [Hz]	125	250	500	1000	2000
R [dB]	38	45	54	62	69

As can be seen, in the lower frequency range (125 to 250 Hz), the direct path is most dominant for the total sound transmission between both rooms; in the middle and higher frequency range (higher than 500 Hz), the flanking paths are dominant. If we look in more detail at the calculation results in section 7.2.4, we see for the frequencies 500 to 2000 Hz that especially the transmission paths related to the lightweight interior wall reduce the total sound insulation. At the lower frequencies also the transmission via the façade has its share. If the lightweight interior wall were perfectly de-coupled from the partition wall, as shown in Figure 7.10, and the sound insulation of the transmission path façade – façade alone played a role, R' and thus D_{nT} at 500 Hz would never be higher than -10 log ($10^{-5.4}$ + $10^{-5.9}$) = 52.8 dB. The determining sound insulation difference would then become approximately 3 dB higher (52.8 – 49.8). And as a result, $I_{lu;k}$ would become +4 dB instead of +1 dB. An even better improvement can be obtained by also de-coupling the interior leaf of the façade from the partition wall.
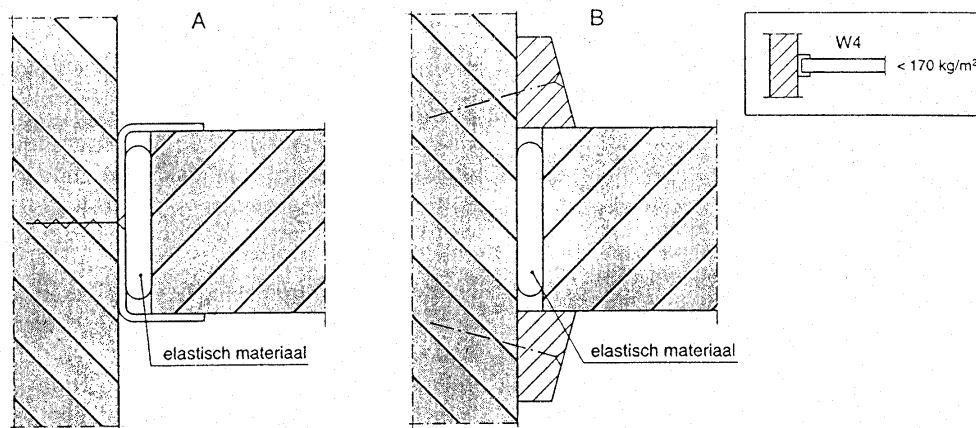
Figure 7.10 – Flexible connection of a lightweight interior wall to a partition wall separating between two dwellings. Materials of the interior wall can be cellular concrete, lightweight concrete, gypsum blocks etc.

More details concerning the connection of flanking walls to partition walls in residential buildings can be found in the Dutch Guideline NPR 5070 "Geluidwering in woongebouwen. Voorbeelden van wand- en vloerconstructies" ("Sound proofing in residential buildings. Examples of wall and floor constructions").

7.4.2   Effect of lightweight walls in front of massive walls
A construction often used to improve the air-borne sound insulation of walls is a lightweight wall placed in front of the original wall, or a suspended ceiling or a floating screed on top of a floor. The essence of these additions is that they are hardly connected to the original wall, floor or ceiling thus creating an unconnected cavity construction. As a result of this type of construction the dynamic behaviour of the original wall, floor is ceiling is not affected by the addition. For flanking sound transmission the effect of this addition can thus be neglected and the modeling described in previous sections can be used. The additional construction however does have an effect on the direct air-borne sound insulation of the construction. This effect can be described as a reduction ΔR of the direct partition wall or of the flanking construction element.

7.4.3   Aluminium-glass facades
A typical example of a curtain wall facade onto which a separation wall is connected is shown in Figure 7.11. Resulting from the desire for flexibility, the façade is designed in such a way that for instance at every 1.80 m or even 0.90 m a separation wall can be connected to the façade. This interior wall then connects to the aluminium mullions of the façade and not to for example a concrete column as part of the load-bearing structure. The total façade construction then acts as a flanking surface. Despite the fact that the requirements on the sound insulation between offices is 8 to 14 dB less than compared to dwellings (Table 7.1), the influence of the sound transmission via the façade is noticeable and important to consider.

Figure 7.2 for instance gives for a lightweight façade construction with $m_{separation\ wall} / m_{facade}$ = 1 a vibration reduction index, K_{13}, of 5 dB and thus D_{13} of approximately 10 dB. Because however the façade is not monolithic but consists of several interconnected parts allowing certain flexibility, Figure 7.2 gives a very rough estimate of the junction dampening. It is therefore wise to use laboratory measurements in stead.

room type	minimum required air-borne sound insulation index for	
	accommodation space	circulation space
normal cellular offices	-14	-26
cellular offices with privacy	-8	-20
open-plan offices	-14	-26
consultation rooms	-14	-26
meeting rooms	-8	-20

Table 7.1 – Required air-borne sound insulation index between rooms from the perspective of functionality.

