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Optimized reference spectrum for rating airborne sound insulation in buildings against neighbor sounds

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ABSTRACT

The aim of the study was to determine an optimized single-number-quantity (SNQ) for airborne sound insulation, which predicts well subjective loudness of neighbor noise. Our study utilized the data of a recent laboratory experiment of Hongisto et al. 2014 (Acta Acustica United with Acustica). The experiment involved six different living sounds, wall constructions, and 59 subjects, thus forming a data basis solid enough for defining an optimized SNQ. The shape of the optimal reference spectrum was sought through optimization by formulating the problem as a nonlinear optimization problem with constraints, and solving it numerically. The new reference spectra were determined for six types of living sounds separately, and for living sounds in general. The optimized SNQs, which were based on the optimized reference spectra, associated much better with subjective loudness than the existing SNQs from ISO 717-1:1996 and ASTM 413 (1999). A suggestion for a reference spectrum for normal living sounds is given at the frequency range of 50–5000 Hz. Low frequencies are substantially less emphasized by the suggested spectrum compared with the reference spectrum of e.g. $C_{50\text{-}5000}$.

Keywords: loudness, sound insulation   I-INCE Classification of Subjects Number(s): 69.3

1. INTRODUCTION

The most disturbing airborne sounds in residential multi-dwelling houses are usually neighbor sounds when the environmental noise level is low (1, 2). Laughter, shouting and crying, TV and music, and pet sounds are experienced as the most annoying neighbor sounds. Sound insulation between dwellings should be designed in such a way that these sounds are efficiently isolated in the first place. Therefore, it is important that the sound insulation performance of constructions is declared with adequate single-number quantities (SNQ). Second, the target levels of sound insulation should be set so high that most of the residents are satisfied. Political decisions are used to choose the adequate SNQs and target values. However, the decisions should be based on solid scientific evidence.

The frequency range deployed in the calculation of standardized single-number-quantities, SNQs, has been under debate. It has been suggested that the SNQ used between residential dwellings should be based on the widest frequency range, 50–5000 Hz, allowed by the measurements standards (3). However, recent psychoacoustic evidence suggests that the application of SNQ exploiting only part of the widest frequency range, e.g. from 100 to 3150 Hz can be sufficient (4–8).

The purpose of our study was to develop an alternative SNQ for airborne sound insulation using the frequency range 50–5000 Hz that explains well the subjectively rated loudness of various kinds of neighbor sounds transmitted from the neighboring dwelling. Data from a recent experimental laboratory study were utilized (6). The reference spectrum was determined using mathematical optimization.

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2. MATERIALS AND METHODS

2.1.1 Data from listening tests

Experimental data from Hongisto et al. (6) was used for the optimization of the reference spectra. The data consisted of subjective ratings (n=59) for six living sounds (guitar S1, music S2-S3, baby cry S4, loud speech S5, and dog bark S6) listened through nine filters representing different wall constructions. R_w of the wall constructions varied between 47 and 75 dB. The sounds were adjusted to realistic, loud levels of living sounds. The subjects were instructed to envision being home in a multi-storey building, while listening to the sounds from the imaginary neighboring dwelling. The background noise level was adjusted to a level corresponding low environmental noise (L_{Aeq} = 23 dB). The subjects rated the sounds with respect to *loudness* and *disturbance* (scale 0 – 10), and *acceptability* (scale 0 – 2). In the next, only *loudness* results are considered.

For optimization, only eight walls out of nine used by Hongisto et al. (6) were used. Wall W4 was excluded, since it had such a high sound insulation resulting in very low sound levels in the receiving room. The subjective variable was defined as the average of the loudness ratings given by 59 subjects.

2.1.2 Solving the optimal reference spectra

Optimal reference spectrum was calculated for each sound type S1 – S6, separately. The resulting optimal single-number quantity was named as R_{S1}, R_{S2}, etc.

To determine a more general reference spectrum for living sound, the six optimized reference spectra were averaged. The resulting optimal single-number quantity was named as R_{opt}.

