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Investigation of the separation of the resonant sound reduction index from measured data for use in EN 12354-1

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ABSTRACT

The application of EN 12354-1 to lightweight construction materials requires that the resonant component of the sound reduction index be separated from the reduction index measured according to ISO 140-3 or ISO 15186-1 which also includes contributions from the non-resonant component. One method of separating the resonant component is to calculate the non-resonant sound reduction index and then subtract it from the total, measured value. In this investigation, the non-resonant component was calculated using different theories and subtracted from the total sound reduction index measured for a steel panel. However, almost all of the resulting resonant sound reduction indices were negative over much of the frequency range. The errors in the separation of the components may have been due in part to measurement uncertainty which may be larger than the difference between the non-resonant and total sound reduction index below the critical frequency. A better method of separation may be a correction factor which is applied to the measured data. However, the correction factor itself must not be prone to errors or it may underestimate the resonant component of the sound reduction index.

1 INTRODUCTION

EN 12354-1 has been developed as a method for predicting the apparent sound reduction index between rooms in a building due to the contribution of flanking paths [1]. The method uses measured quantities such as the sound reduction index of the first and last walls of a flanking path to predict the surface velocity of the walls and the structure-borne noise transmitted between them. Theoretically, only resonant transmission is important to the calculation of flanking transmission [2]. Therefore, the sound reduction index used for the predictions should only be that for the resonant component of the sound reduction index without the contribution of the non-resonant component.

The use of data which includes the non-resonant contributions will tend to underestimate the predicted apparent sound reduction index because the non-resonant contributions represent a fictitious source of energy in the method [3]. For monolithic structures with critical frequencies at the low end of the frequency range of interest, the inclusion of the non-resonant components may result in a conservative estimation of the apparent sound reduction index since the sound reduction index above the critical frequency is dominated by the resonant contributions [4]. However, in the case of lightweight structures where the critical frequency may be above the frequency range of interest, the majority of the measured sound reduction index will be due to the non-resonant component. For these materials, the inclusion

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of the non-resonant component in the EN 12354-1 method may lead to a considerable underestimation of the apparent sound reduction index [5].

Since measured data is required for the EN 12354-1 method, it would be advantageous to be able to use the sound reduction index data measured per ISO 140-3 or ISO 15186-1. However, the data measured per these standards includes the contributions of both resonant and non-resonant components. EN 12354-1 does not give guidance of a method to isolate the non-resonant sound reduction index since the standard was written to be applicable to heavy monolithic constructions with critical frequencies at the low end of the frequency range of interest and therefore the separation was not necessary [5]. The total sound reduction index is a sum of the non-resonant and resonant components such that

$$R_{total} = -10log\left[10^{\frac{-R_{non-resonant}}{10}} + 10^{\frac{-R_{resonant}}{10}}\right] \qquad (1)$$

where R is the sound reduction index and R_{total} is a measured value. Therefore, it may be possible to isolate the resonant component from the measured data if the non-resonant component can be accurately predicted. Alternatively, Nightingale [3] has proposed multiplying the total sound reduction index by a correction factor based on the ratio of the magnitudes of the resonant and non-resonant components of the time and spatially averaged mean square velocity of the element being tested..

In this paper, the methods of isolating the resonant component of the sound reduction index are assessed using the measured sound reduction index of a steel panel.

2 MEASUREMENTS

2.1 Measurement Methods

A single, steel panel was chosen for the testing to assess the accuracy of separating the resonant sound reduction index from measured data. Although a double-leaf wall would be a more accurate representation of the structures to which EN 12354-1 is applied, a simple plate was chosen to limit the complexity of the predictions and therefore the potential sources of error. The plate used for the measurements was 1.6 mm thick. The critical frequency of the plate was calculated to be 7751 Hz and measurements confirmed that the critical frequency was in the 8000 Hz 1/3 octave band, well above the frequency range of interest.

