Measurement of flanking sound transmission at low frequencies with a laser doppler vibrometer

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Summary
In a recent research project one new and two existing approaches for the measurement of flanking sound transmission by a particular path were applied at a wall-floor junction mock-up and the measurement results were analyzed. With the common indirect method of ISO 10848 the sound pressure level difference between two rooms is measured, when transmission occurs by a single flanking path. This is realized by shielding certain surfaces of the separating and flanking elements in the source and receiving room to suppress their excitation and radiation. However, the method lacks in the low frequency range, as there, usually only very conservative estimates can be obtained for flanking sound insulation, because the direct sound insulation of shielded separating element is still smaller. With the second existing approach flanking sound transmission is predicted with the EN 12354-methods using measured input data of the element performance and of the vibration reduction index K_{ij} for the junction. Hereby, the source element is excited structurally and velocity level differences are measured on the coupled elements. The third new method is more related to the first approach as in the source room the measurement procedure is the same. In the receiving room the sound power radiated by an element is determined numerically with the so-called Discrete-Calculation-Method from its surface velocity distribution that is measured with a scanning laser Doppler vibrometer. In this paper the applied methods are outlined and their benefits and disadvantages are highlighted regarding to the obtained low frequency flanking sound insulation estimates.

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1. INTRODUCTION

The standard-series EN 12354, aka ISO 15712, contains methods for the prediction of the apparent sound insulation in buildings in the stage of their design. It accounts for direct sound transmission through the separating element as well as for so-called first order flanking paths. The standard series ISO 10848 contains test protocols to measure part of the necessary input data for EN 12354 calculations, namely the structure-borne sound transmission at junctions of adjoining building elements. For junctions of homogeneous monolithic elements the so-called Vibration Reduction Index K_{ij} can be determined from measured velocity level differences using the direct method of the standard ISO 10848. For junctions of lightweight framed building elements, that are certainly less homogeneous, the indirect method of ISO 10848 is more suitable, where flanking sound transmission of a single isolated flanking path is measured in a section of a building using common airborne sound measurements.

The indirect method was already successfully applied in other laboratories [1], however, in the low frequency range only very conservative estimates can be obtained for some flanking paths due to dominating direct sound transmission. Methods to improve data for symmetric cross-junctions use the similarity of paths [2], but unfortunately this is not suitable for non-symmetric T-junctions in the scope of current research projects at Empa. To validate and improve data for this case, in this paper path estimates from the indirect and direct method are compared with results from a new method based on the so-called Discrete-Calculation-Method [3]. Hereby, the sound power radiated from the building element on the receive side is calculated numerically assuming an array of piston sources with same velocity amplitude and phase as measured on a grid on the surface with a laser Doppler vibrometer. This paper mainly focusses on airborne sound insulation. Nevertheless, methods and findings are also valid for impact sound insulation.