The goal was to find an optimal reference spectrum for each sound type, so that the fit between the optimized SNQ, x, and the subjective variable, y, was at its best. It was assumed that the subjective variable had a linear dependence on SNQ, based on the data by Hongisto et al. (6).

Calculation of SNQ was based on the A-weighted sound pressure levels such as R_w+C by ISO 717-1 (9). According to (3), a SNQ can be calculated from

$$x_i = 10\lg\sum_{j=1}^{K} 10^{L_j/10} - 10\lg\sum_{j=1}^{K} 10^{(L_j - R_{ij})/10} \tag{1}$$

where x_i is the SNQ for wall i=1,…,8, L_j is the reference spectrum value at frequency band j, R_{ij} is the sound reduction index of the wall i at one-third octave frequency band j. The frequency range was 50–5000 Hz, i.e. K=1, …, 21.

The reference spectrum was normalized to zero, which means that the first term in equation (1) was set to zero.

To find a rather smooth result, the maximum difference between adjacent third-octave band levels of the reference spectrum was limited to 5 dB. Also for the same reason, the squared Pearson's correlation coefficient was limited to a target value of r^2=0.95.

The best fit between y and x can be found using linear least squares method. To find the optimal values for reference spectrum L, the problem becomes a non-linear optimization problem with constraints. It was solved using an algorithm for finding the minimum of a constrained nonlinear multivariable function with Matlab R2015a. The reference spectrum of $C_{50–5000}$ (9) was used as an initial guess for the algorithm. Local optimum was found for each sound type.

To clarify our method, the subjective variable is presented as a function of R_w+$C_{50–5000}$, R_w, and R_{S4} in Figure 1. Variation of the average loudness values as a function of the standardized SNQs is substantial, but the algorithm finds suitable values for the reference spectrum L_{S4}, so that r^2=0.95 is achieved.

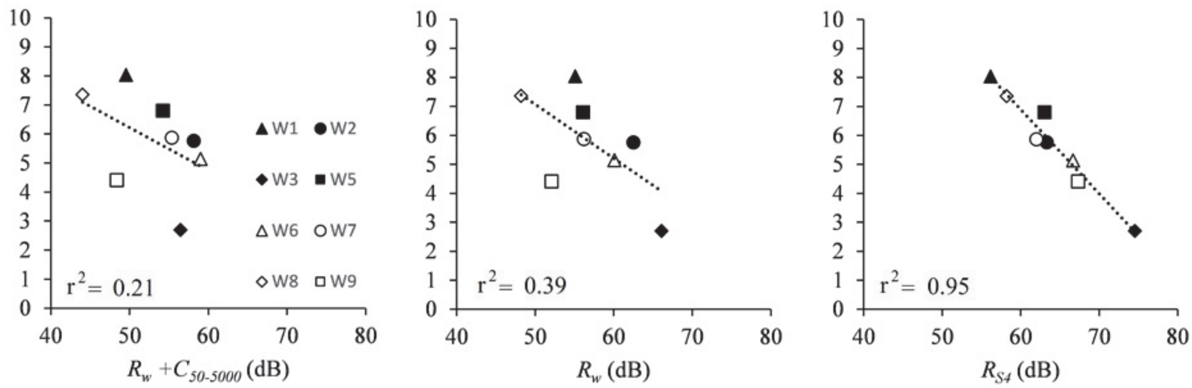


Figure 1 – Subjective variable as a function of R_w+$C_{50–5000}$, R_w, and R_{S4}.

2.1.3 Estimation of the uncertainty of the reference spectrum

Due to individual factors, the subjective ratings have some degree of variation. The optimal reference curve would probably look different, if the listening test was repeated on another day or with other subjects. To estimate, how this would effect on the optimized reference spectrum, the reference spectra were calculated multiple times with slightly changed subjective values. The disturbed value of subjective variable was chosen randomly within the 95% confidence interval, and the calculation was repeated 250 times.

