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Error in predicted flanking sound reduction index due to reduction of average area in velocity measurements

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ABSTRACT

In a recent research project equations for the prediction of flanking sound transmission through lightweight framed assemblies are derived in a statistical energy analysis (SEA) framework and prediction results are validated with well established measurement method. The equations of the new method are similar to those of the EN 12354 method for heavy homogenous monolithic structures that are weakly damped and support a diffuse structure-borne wave field. However, good prediction results are obtained with the new method only if measured velocity level differences are used as input data because propagation of bending waves is strongly attenuated in lightweight framed structures due to the fairly high loss factor of the structure in combination with the rather short bending wavelength of the leaves. The great velocity gradient on the receive element leads to the assumption that most sound power is radiated by the area of high velocity close to the junction into the receive room. Good prediction results are also obtained when the area that is considered on the receive leaf for the velocity level measurement is reduced moderately and the element area in the prediction is adjusted accordingly. The change in flanking sound reduction index due to this area reduction is investigated more thoroughly in this paper and a simple model of a plane propagating banding wave on a damped infinite plate is used to estimate the error in the prediction.

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1. INTRODUCTION

The standardized methods of EN 12354 allows prediction of the apparent sound reduction index in buildings made of monolithic, weakly damped structures. The apparent sound reduction index is the sum of the direct transmission through the separating partition and all flanking between the dwellings. However, currently no standardized methods are available to predict flanking sound transmission in buildings made from lightweight framed elements, like gypsum board walls and joist floors. However, a new non-standardized prediction method for this type of structures was derived in a statistical energy analysis (SEA) framework similar to the EN 12354 method, that was validated in earlier publications [1, 2]. The new method uses the measured velocity level difference between the two coupled elements as input data. Propagation of structure-borne sound is attenuated effectively in lightweight framed elements and hence the velocity level decreases significantly with distance to the junction on the flanking elements in the receive room. However, a good estimate of flanking sound reduction index could be obtained if the average velocity level is measured on the receive element only in a small area of high velocity close to the junction. In this paper, first the applied prediction model, used equations, and prediction results are reviewed briefly. Afterwards the change of the average velocity level due to reduction of the considered area and the error in the predicted sound reduction index are investigated theoretically.

2. PREDICTION OF FLANKING SOUND TRANSMISSION

SEA System, Subsystems, Power Flow and Equations

A detailed description of the applied prediction model with all underlying assumptions and derivation of equation is given in [1]. In this paper only the major equation and input data that are necessary for the prediction are presented briefly in the following. The system – a junction of four walls, two of which are gypsum board walls and two are not specified further and referred to as partition– is presented in Figure 1 on the left. For prediction of power flow the system is further split into subsystems that represent groups of modes as follows. The four rooms and the cavity in-between the leaves are considered as room-like sub-systems and the four leaves of the two walls of interest as plate-like sub-systems. The framing members between the leaves are considered as coupling elements. The junction is a "black-box" and allows only transmission of free bending waves that represent resonant power flow between the leaves.

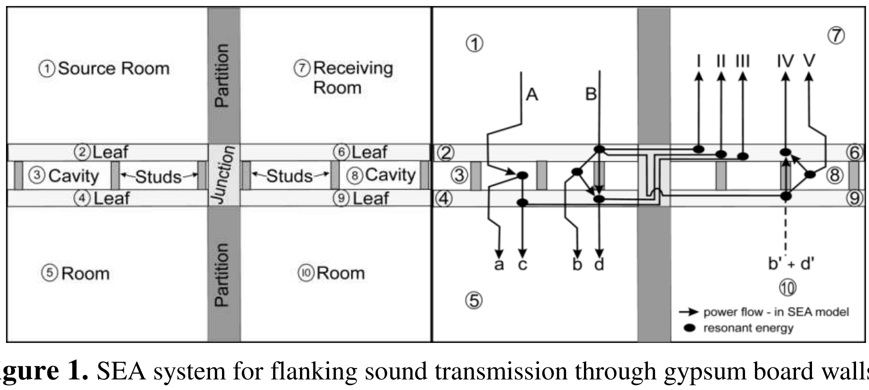

Figure 1. SEA system for flanking sound transmission through gypsum board walls – left: subsystems and denotations, right: power flow in SEA system