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2. APPLIED METHODS

2.1. Indirect Method of ISO 10848

The measurement protocol of the indirect method is essentially the same as in ISO 10140 for sound insulation testing of building elements in the laboratory. However, a special flanking facility is necessary to accommodate a complete building junction. The facility has to provide a high sound insulation to avoid unwanted flanking. To further isolate a single (flanking) transmission path, some surfaces of the junction are shielded to suppress their excitation or radiation. The applied shielding usually consists of additional layers of board materials placed on thick layers of fibrous absorbers in front of the test specimen. Care has to be taken that there are no rigid connections between the shielding and the specimen and that all joints are sealed elastically.
For a T-junction the necessary shielding conditions for all relevant paths are shown in Figure 1. Denotations are according to EN 12354, where "F" and "f" indicates paths with flanking element and "D" and "d" with the separating element. Capital letters indicate the source and lower case letters the receiving room. The green blocks are shieldings.
Further, it is advisable to determine further the contribution of direct transmission through the shielded separating element for each shielding condition "Ff", "Fd" and "Df" in Figure 1. This limit due to direct sound insulation is measured when flanking transmission is suppressed by shielding all flanking surfaces as shown exemplary for condition "Fd" in Figure 2. The direct transmission can be subtracted energetically from the measured flanking sound reduction index. However, this component is often much larger at low frequencies due to the mass-spring-mass resonances of the shielding. If the difference of measured sound reduction index is less than a threshold of 3 dB it is assumed that flanking sound insulation is only 6 dB larger than the measured limit, which gives a conservative estimate. In Figure 3 the measured sound reduction index for shielding condition "Fd", the limit of direct sound insulation and the corrected flanking path estimate are presented. Below 100 Hz direct sound transmission is dominating and a correction of 6 dB was used. Above 4 kHz the correction was omitted as all measured data are limited by background noise due to the high sound insulation.
In the Empa flanking facility the sound pressure levels were measured with rotating microphones in all rooms simultaneously. The source room was excited at two fixed loudspeaker positions with broad band noise. The reverberation times were measured using impulse response techniques and sweep excitation. The sound reduction index was always determined in both directions and averaged arithmetically to reduce measurement uncertainty, e.g. by calibration errors.

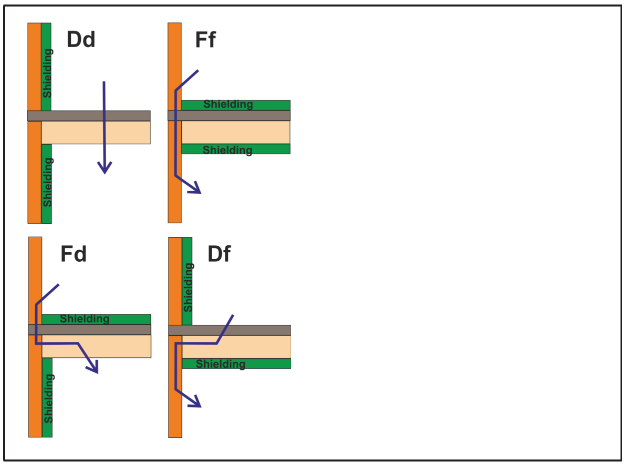

Figure 1. Shielding conditions, indicated by green blocks, necessary to characterize all flanking paths at a T-junction using indirect method according to ISO 10848. Denotations are according to EN 12354.

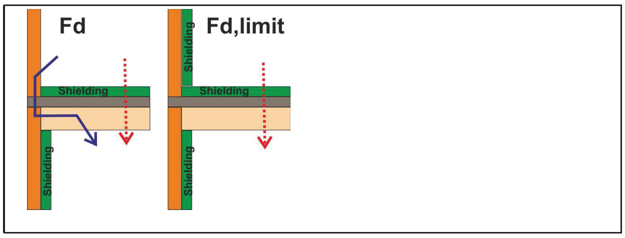

Figure 2. Shielding conditions for the measurement of the flanking path sound insulation "Fd" (left) and for the corresponding limit of direct transmission (right).

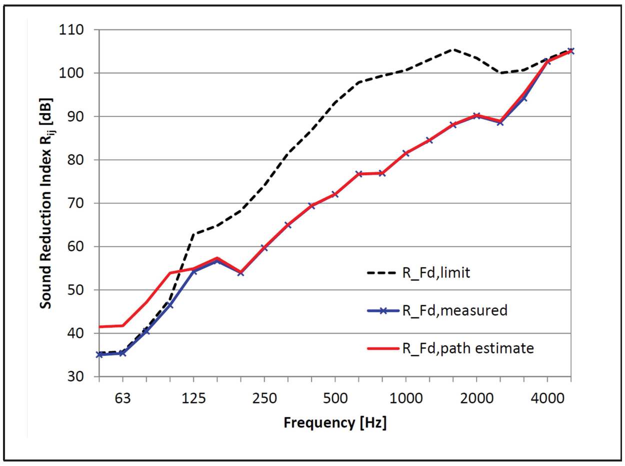

Figure 3. Measured sound reduction index of shielding condition "Fd", "Fd,limit" and estimate of flanking path "Fd" of indirect method acc. to ISO 10848.