The sound reduction index of the panel was measured using the sound intensity technique per ISO 15186-1:2000. The intensity level on the receiving side of the panel was measured by making four sweeps of the panel per measurement for a total of three measurements. The structural reverberation time of the panel was measured using an impact hammer and the integrated impulse response method defined in ISO 3382 with backward integration of the squared impulse response. The panel was impacted in fifteen locations and the surface velocity of the panel was simultaneously measured with five Brüel & Kjær 4517 0.6g accelerometers which were glued to the panel. The accelerometers were also used to measure the time and spatially averaged mean square velocity of the panel when during the measurement of the sound reduction index. Ten averages of the velocity of five positions for each average were made over a period of 45 seconds per measurement. The velocity could then be used to determine the radiation efficiency of the panel.

2.2 Measurement Uncertainty

The standard deviation of the intensity measurements as well as the standard deviation between the sound pressure levels measured by the five microphones in the reverberant chamber were calculated to determine the standard deviation of repeatability σ_r of the sound reduction index. The value of σ_r is a measure of the variation between measurements made under identical conditions and includes contributions due to the spatial variations in the sound pressure level in the reverberant chamber and sources of errors in the intensity measurements which have been described in detail by Jacobsen [6]. In addition, the standard deviation of reproducibility σ_R for the measurements is estimated in ISO 15186-1 [7]. The standard deviation of reproducibility is an indication of the measurement uncertainty if the tests were to be repeated in different laboratories under different conditions and includes the standard deviation of repeatability. In addition, there are also standard deviations in the materials being tested which are described by the standard deviation of production σ_p. The value of σ_p is generally not known but may be estimated from a sample of products and the standard deviation of the measurements [8].

The values of σ_r and σ_R and the 95% confidence of the measured sound reduction index data based on σ_r for three measurements are listed in Table 1.

Table 1: Standard deviations and the total and confidence of measured sound reduction index data.

1/3 Octave Band Center Frequency (Hz)	Sound Reduction Index R (dB)	σ_r Measured (dB)	σ_R Per ISO 15186-1 (dB)	95% Confidence Based on σ_r (dB)
100	21.1	1.3	2.0	1.5
125	21.1	0.8	1.5	0.9
160	22.5	0.7	1.5	0.8
200	22.6	1.0	1.5	1.1
250	26.2	0.2	1.5	0.2
315	27.1	0.5	1.5	0.5
400	29.8	0.6	1.5	0.7
500	30.6	0.5	1.5	0.6
630	32.2	0.5	1.5	0.6
800	33.5	0.3	1.5	0.4
1000	35.3	0.2	1.5	0.3
1250	36.8	0.4	1.5	0.5
1600	38.7	0.3	1.5	0.3
2000	40.4	0.3	2.0	0.4
2500	41.6	0.5	2.0	0.6
3150	43.8	0.2	2.0	0.2
4000	45.3	0.4	2.0	0.5
5000	46.5	0.5	3.0	0.5

The data in the table shows that although the uncertainty in the measurements based on the repeatability of the data is small at the higher frequencies, the uncertainty between measurements made at different laboratories may be between 1.5 and 3 dB over the frequency range. Although the values of σ_r for this study are generally under 1dB, the values of σ_R indicate that the measured values of the sound reduction index may differ by several dB from the sound reduction index measured at other laboratories.

As a comparison between measurement methods, the standard deviations for measurements made per ISO 140-3 are shown in Table 2.

Table 2: Standard deviation of repeatability, reproducibility and the total value per ISO 140-2:1991.

1/3 Octave Band Center Frequency (Hz)	σ_r Per ISO 140-2 (dB)	σ_R Per ISO 140-2 (dB)
100	4.5	9.0
125	4.0	8.5
160	3.5	6.0
200	3.5	5.5
250	2.5	5.5
315	2.5	4.5
400	2.0	4.5
500	2.0	4.0
630	1.5	3.5
800	1.5	3.0
1000	1.5	2.5
1250	1.5	3.0
1600	1.5	3.5
2000	1.5	3.5
2500	1.5	3.5
3150	1.5	3.5
4000	1.5	3.5
5000	1.5	3.5

The data in the table is from Table A.1 and Table A.2 of ISO 140-2:1991 [9]. The measurements made per ISO 140-3 have a larger standard deviation of reproduction than measurements made per ISO 15186-1, particularly at the low frequencies, possibly due to the influence of the mounting of the panels and the construction design of the test facility [10]. The magnitude of the uncertainties, especially at the low frequencies underlines the importance of repeating measurements because in principle repeated measurements lead to an average result that comes closer to the "true value".