Airborne flanking transmission is investigated between room 1 and room 7 through the two gypsum board walls and the assumed power flow when room 1 is the source room is shown in Figure 1 on the right. Hereby, five possible paths (denoted by numbers I to IV) are identified since sound can be transmitted either resonantly or non-resonantly through each leaf of the wall below the coincidence frequency f_c. For gypsum board f_c is close to the upper end of frequency range of interest. However, only the resonant energy component of each leaf on the source side can couple with the resonant energy of both leaves on the receive side. It is also assumed that power flow along each path is independent of the other paths and only occurs from the subsystem of higher energy to the one of lower energy. The SEA path-by-path analysis [3] can be applied and transmission is calculated for each path separately.

In an earlier paper [2] it has been shown that the flanking sound reduction index R_{1267} of path I (denoted simply as R_I in the following) involving only leaf 2 and leaf 6 is the dominating wall-wall path for the junction considered in this paper and gives a good estimate of the total transmitted sound power. The equations of the flanking sound reduction index R_I are derived in terms of SEA loss factors for both directions and the SEA loss factors are evaluated in terms of acoustical quantities. Since reciprocity holds, direction averaging is applied to reduce the number of unknowns. Finally, the average flanking sound reduction index $\overline{R}_I$ is given in terms of acoustic quantities by Equation 1 that is similar to the equation given in EN 12354 for homogeneous weakly damped building structures.

$$\overline{R}_I = \frac{R_{13} + R_{78}}{2} + \frac{D_{v,26} + D_{v,62}}{2} + 5\lg\frac{f_{c,6}\, m_2'^2\, \eta_2}{f_{c,2}\, m_6'^2\, \eta_6} + 5\lg\frac{S_s^2}{S_2\, S_6} \qquad (1)$$

Equation 1 expresses $\overline{R}_I$ in terms of the resonant component of the sound reduction index R_{13} of leaf 2 and R_{78} of leaf 6, their loss factor η, their mass per unit area m', their coincidence frequency f_c and their surface area S. R_I is normalized to the surface area S_S of the partition between the source and receiving room. The second term on the right hand side includes the velocity level differences between leaves 2 and 6 when either leaf 2 ($D_{v,26}$) or leaf 6 ($D_{v,62}$) is excited structurally; hence both are for resonant motion only.

In this paper, necessary input data for equation 1 are either measured using the test specimen (resonant velocity level differences $D_{v,ij,}$ and total loss factor η) or predicted (resonant sound reduction index R_{ij} as outlined in detail elsewhere [1]).

Review of prediction results

The measured and predicted results have already been published in an earlier paper [4] and are only briefly reviewed here to provide the necessary background for the following analysis.

The velocity level differences necessary to predict R_I of the wall-wall flanking path with Equation 1 were measured between the room SW (south-west) and room SE (south-east) on the ground floor of the two-story NRC-IRC Flanking Facility in Ottawa. The orientation of the four rooms on the ground floor, their designations, and the investigated flanking path are given in Figure 2. The test specimen consisted of two load bearing walls and two non-load bearing walls. Both are made with a 38 x 89 mm wood frame with 406 mm stud spacing and 90 mm glass fiber bats as cavity absorption. On one side a double layer of 16 mm gypsum board was directly attached to the frame and on the other a single layer of 16 mm gypsum board was mounted on resilient channels. The non-load bearing walls that are not considered in the paper were shielded with additional layers of absorption and gypsum board to suppress any additional flanking paths involving those surfaces. The wall-wall path considered involves the two load bearing walls and the velocity levels were measured with a scanning laser vibrometer system in a grid on the double layer leaf in the source and receive room. The spacing of the measurement points on the grid was at most 300 mm and the source leaf was excited with an electro-dynamic shaker at 6 to 9 randomly chosen excitation positions. After averaging over all excitation positions the velocity level on the source leaf was rather uniformly distributed whereas on the receive leaf the velocity level distribution had a strong gradient and was much greater in the vicinity of the junction.