2.2. Direct Method of ISO 10848

The direct method determines structure-borne sound transmission between two elements of a junction "directly" from the measured velocity level differences $D_{v,ij}$ and $D_{v,ji}$ between the two elements i, j when the first is excited mechanically. From the direction averaged velocity level difference $\overline{D_{v,ij,lab}}$ of both directions a situation independent quantity, the so-called Vibration Reduction Index K_{ij}, can be obtained by normalization with the junction length l, with the areas S_i and S_j and the structural reverberation times T_s of the two elements. However, in this paper the flanking sound reduction index is of main interest and in the lab measured $\overline{D_{v,ij,lab}}$ is directly used as input data $\overline{D_{v,ij,situ}}$ to predict the Flanking Sound Reduction Index R_{ij} in the lab using Equation 1 from EN 12354-1.

$$R_{ij} = \frac{R_{i,situ} + R_{j,situ}}{2} + \overline{D_{v,ij,situ}} + 10\lg\frac{S_S}{\sqrt{S_i S_j}} \quad (1)$$

Hereby, the area S_S of separation and the sound reduction index $R_{i,situ}$ and $R_{j,situ}$ of the coupled elements for direct, resonant transmission have to be known. To transfer $R_{i,lab}$ from the lab to a field situation two steps are necessary. First, below coincidence frequency f_c sound is transmitted also by forced waves. This non-resonant component can be removed with equation 2 using the radiation efficiency for airborne σ_a and for structure-borne excitation σ_s. The method was proposed by [3] and is already included in a working group draft for revision of EN 12354-1.

$$R^* = R_{i,lab} + 10\lg\frac{\sigma_a}{\sigma_s} \quad (2)$$

For common monolithic buildings elements the coincidence frequency is usually low. Equation 2 can be omitted and marginally more conservative results are obtained in the prediction. The coincidence frequency of the relatively light and stiff elements in this paper is in the mid-frequency range. Thus, non-resonant transmission has a much greater effect and the use of Equation 2 is advisable.

The next step is the adjustment of R^* by using Equation 3 accounting for the difference in the structural reverberation time T_s when installed in the lab and the field situation. This adjustment is especially important for elements with small internal loss factors (<0.03). In this case the total loss factor is governed by edge losses due to transmission of structure-borne sound to adjoining building elements which might be grossly different for laboratory and field situation.

$$R_{i,situ} = R^* - 10\lg\frac{T_{s,situ}}{T_{s,lab}} \quad (3)$$

In this research project the velocity level differences were measured with a PAK-MK II data acquisition system from Müller BBM VAS. Each element was excited with a shaker and pink noise at 3 positions. For each excitation position the velocity was measured at 12 fixed positions on each of the four elements of interest (lower and upper wall, floor and ceiling). Excitation and measurement positions were randomly distributed on the whole surface except for the floor where only accelerometer positions on the excited one of the two prefab floor elements were considered. Further, always the surface exposed to the source room was excited and also the velocity levels were measured on this side. For double leaf elements like the floor-ceiling-assembly this measurement strategy requires that $R_{i,situ}$ and $R_{j,situ}$ is the sound insulation of the leaf only and not of the complete floor-ceiling - assembly [5]. Often, this data is not available from testing, but can be estimated using Equation 4. For simplicity the radiation efficiency σ_s is assumed being equal on the room-side and cavity-side. This is a good first approximation as measurements in the cavity are not possible. Only the mass-per-unit area m" of the leaf and the specific impedance of air $\rho_0 c_0$ are necessary, in addition to the data required for the prediction of flanking.

$$R^* = 10\lg\frac{4.4\pi f^2 m"^2}{\rho_0^2 c_0^2 f_c T_s \sigma_s^2} \quad (4)$$

The advantage of the direct method is that no special facility and no shielding is necessary. Measurements can be conducted at junction mock-ups or in real buildings and all relevant velocity level differences can be measured at once. However, the prediction using EN 12354 also requires additional data of the coupled elements that often are not readily available for lightweight elements and have to be measured.