3 CALCULATION OF THE NON-RESONANT COMPONENT

In order to separate the resonant and non-resonant components of the sound reduction index, some authors have advocated subtracting the mass law from the measured, total sound reduction index to predict the non-resonant components [11]. Other equations for the non-resonant sound reduction index used in this study include those of Leppington [12] and Sewell [13] as well as adaptations of Sewell's equation including a simplification by Lee and Ih [14] and by Rudder [15]. Additionally, EN 12354-1 also makes use of Sewell's equations as a means of calculating the non-resonant radiation efficiency. This calculation is then used to calculate the transmission loss for frequencies below the critical frequency which Annex B gives as:

$$\tau = \left(\frac{2p_o c_o}{2\pi f \rho_s}\right)^2 2\sigma_{non-resonant} + \left(\frac{2p_o c_o}{2\pi f \rho_s}\right)^2 \frac{(l_1 + l_2)^2}{l_1^2 + l_2^2} \sqrt{\frac{f_c}{f}} \frac{\sigma_{resonant}^2}{\eta_{tot}} \qquad (2)$$

where τ is the transmission loss, ρ_s is the mass per unit area, l_1 and l_2 are the dimensions of the element where $l_1 > l_2$, f_c is the critical frequency and η_{tot} is the total loss factor. The left side of the equation predicts the non-resonant transmission loss and therefore, the right side of the equation should be omitted when calculating the non-resonant sound reduction index [11].

Alternatively, Nightingale [3] based a correction factor in part on equations given in Annex B of EN 12354-1. The correction factor is applied to the total, measured sound reduction index such that:

$$R_{resonant} = R_{measured} + 10log\frac{1}{\xi} \qquad (3)$$

where the correction factor ξ is defined for $f < f_c$ as:

$$\xi = \frac{\pi f_c}{2f\eta_{tot}}\left(\frac{\langle\tilde{v}^2_{non-resonant}\rangle}{\langle\tilde{v}^2_{resonant}\rangle}\right) \qquad (4)$$

where $\langle v^2 \rangle$ is the time and spatially averaged mean square velocity. Therefore, the calculation of the correction factor is dependent on a knowledge of the resonant and non-resonant components of the total time and spatially averaged mean square velocity $\langle v^2_{total}\rangle$. The total value was measured experimentally and is a sum of the components such that [16]:

$$\langle\tilde{v}^2_{total}\rangle=\langle\tilde{v}^2_{non-resonant}\rangle+\langle\tilde{v}^2_{resonant}\rangle \qquad (5)$$

Therefore, the value of $\langle\tilde{v}^2_{non-resonant}\rangle$ may be estimated from Equation 5 if the value of $\langle\tilde{v}^2_{resonant}\rangle$ can be estimated. However, the separation of the components of $\langle\tilde{v}^2_{total}\rangle$ has the same problem as the estimation of the components of the total sound reduction index. Separation below the critical frequency may not be possible due to measurement uncertainties which can result in negative values of $\langle\tilde{v}^2_{non-resonant}\rangle$ which is not possible.

Alternatively, an estimate of the correction factor is proposed such that:

$$\xi' = \frac{\pi f_c}{2f\eta_{tot}}\left(\frac{\langle\tilde{v}^2_{total}\rangle}{\langle\tilde{v}^2_{resonant}\rangle}\right) \qquad (6)$$

The use of $\langle\tilde{v}^2_{total}\rangle$ in the equation instead of $\langle\tilde{v}^2_{non-resonant}\rangle$ prevents the estimation from having a negative value if the resonant and non-resonant contributions to $\langle\tilde{v}^2_{total}\rangle$ can not be separated correctly. However, ξ' may still lead to errors in the estimation of the resonant sound reduction index if $\langle\tilde{v}^2_{resonant}\rangle$ is inaccurately calculated. For this study, $\langle\tilde{v}^2_{resonant}\rangle$ was estimated from statistical energy analysis such that:

$$\langle\tilde{v}^2_{resonant}\rangle = \frac{\langle\tilde{p}^2\rangle f_c\sigma_{resonant}}{8\pi f^3\eta_{total}\rho_s^2} \qquad (7)$$

where $\langle\tilde{p}^2\rangle$ is the time and spatially averaged mean square pressure in the reverberant chamber and the resonant radiation efficiency was calculated per Annex B of EN 12354-1.