Figure 7.11 - Aluminium curtain wall suitable for connection with interior walls.

For determining the flanking sound transmission in a laboratory the following equation applies

$$R_f = L_{p;s} - L_{p;r} + 10\log\frac{S_o}{A_r} + 10\log\frac{l}{l_o} \qquad (7.26),$$

with

R_f = the flanking sound reduction in a laboratory [dB]
S_0 = a reference surface area (=10 m^2)
l = the length of the mutual line between the partition wall and the flanking wall [m]
l_0 = a reference length (=2.8 m)
A_r = the sound absorption in the receiver room [m^2 sabin].

The flanking sound transmission reduction occurring in an actual non-laboratory situation can now be calculated from

$$R_{ij} = R_f + 10\log\frac{S_d}{S_o} + 10\log\frac{l_{ij}}{l_o} \qquad (7.27).$$

Research has shown that the total surface area of the flanking façade on both the sending and the receiving side is not relevant. The surface of the façade further than about 2.5 m away from the interior wall no longer participates in the flanking sound transmission. Measurements have shown that the sound transmission is mainly determined by the surface of the façade which continues from the interior wall to the second mullion at most; each mullion also adds a certain amount of dampening. The junction dampening between mullion and glass can be increased if an operable window in stead of a fixed glass sheet is used (Figure 4.12); the improvement of the flanking sound reduction can be about 6 dB in that case since the material used for closing the gaps dampens the vibrations. In stead of connecting the elements of

the aluminium-glass façade rigidly, the posts onto which the interior wall connects can also be dilated. This also gives a performance improvement of about 7 dB compared to the rigid construction.

Curtain walls are mostly constructed of tubular profiles giving stiffness and strength to the façade. These tubular profiles, if they are situated on the inside of the façade, are so to speak part of the direct separating construction. This implies that in case of a mullion with a depth of 80 mm and a room depth of 5.2 m approximately 1.5% of the partition area consists of this tubular profile. The sound insulation of such tubular profiles is negatively influenced by resonances inside its cavity. For particularly the bigger profiles this resonance occurs in the mid-frequency range which is especially important for I_{lu}. An effective means to improve the sound insulation of the tubular profile is to increase its mass or to add absorption material in its cavity.

Table 7.2, taken from (Meyer and Neumann, 1979), finally, presents an overview of the flanking sound reduction, R_f, of aluminium-glass façades.
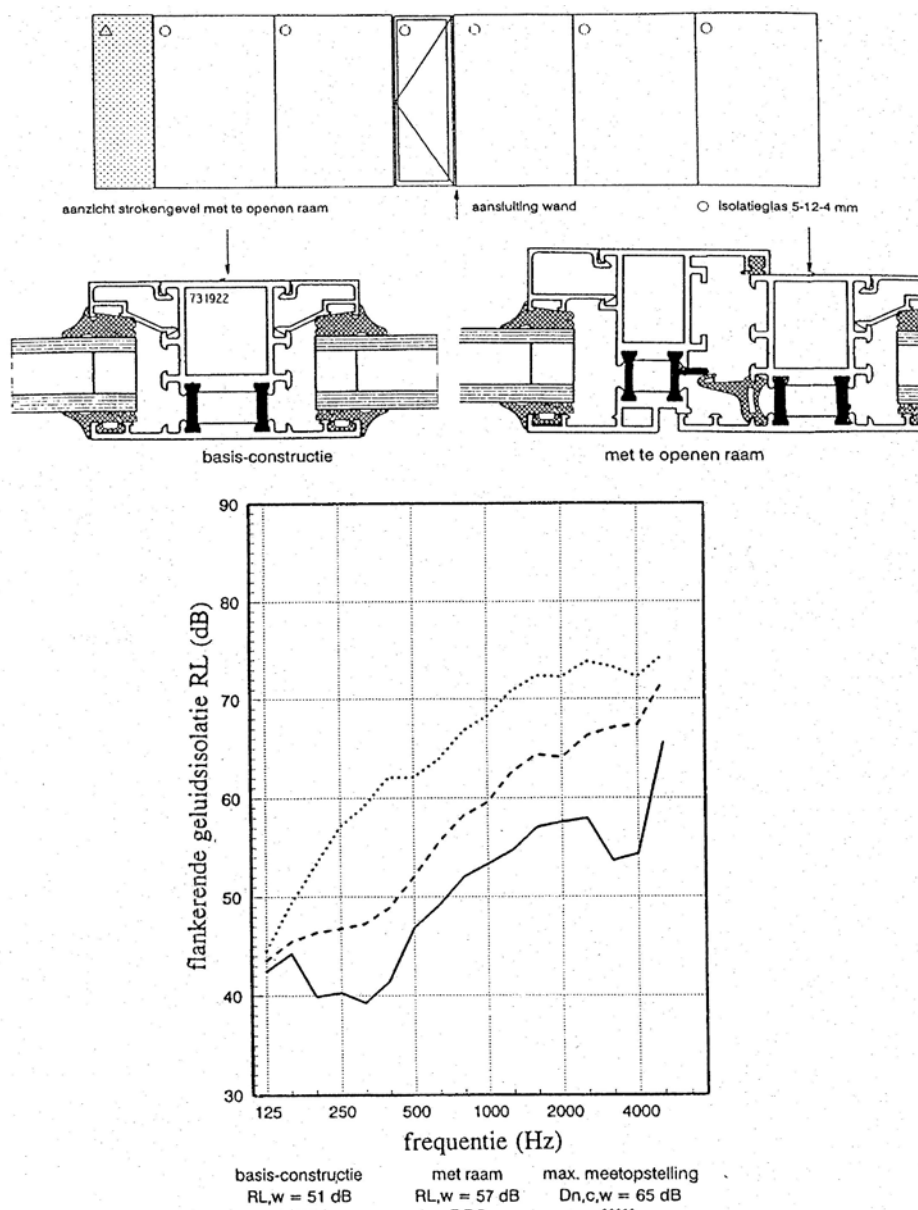