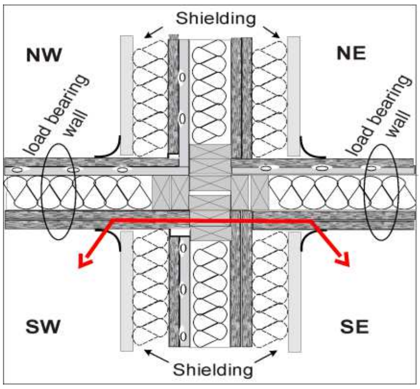

Figure 2. Junction, orientation of rooms in this paper (southeast (SE), southwest (SW), northwest (NW); northeast (NE)) and considered transmission path

It was assumed that most of the sound power is radiated into the receive room by the small area of high velocity close to the junction. Thus, three areas of different size –i.e. the whole leaf (4 m and 3,4 m respectively), less than 2.4 m from the junction, and less than 1.6 m from the junction - were considered for the velocity level averaging on the receive leaf as well as for S_i and S_j in Equation 1. The prediction results are presented once again in Figure 3. As expected the predicted R_I increased with decreasing area resulting in a maximal overestimation of only 2 dB for the smallest area. However, it was also found that R_I increases significantly and overestimates flanking sound insulation grossly if the considered area would be reduced further.

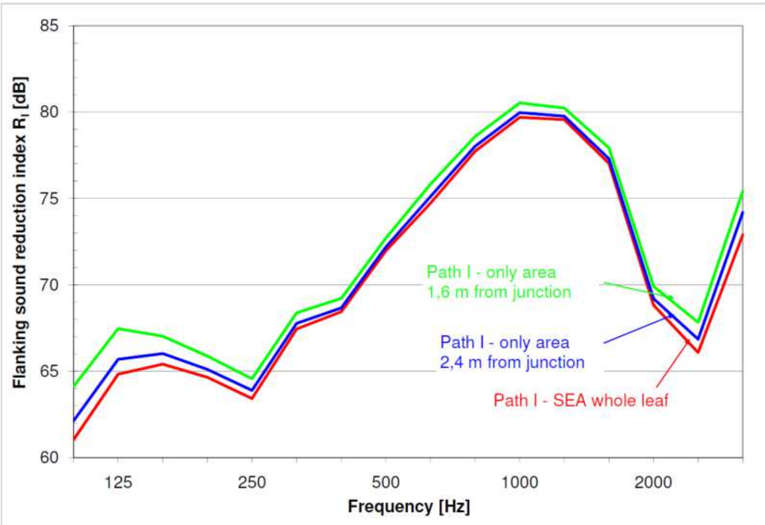

Figure 3: Flanking sound reduction index R_I for wall-wall path measured with indirect method of ISO 10848 and predicted according Equation 1 as function of considered area on receive leaf

3. ANALYSIS OF AVERAGE VELOCITY LEVEL OF A DAMPED INFINITE PLATE

Results of the earlier paper suggest that the area on the receive leaf that must be considered can be reduced to some extent when predicting flanking transmission of damped structures using Equation 1. To estimate the prediction error a simple analysis is done on the velocity level decay of a plane bending wave on a thin damped infinite plate.

Average velocity level on damped infinite plate

A thin damped infinite Kirchhoff plate is excited by a line source at x = 0 with velocity $\hat{v}$. Because the velocity is uniform along the whole wave front and velocity decays only in x-direction the problem reduces to a one dimensional problem. The complex surface velocity $\underline{v}$ of an excited bending wave is given for $x \geq 0$ by Equation 2 as product of the space harmonic and the time harmonic $e^{i\omega t}$ – the latter is suppressed henceforward in this paper. The first part of the space harmonic describes a free damped bending wave propagating in x-direction and the second term an evanescent wave – the so-called near field. Both terms are functions of the bending wavenumber k_B and of the loss factor η due to internal and radiation losses. The decay with distance to the source is much greater for the near field term than for the propagating wave and thus contributes only in the direct vicinity of the source. Therefore the near field term is neglected in the analysis henceforward for matter of simplicity.