4 COMPARISON OF MEASUREMENTS AND PREDICTIONS

The non-resonant component of the sound reduction index calculated per the different theories are compared to the total sound reduction index in Figure 1.

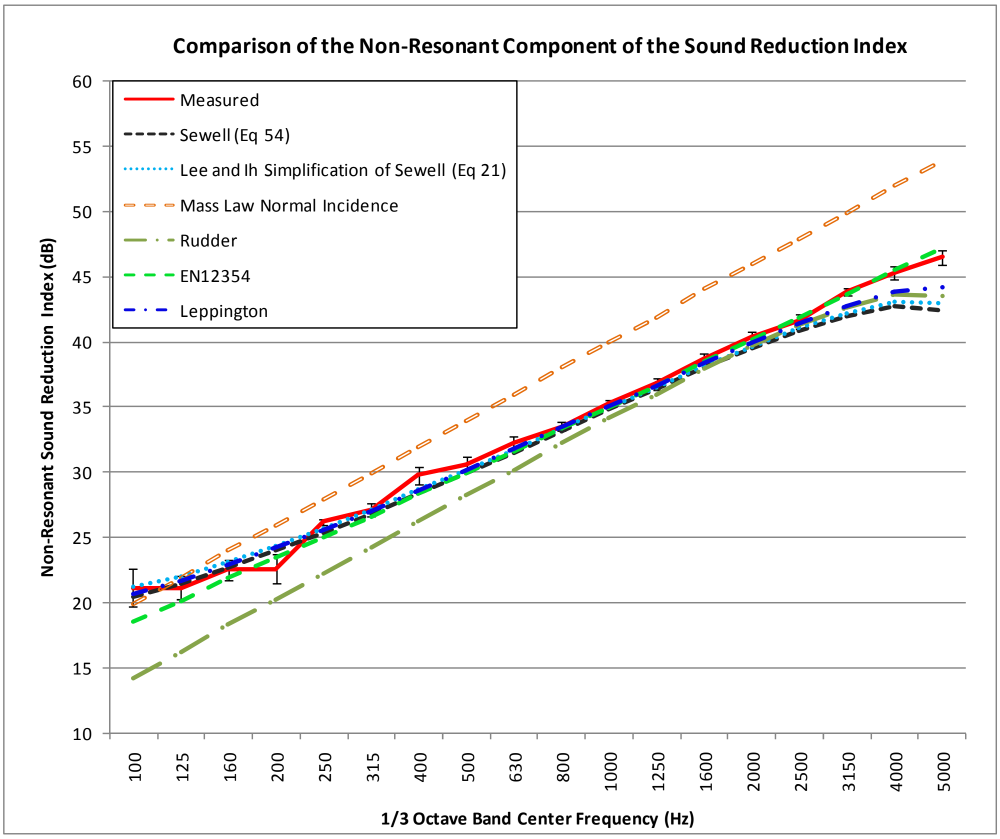

Figure 1: Comparison of the non-resonant components of the sound reduction index.

The error bars shown on the total, measured sound reduction index are the 95% confidence based on the standard deviation of repeatability σ_r. The figure shows that over most of the frequency range, the estimates of the non-resonant component of the sound reduction index is less than the total sound reduction index, the exception being the normal incidence mass law. The underestimation of the non-resonant component will result in a negative resonant component if the non-resonant is subtracted from the total value per

$$R_{resonant} = -10log\left[10^{\frac{-R_{total}}{10}} - 10^{\frac{-R_{non-resonant}}{10}}\right] \tag{8}$$

as shown in Figure 2.