2.3. Discrete Calculation Method

The third applied method is a new approach based on the "Discrete Calculation Method" (DCM) [4]. Hereby, in the source room it is proceeded equally as for the indirect method. The room is excited with a loudspeaker, shielding has to be applied to isolate certain flanking paths and the average sound pressure level L_1 is measured. In the receiving room no shielding is applied and the sound power radiated from the flanking element $L_{w,2}$ in Equation 5 is determined numerically by using the DCM from the complex surface velocity measured in a regular spaced grid on the elements.

$$R_{ij} = L_1 - L_{W,2} - 6 - 10\lg(S_S) \quad (5)$$

The radiated sound power $W_{rad,2}$ is calculated numerically using Equation 6 assuming an array of piston sources that have the same amplitude and phase as the measured FFT velocity spectra.

$$W_{rad,2} = \sum_{i=1}^{N}(\Re(Z_{ii}G_{vivi}) + \sum_{j=1,j\neq i}^{N}\Re(Z_{ij}G_{vivj})) \quad (6)$$

The first term in Equation 6 describes the sound power radiated by each piston source independently

from the others. It is a function of the velocity autospectrum G_{vivi} at the N-measurement points and of the complex self radiation impedance Z_{ii} of each piston source i. The second term accounts for the interaction between the piston sources. This term is a function of the velocity cross spectrum G_{vivj} of the grid points i and j and the mutual radiation impedance Z_{ij} of the piston sources. For simplification circular piston sources are assumed that have the same area as the rectangular cells of the measurement grid. Equations for Z_{ii} and Z_{ij} are omitted in this paper as they can be found in [4] and many text books. An important requirement for DCM is the spacing of neighbouring measurement points s that should be less than half a bending wavelength λ_B at the maximum frequency of interest, or at the coincidence frequency, whatever is lower. Above coincidence the radiation efficiency of a plate approaches unity as it will be the case in Equation 6 for $s > \lambda_B/2$, too. Equation 6 is evaluated for each frequency line of the FFT-spectrum and the results are digitally filtered to one-third octave bands.
The great advantage of the described method is that the radiated sound power of a plane surface can be determined relative easy without any measurements of airborne sound. This holds also for surfaces that are not the dominating sources in a receiving room, in which case sound intensity measurements fail. The DCM-method was also applied and validated at Empa for the measurement of the sound radiation efficiency at lightweight structures [5].
In this research project the complex velocity distribution was only measured with a laser vibrometer from outside on the lower wall of the T-junction specimen. The regular spaced point grid had 1118 points with 10.8 cm horizontal and vertical spacing. An FFT with 3200 lines and with a frequency resolution of 2 Hz was performed. The phase relationship between the grid points was determined from the transfer function of the velocity at the grid points and at a fixed reference point on the wall. The upper room was excited with a loudspeaker and pseudo-random noise. The sound pressure level in the source room was measured with a rotating microphone and averaged over the whole measurement period.

3. EXPERIMENT

3.1. Empa Flanking Facility

The Flanking Facility for lightweight construction on the Empa-Campus in Dübendorf was realized and is operated with the Berne University of Applied Sciences in Biel. The facility can accommodate test specimens that divide the space into a maximum of four rooms, with two on the ground floor and two above. One side and one back wall of the facility consists of a permanent concrete L-shaped structure, the so-called backbone, to provide the necessary structural support for the specimens. After installation of a specimen missing walls and floors are added with movable wooden wall and roof elements that belong to the facility. This gives a very flexible system suitable for all kind of investigations. Further, all facility walls and floors have a very high direct and flanking sound insulation to avoid sound transmission between rooms and from the outside.