Figure 7.12 – Results of measured flanking sound reduction of a curtain wall with and without operable windows.
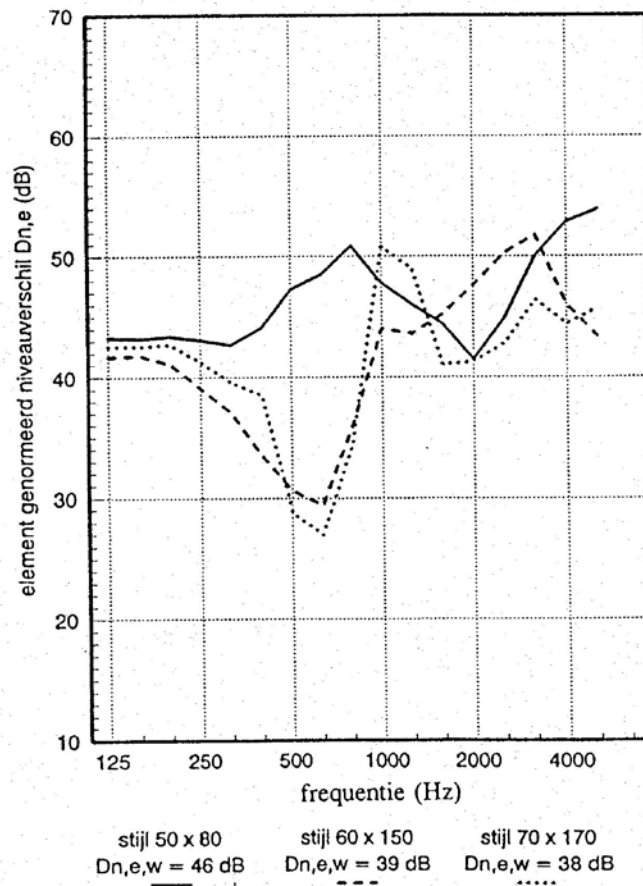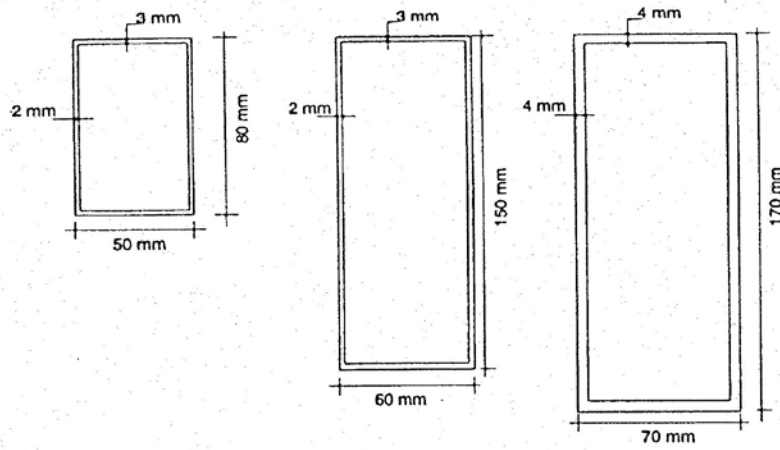
Figure 7.13 - Measured air-borne sound insulation of three types of tubular profiles.

7.5   Literature

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