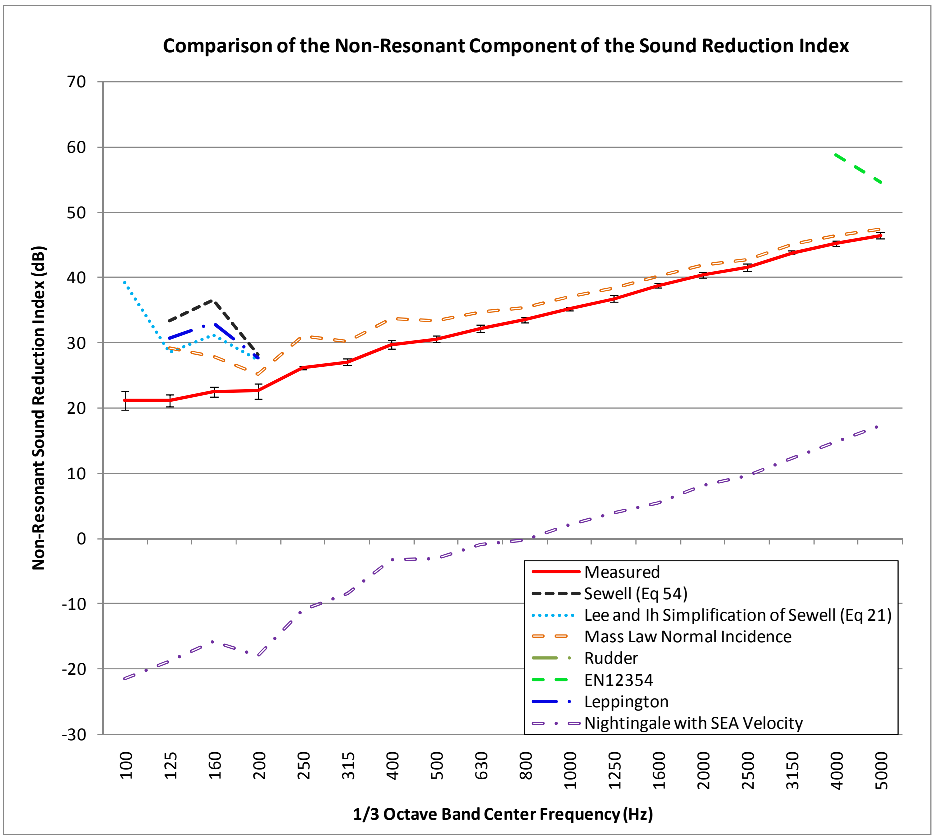

Figure 2: Comparison of the resonant components of the sound reduction index.

The figure shows the total, measured value with error bars indicating the 95% confidence interval. The series shown above the total, measured value are those calculated using Equation 8. The figure only shows a limited number of points for most of the series because the calculated resonant component of the sound reduction index was negative over most of the frequency range. The only exception was the calculation from the normal incidence mass law which could be successfully used in Equation 8 to calculate the resonant component of the sound reduction index.

Because the predictions of the non-resonant component were similar in magnitude to the measured sound reduction index, measurement uncertainties may have limited the ability to separate the components by subtracting one from the other. A negative transmission loss is not possible and therefore separating the resonant component by subtracting the non-resonant component from the average total sound reduction index may not be a viable means of determining the resonant sound reduction index.

Unlike the rest of the series, the series calculated from the estimated correction factor per Equation 6 was calculated directly rather than from the non-resonant component. The figure shows this resonant sound reduction index to be small over the frequency range which will result in a negative non-resonant component if the calculated resonant component is subtracted from the total. The error was largely due to errors in properly separating the $\langle \tilde{v}^2 \rangle$ terms, resulting in a negative value for $\langle \tilde{v}^2_{non-resonant} \rangle$ over almost all of the frequency range. As with the separation of the sound reduction index, the errors in the separation of the $\langle \tilde{v}^2 \rangle$ terms may be due in part to measurement uncertainty and due to errors in the estimation of the resonant component. Additionally, the assumptions made for the estimated correction factor in Equation 6 may be a poor approximation below the critical frequency [3].