$$\underline{v} = \left(\hat{v}\, e^{-i\underline{k}_B x} + \hat{v}\, e^{-\underline{k}_B x}\right) e^{i\omega t} \qquad \text{with} \qquad \underline{k}_B = k_B \left(1 - i\,\frac{\eta}{4}\right) \tag{2}$$

$$v^2_{Ave} = \frac{1}{2(l_2 - l_1)} \int_{l_1}^{l_2} |\underline{v}|^2 dx = \frac{\hat{v}^2}{2(l_2 - l_1)} \int_{l_1}^{l_2} e^{-\frac{k_B \eta}{2} x} dx = \frac{-\hat{v}^2}{k_B \eta (l_2 - l_1)} \left(e^{-\frac{k_B \eta}{2} l_2} - e^{-\frac{k_B \eta}{2} l_1} \right) \tag{3}$$

The space average mean square velocity v^2_{Ave} is given by Equation 3 where l_1 and l_2 are two distances to the line source marking the boundaries of the area considered. For this analysis the first boundary is set right at the source ($l_1 = 0$) and l_2 is kept variable ($l_2 = l$). The change ΔL_v of the average velocity level relative to the mean square velocity v^2_0 at the source is given in Equation 4.

$$\Delta L_v(l) = 10\,\lg\left(-\left(\exp\left(-\frac{k_B \eta}{2} l \right) - 1 \right) \cdot \left(\frac{k_B \eta}{2} l \right)^{-1} \right) \tag{4}$$

Error due to size of considered receive leaf area

The error ΔR_I in the flanking sound reduction index due to change of the considered area on the receive leaf of a structure with a large velocity level decay is simply the difference between the predicted $R_{I,all}$ when the whole receive leaf is taken into account and $R_{I,p}$ when only the area of high velocity close to junction is considered (see Equation 5). Most terms, except the ones with velocity level differences and the area of the receive leaves cancel out. Further, the area term depends only on the lengths of elements ($l_{2,all}$ and $l_{6,all}$) as well as the distance of the borders of the area considered ($l_{2,p}$ and $l_{6,p}$) to the junction. The second dimension – the junction length – is kept constant. In the velocity term, only the space average level on the receive leaf remains, which can be expressed in terms of ΔL_v given by Equation 4.

$$\Delta R_I = R_{I,p} - R_{I,all} = \frac{\Delta L_v(l_{6,all}) + \Delta L_v(l_{2,all})}{2} - \frac{\Delta L_v(l_{6,p}) + \Delta L_v(l_{2,p})}{2} - 5\lg\frac{l_{2,p}\, l_{6,p}}{l_{2,all}\, l_{6,all}} \tag{5}$$

The error in predicted R_I due to reduction of the velocity averaging area on a leaf with similar velocity decay similar to a plane bending wave on an damped infinite plate can easily be estimated from the product of the loss factor η and the bending wavenumber k_B of the leaf in direction perpendicular to the junction.

Discussion of error

To simplify Equation 5 further, first it is assumed that that the length of both leaves is equal ($l_{all} = l_{2,all} = l_{6,all}$) and that the area considered is reduced equally on both leaves ($l_p = l_{2,p} = l_{6,p}$). If l_{all} approaches infinity then the exponential term in $\Delta L_v(l_{all})$ approaches zero and can be neglected. For this specific case ΔR_I is then simply given by Equation 6 as function of $k_B\eta$.

$$\Delta R_I(l_{2,p} = l_{6,p} = l_p, l_{2,all} = l_{6,all} \rightarrow \infty) = -10\lg\frac{-e^{-0.5\,k_B\eta\,l_p}+1}{l_p} + 10\lg\frac{1}{l_p} \qquad (6)$$

Values of k_B and η were measured on a limited number of typical gypsum board walls [1]. Although the thickness of gypsum board, the number of layers, their attachment (directly or mounted on resilient channels) as well as the framing (metal channels and wood studs) was different, all results showed that k_B in direction perpendicular to the wall studs – hence also perpendicular to the wall-wall junction considered in this paper - is determined by the stiffness of the gypsum board leaf in the frequency range of interest. The product $k_B\eta$ that is need as input data for Equation 4 is presented in Figure 3 for the measured walls. The solid lines are the average result of measurements of similar specimens and the dashed lines indicate their standard deviation.