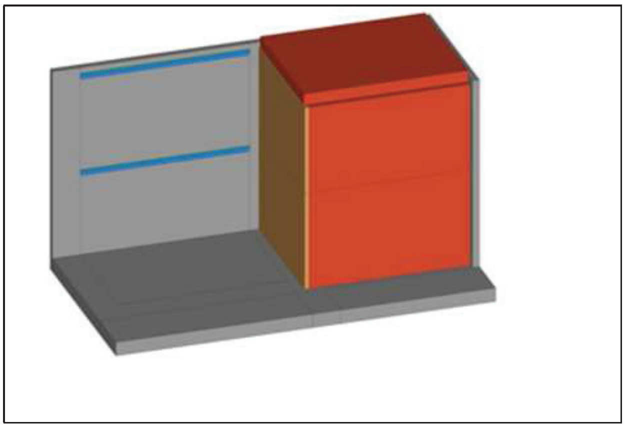

Figure 4. Sketch of the Empa Flanking Facility with the two room set-up considered in this paper (grey: permanent strucutrue of facilty, red: movable facility walls and floors, brown: T-junction under test).

Figure 4 shows a three-dimensional sketch of the facility with the set-up with two rooms one-above-the-other separated by a T-junction that is considered in this paper. The brown elements are the test specimen, grey indicates the permanent structure and in red the movable walls and floors of the facility.

3.2. Test specimen

The test specimen was a T-junction made of a wood-concrete composite floor (HBVR) with a 80 mm thick cross laminated solid wood wall (CLT, mass-per-area: 38 kg/m^2) below and on top. The floor consisted of a 70 mm thick reinforced concrete slab on a 12 mm wooden subfloor that rested on 260 mm high and 80 mm wide wooden joists spaced 440 mm on center. Both, slab and joists were shear connected. The cavity between the joists was filled with 120 mm thick glass fiber batts. Elastic connectors (17 mm high) were attached to the underside of the joists and supported a 24 mm wood furring with a single layer directly attached 12.5 mm thick gypsum board ceiling.
The floor size was 4.50 m by 5.50 m with the wood joists oriented along the long axis. The concrete slab rested on top of the lower CLT wall and the joists that are perpendicular to the junction were connected with angle brackets to it. The upper CLT wall rested on the concrete and was secured with only two angle brackets over the whole length. In the middle along the joists the floor was split into two equally wide prefabricated elements. Their rebar was welded together at two spots and the small gap in the slab between the

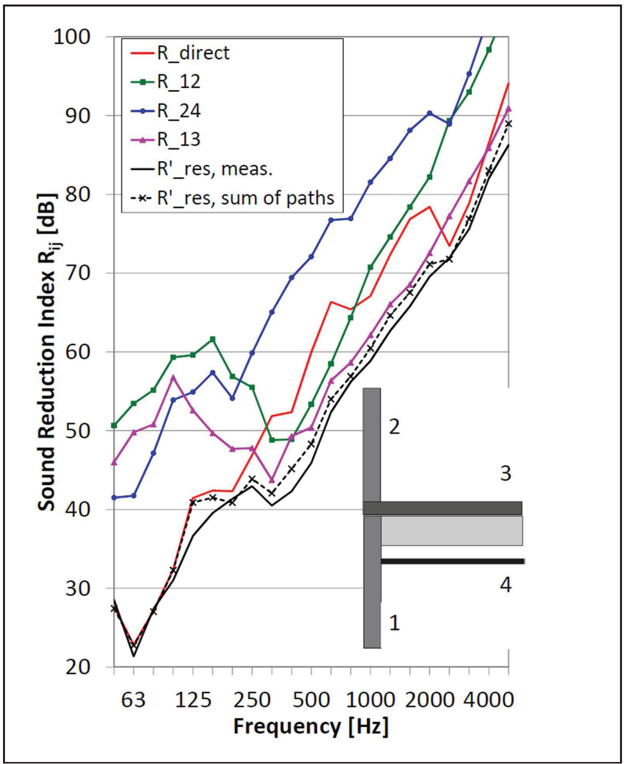

Figure 5. Estimates of sound reduction index of direct and flanking paths from indirect method, as well as resulting from contribution of paths and measured.