3. Results

The optimized reference spectrum for each sound type is presented in Figure 2 together with the uncertainty limits.

The squared Pearson's correlation coefficients for standardized and optimized SNQs are presented in Table 1 for each sound type.

The reference spectrum for living noise, acquired by averaging the individual reference spectra, is presented in Figure 3.

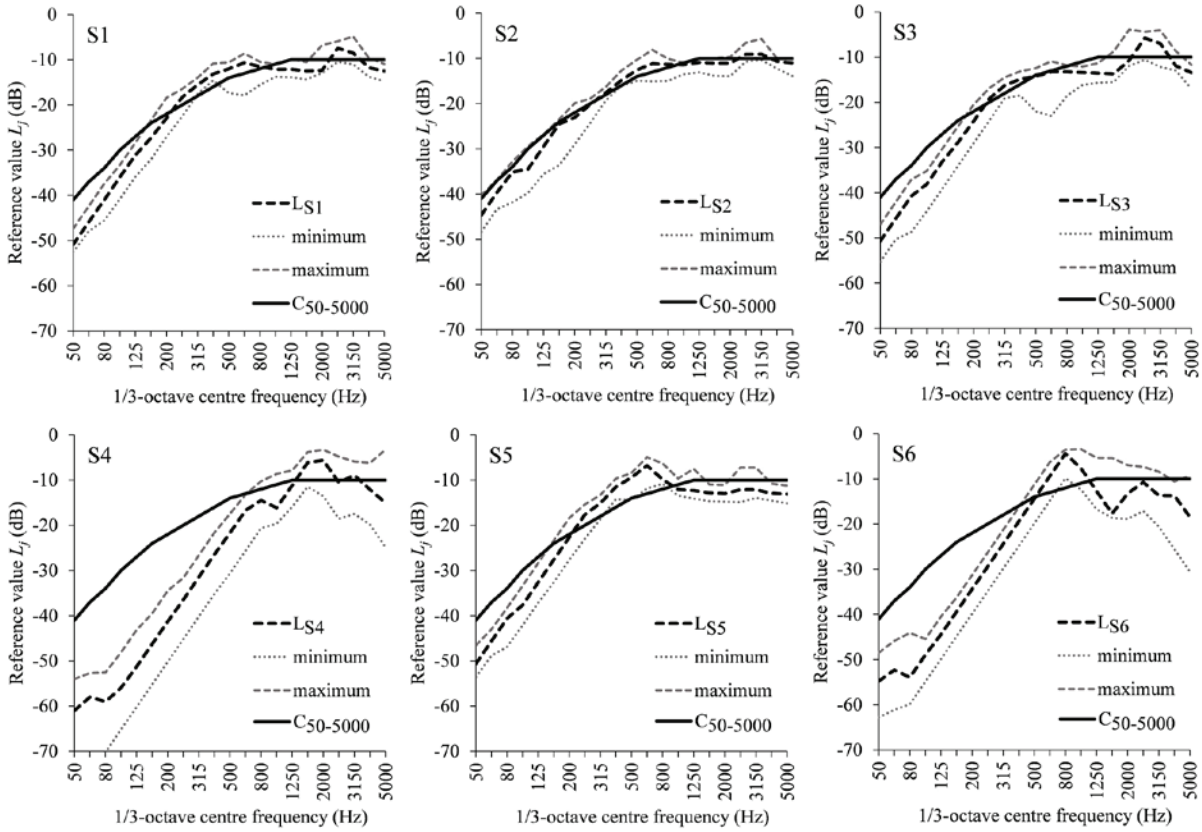
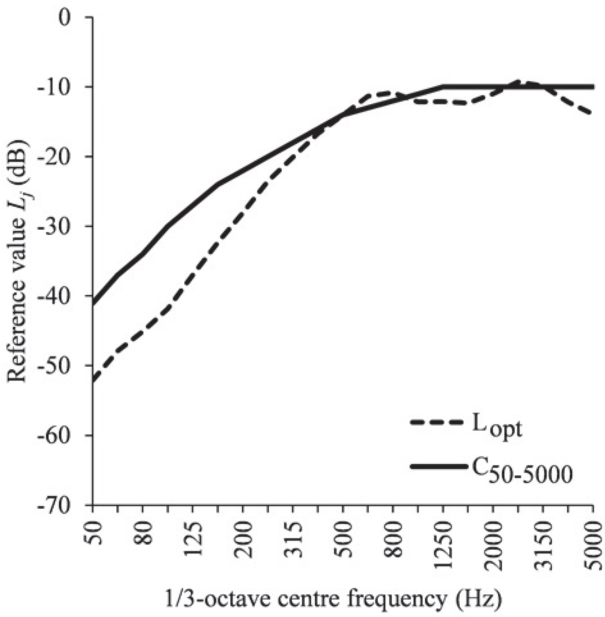