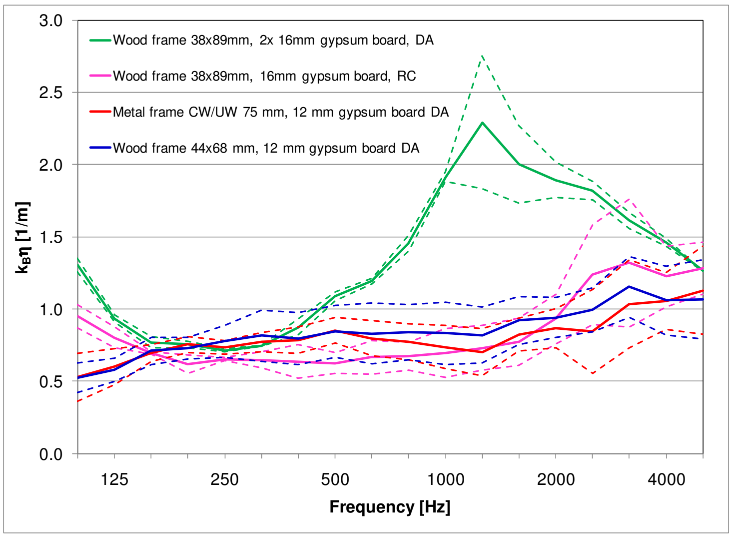

Figure 4. $k_B\eta$ of different wall specimens with bending wavenumber k_B measured in direction perpendicular to studs (leaf attachment: directly to the frame (DA), on resilient channels (RC))

The product $k_B\eta$ is similar for most walls in all bands because k_B increases and while η decreases with frequency. Most values of $k_B\eta$ lie in the range between 0.5 and 1.0 excluding the peak of 2.2 at 1600 Hz around the coincidence frequency due to an increase of radiation losses and internal losses caused by interaction between the two layers .

After the range of the input data is known, ΔR_I is presented as the red curves for typical values of $k_B\eta$ ranging from 0.5 to 2. The black curve represents the second term on the right hand side of Equation 6 that is related to the change of area in Equation 1. The blue curves represent the first term of Equation 6 (the change of the velocity level) again for typical values of $k_B\eta$ ranging from 0.5 to 2. For distances farther away from the junction all blue graphs approach the black because the exponential term in Equation 6 vanishes for ($-0.5\ k_B\eta l_p$) $\gg$ 1. Hence, velocity term and area term become equal and compensate because both are subtracted. ΔR_I given by the red graphs has only a small gradient and approaches zero in this region. However, if only very small areas on the receive leaf are considered then ΔR_I would be very large. Further, Figure 5 shows that ΔR_I approaches zero earlier, and that smaller areas need to be considered, if $k_B\eta$, which describes the velocity decay with distance to the junction, is great.