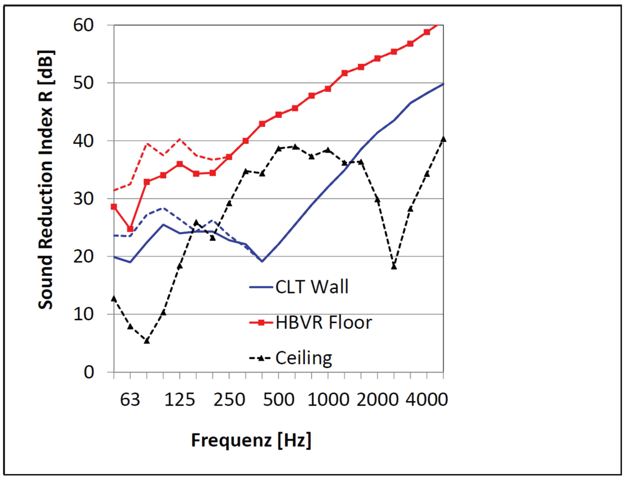

Figure 6. Direct Sound Reduction Index of elements as input for direct method (solid: measured data; dashed: resonant only).

two floor elements was filled with grout. The number of connections between the specimen and the facility were minimized, elastically supported and sealed to prevent sound leaks.

4. RESULTS

4.1. Indirect Method of ISO 10848

Figure 5 presents the sound reduction index of direct and flanking paths obtained from the indirect method. The presented flanking data is already corrected for transmission through the shielded floor at low frequencies. Further, the black lines in the diagram are the measured resultant sound reduction index of all paths (solid) and one predicted by energetically summing the contribution of all paths (dashed with crosses). Below 250 Hz flanking sound insulation is much larger (10 to 20 dB) than direct and hence has no influence on the overall transmission. Thus, the sum of the paths can not be used to validate the conservative path estimates from the indirect method at this point. Above 250 Hz the floor-wall-path (R_13) is dominating with a sound reduction index that is between 315 Hz and 3150 Hz even smaller than the one for direct transmission. Reason for the low flanking sound insulation is the strong coupling between the lower wall and the floor with the concrete resting the wall as well as the many connections at the joists. The wall-wall path (R_12) contributes to overall transmission only between 315 Hz and 630 Hz. Both the floor-wall-path as well as the wall-wall-path have the lowest flanking sound insulation just around the coincidence frequency of the CLT walls, where they are efficiently excited and radiate airborne sound. The highest sound reduction index is the one of the wall-ceiling-path (R_24) with values about 20 dB above resultant sound reduction index of all paths and thus does not contribute at all. The high sound insulation is due to the efficient decoupling of the elastically supported gypsum board ceiling. The resultant sound reduction index predicted from the path estimates overestimates the sound insulation by 1-2 dB in the mid and high frequency range compared to measurement. However, considering an uncertainty of about 1 dB for each measured path the difference is well acceptable.

4.2. Input Data for Direct Method

Figure 6 gives the direct sound reduction indices of the flanking elements used as input in Equation 1. The solid red graph is the sound reduction index of the concrete slab without hung ceiling measured directly in the flanking facility when all the other elements were shielded. The dashed red line is for resonant transmission only and has about 5 dB higher values below 250 Hz. Since it was measured in the predicted situation no adjustment according to Equation 3 is necessary. The blue lines are measured (solid) and resonant (dashed) sound reduction index for the CLT walls. Since the data was from Empa's wall transmission facility the adjustment using measured structural reverberation times of both situations was done. The black curve is the resonant sound reduction index of the hung ceiling without the floor structure above predicted with Equation 4 and input data that was measured at the flanking specimen.