5 DISCUSSION

Almost all of the equations used to calculate the non-resonant component of the sound reduction index predicted that the non-resonant component is dominant for the panel below the critical frequency. The results emphasize the importance of removing the non-resonant component from the data used in EN 12354-1. Of the equations used, only that of the mass law resulted in a resonant sound reduction index which was not negative. The negative values calculated from the other equations may have resulted from an underestimation of the non-resonant sound reduction index. As a means of verifying the accuracy of the different equations used in the predictions, it would be useful to know the value of the resonant and non-resonant components and work is currently underway at the University of Canterbury to measure the magnitude of the components of the sound reduction index of the steel panel.

The negative values of the resonant sound reduction index may also be due to the variance of the measured sound reduction index. The use of the average total sound reduction index as a basis from which to subtract the non-resonant component resulted in a negative resonant component, but if values at the bottom of the confidence interval are used, this would not be the case as shown in Figure 3.

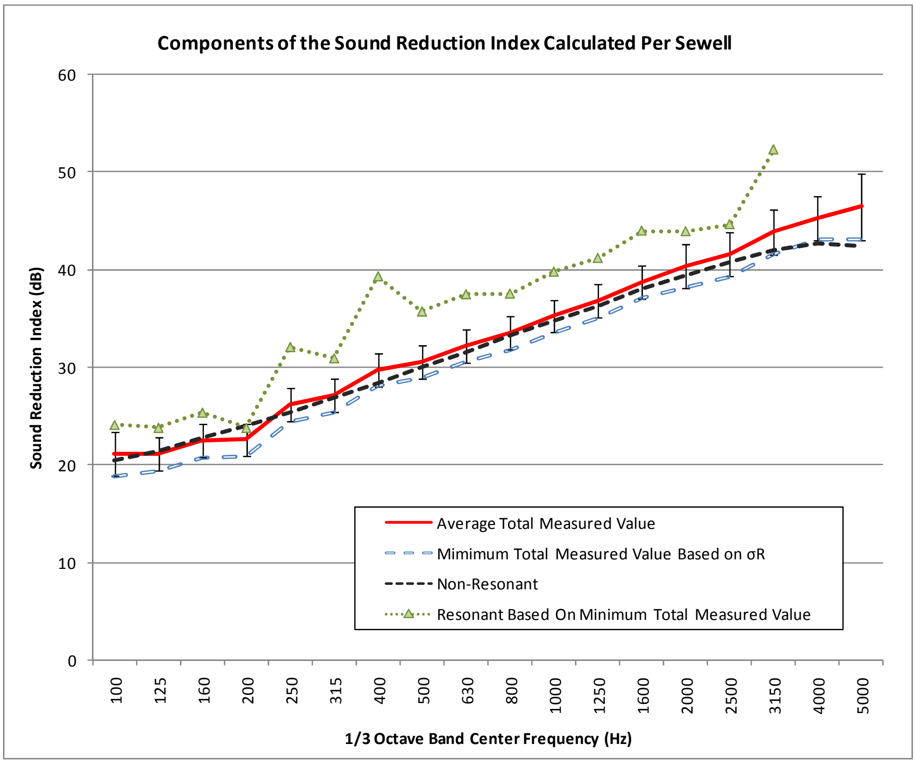

Figure 3: Comparison of the components of the sound reduction index calculated per Sewell equations.

The figure shows the total, measured sound reduction index with 95% confidence intervals calculated from σ_R. The *Resonant Based on Minimum Total Measured Value* curve represents measurement results at the bottom of the confidence interval which due to σ_R could theoretically be possible if the measurement were to be made in a different laboratory. The figure shows that if this were to occur, the resonant component could be calculated over most of the frequency range from Sewell's equation for the non-resonant sound reduction index, underscoring the influence of the measurement uncertainties on the results.