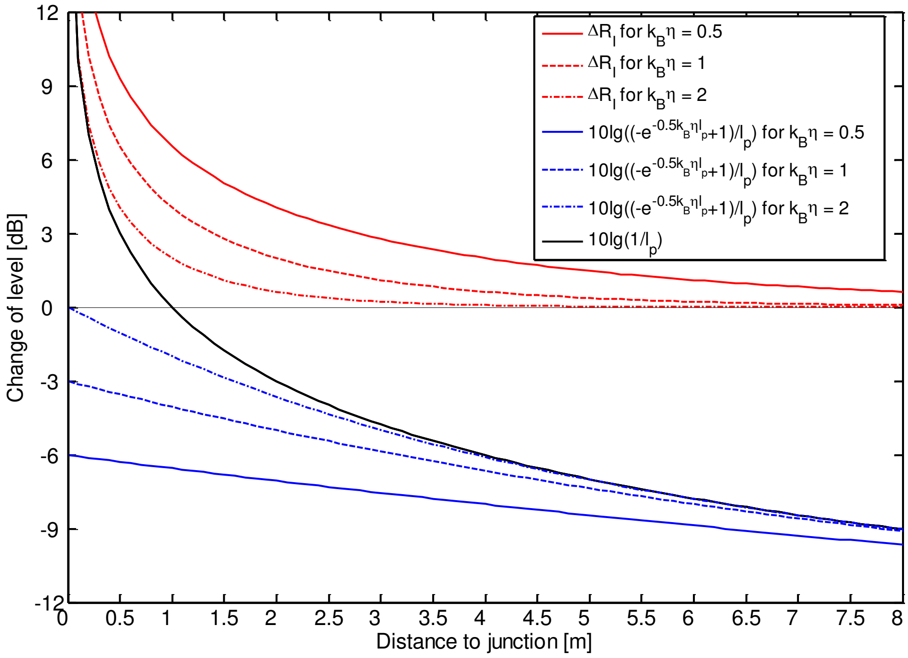

Figure 5. ΔR_I and the two terms of Equation 6 for typical values of $k_B\eta$

4. ESTIMATE OF ERROR DUE TO REDUCTION OF AREA CONSIDERED

To estimate ΔR_I of the predicted flanking sound reduction R_I presented in Figure 3, Equation 5 that is based on the plane wave model is applied with measured $k_B\eta$ of Figure 4 as input data.

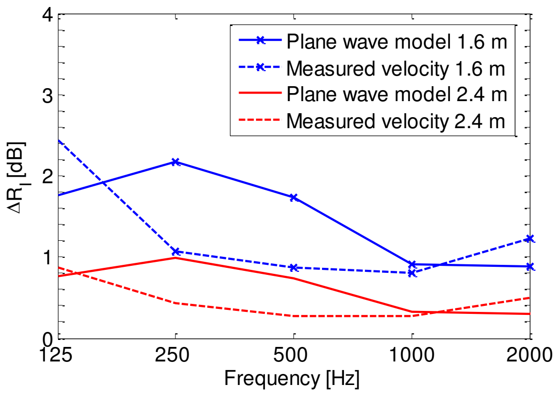

Figure 6. Predicted ΔR_I according to Equation 5 and of results in Figure 3

ΔR_I of both data sets are given in Figure 6 for all considered octave bands. Octave bands are used to show better the overall trend. The agreement between predicted ΔR_I using Equation 5 and the one of Section 2 using measured velocity levels as input data is good. Differences between the two results are far less than 0.5 dB in the low and high frequency range, whereas in the mid frequency range Equation 5 slightly over estimates ΔR_I. This can be explained because in the low frequency range the whole wall moves like single damped plate and in the high frequency range the studs can be considered as point connected. The velocity level on the leaf decays in both cases rather uniformly with distance to the junction like for a plane wave on an infinite plate. In the mid frequency range the studs have to be considered as line connected and the leaf acts like a series of smaller weakly damped plates. The velocity level decay is not as uniform in this frequency range – there are greater decays between the excited first bay and the second [5] - and hence the results of plane wave are less good.

4. SUMMARY AND CONCLUSIONS

The flanking sound reduction index R_{ij} of a flanking path that involves fairly highly damped elements can be predicted with the EN 12354-method or similar methods, if measured velocity level differences are used as input data. Further predicted R_{ij} does not change significantly when only the area of high velocity close to the junction is taken into account on a receive leaf with a strong velocity decay with distance to the junction during measurement and the element area is adjusted accordingly in the prediction. The impact of the averaging area reduction on the average velocity level is investigated with a simple model of a plane propagating bending wave on an infinite damped plate. A relationship for the change of the average velocity level is obtained that only needs the product of the bending wavenumber k_B in direction of wave propagation and the internal loss factor η as input data. With this simple relationship the error in R_{ij} due to the averaging area reduction on the receive leaf is estimated for typical values of $k_B\eta$ for gypsum board walls. If the velocity level decay is great and a sufficient great averaging area is chosen then the error in R_{ij} is very small because the change in the average velocity level is compensated by the change of the surface area. However, if velocity decay or averaging area is too small the error becomes significant.

The relationship is further used successfully to estimate the error in R_{ij} of two coupled gypsum board walls predicted with velocity level differences of different areas as input data although the velocity level decay on leaf of a gypsum board wall is only in a limited frequency range comparable to that of a damped plate with a plane propagating wave. Hence, the relationship is very useful to determine the minimum area that has to be considered in the velocity level difference to optimize both, the time effort for measurement as well as the error in prediction.

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