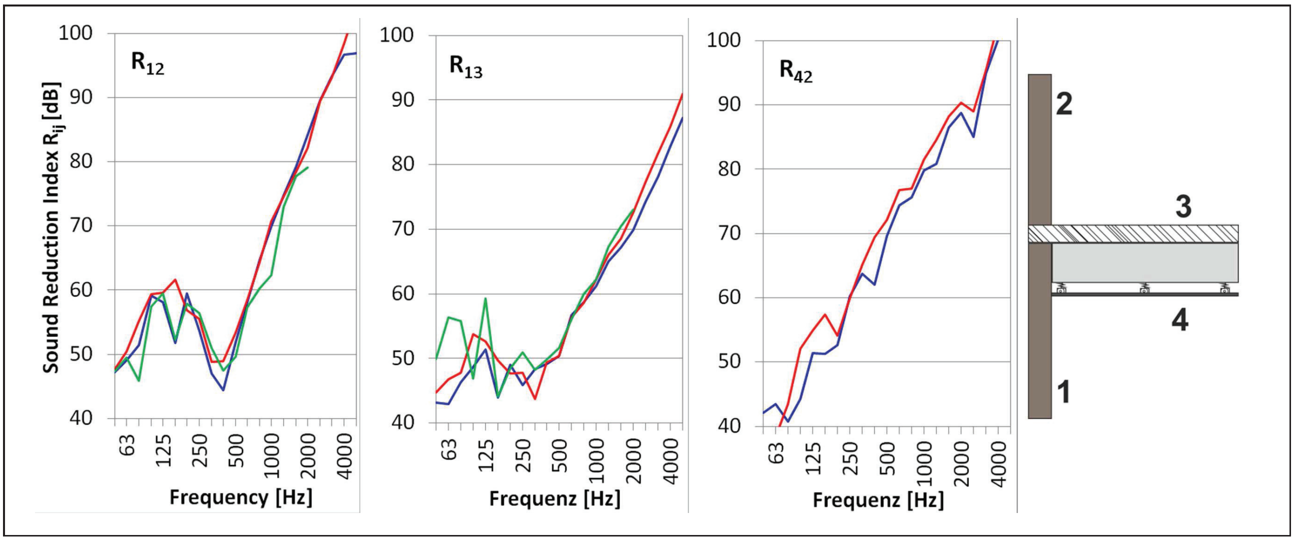

Figure 7. Comparison of Flanking Sound Reduction Index of paths from different methods (red: indirect, blue: direct, green: DCM).

4.3. Comparison of methods

In Figure 7 the results of the indirect, direct and the DCM method are compared for the flanking paths. Red results are from the indirect, blue from the direct method and green from the DCM. DCM was only applied on the lower wall (Element 1) of the T-junctions and thus no results are shown for the wall-ceiling path (R_{42}). Further, DCM results are only shown below 2 kHz because of a poor signal-to-noise-ratio at higher frequencies. Generally, the agreement of all methods is very good, R_{12} and R_{13} with somewhat greater scatter at low frequencies that is not unusual due to the small number of modes per frequency band in the rooms and on the building elements. In case of R_{42} the direct method tends to underestimate the sound reduction by approximately 2 dB in the whole frequency range. This is probably due to the bigger uncertainty in the prediction of the direct sound reduction index of the ceiling that was used as input data for the direct method.

5. CONCLUSIONS

Three methods to determine the sound reduction index of flanking paths at a T-junction were presented in this paper. The methods had all advantages and disadvantages and varied in the degree of complexity of application. The indirect method was found to be the most robust in application, the conservative estimates at low frequency are not worse than the results of the other methods. The direct method is easy to apply as no facility is necessary, however, additionally required input data for the coupled elements often is not available yet. The new DCM method is more sophisticated, however, still relatively easy in its applications, but a scanning laser doppler vibrometer is necessary for the measurements. The results of all three method agree very well at mid and high frequencies. At low frequencies the uncertainties are somewhat greater and even though only conservative estimates were obtained by using the indirect method in this frequency range, there is no systematic trend evident that puts one or the other method in doubt.

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