6 CONCLUSIONS

The predictions of the non-resonant transmission loss indicate that below the critical frequency, the resonant component of the sound reduction index may be quite small. Therefore, it is important that an accurate method of isolating the resonant component be used or EN 12354-1 may underestimate the apparent sound reduction index due to flanking paths. Estimating the non-resonant sound reduction index and subtracting it from the measured, total sound reduction index would be an attractive means of estimating the resonant component. However, for materials where the non-resonant component of the sound reduction index is similar in magnitude to the total value, measurement uncertainties may render the separation of the components by this method inadvisable since negative values for the resonant sound reduction index may result.

A better method of isolating the non-resonant component may be to use a correction factor. This method would also include errors in the results due to errors in the measurement data, but it would prevent the calculation of negative values for the resonant transmission loss. If a correction factor were to be used which is dependent on the calculation of the resonant component of the time and spatially averaged mean square velocity, then the velocity components must be separated accurately.

Measurements reported per ISO 140-3 or ISO 15186-1 should be the result of averaging several measurements to reduce the measurement uncertainty if the data is to be used to calculate the resonant component of the sound reduction index.

7 REFERENCES

[1] *Building acoustics. Estimation of acoustic performance in buildings from the performance of elements. Airborne sound insulation between rooms*, International Standard EN 12354-1:2000 (European Committee for Standardization, Brussels, Belgium, 2000).

[2] E. Gerretsen, "European developments in prediction models for building acoustics," Acta Acustica, **2**, 205-214 (1994).

[3] T. R. T. Nightingale, "Application of the CEN draft building acoustics prediction model to a lightweight double leaf construction," Applied Acoustics, **46**, 265-284 (1995).

[4] S. Ljunggren, "Airborne sound insulation of thin walls," The Journal of the Acoustical Society of America, **89**, 2324-2337 (1991).

[5] E. Gerretsen and T. R. T. Nightingale, "Prediction models in building acoustics: introduction to the special session at Forum Acusticum 1999 in Berlin," Building Acoustics, **6**, 151-158 (1999).

[6] F. Jacobsen, "On the uncertainty in measurement of sound power using sound intensity," Noise Control Engineering Journal, **55**, 20-28 (2007).

[7] *Acoustics : Measurement of sound insulation in buildings and of building elements using sound intensity. Part 1 - Laboratory measurements*, International Standard ISO 15186-1:2000 (E) (International Organization for Standardization, Geneva, Switzerland, 2000).

[8] E. Gerretsen, "Interpretation of uncertainties in acoustic measurements in buildings," Noise Control Engineering Journal, **55**, 50-54 (2007).

[9] Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 2: Determination, verification and application of precision data, International Standard ISO 140-2:1991 (International Organization for Standardization, Geneva, Switzerland, 1991).

[10] A. Schmitz, A. Meier, and G. Raabe, "Inter-Laboratory Test of Sound Insulation Measurements on Heavy Walls: Part I - Preliminary Test," Building Acoustics, **6**, 159-169 (1999).

[11] E. Gerretsen, "Using the structural reverberation time in standardizing laboratory measurements on the sound reduction index," presented at Forum Acusticum, Sevilla, 2002.
[12] F. G. Leppington, E. G. Broadbent, K. H. Heron, and S. M. Mead, "Resonant and Non-Resonant Acoustic Properties of Elastic Panels. I. The Radiation Problem," Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences (1934-1990), **406**, 139-171 (1986).
[13] E. C. Sewell, "Transmission of reverberant sound through a single-leaf partition surrounded by an infinite rigid baffle," Journal of Sound and Vibration, **12**, 21-32, (1970).
[14] J.-H. Lee and J.-G. Ih, "Significance of resonant sound transmission in finite single partitions," Journal of Sound and Vibration, **277**, 881-893 (2004).
[15] F. F. Rudder, "Airborne Sound Transmission Loss Characteristics of Wood-Frame Construction," United States Department of Agriculture - Forest Service - Forest Products Laboratory, Madison, WI General Technical Report FPL-43, 1985.
[16] M. Heckl, "Tenth Sir Richard Fairey Memorial Lecture: Sound Transmission in Buildings," Journal of Sound and Vibration, **77**, 165-189 (1981).