Figure 2 – Optimized reference spectra for each sound type (black dashed line). The uncertainty limits are also presented (grey lines).

Table 1 – Squared Pearson's correlation coefficient r^2 between the SNQs and the mean rating of *loudness* for the sound types S1– S6. The standardized SNQs are above the middle line and the optimized SNQs determined by our study are below the middle line.

	S1	S2	S3	S4	S5	S6
R_w+$C_{50-5000}$	0.73	0.89	0.69	0.21	0.56	0.17
R_w	0.90	0.84	0.80	0.20	0.90	0.51
R_w+$C_{50-3150}$	0.73	0.89	0.69	0.20	0.56	0.17
R_w+$C_{100-3150}$	0.87	0.87	0.77	0.30	0.80	0.37
STC	0.95	0.85	0.87	0.49	0.94	0.58
R_{S1}	0.95	0.88	0.87	0.47	0.93	0.56
R_{S2}	0.87	0.95	0.81	0.32	0.75	0.34
R_{S3}	0.97	0.93	0.95	0.56	0.88	0.52
R_{S4}	0.69	0.56	0.76	0.95	0.63	0.72
R_{S5}	0.85	0.73	0.73	0.40	0.95	0.65
R_{S6}	0.67	0.48	0.61	0.66	0.85	0.95
R_{opt}	0.96	0.87	0.90	0.61	0.95	0.70



f [Hz]	L_j [dB]
50	-52
63	-48
80	-45
100	-42
125	-37
160	-32
200	-28
250	-24
315	-20
400	-17
500	-14
630	-11
800	-11
1000	-12
1250	-12
1600	-12
2000	-11
2500	-9
3150	-10
4000	-12
5000	-14

Figure 3 – Optimized reference spectrum L_{opt} for living sounds. The values of the L_{opt} are presented at the right.

4. Discussion

The optimized spectrum for each sound type differed from each other. They are specific for the sound type in question, and do not explain very well the perceived loudness of other sound types (Table 1). The optimized SNQ for living sound in general, R_{opt}, correlates better than any of the standardized SNQ with all sound types excluding S2. It should be noted that sounds S4 (baby cry) and S6 (dog bark) are often encountered living sounds, and yet correlations with standardized SNQs are quite low. R_{opt} manages to achieve a satisfactory correlation also with these sound types.

Spectrum adaptation term C is guided to be used by ISO 717-1 for living activities. The optimized reference spectra of our study have considerably lower values at low frequencies than the C spectrum except for the sound type S2, which had a strong bass element. Even when the uncertainty of the optimized reference spectrum is considered, it can be concluded that $C_{50\text{–}5000}$ overestimates the weight of low frequencies for living sounds. This should be considered in the future standardization work.

The data used for optimization was taken from a laboratory experiment. It is clear that laboratory conditions do not correspond to residential conditions in every way. The data could also be gathered from field studies. However, field studies are sensitive to the effects of non-acoustic variables, such as personal and social factors which can have larger association with the perceived loudness than the sound level transmitted from the neighbor (10). The experimental situation in laboratory is artificial but personal and social factors play much smaller role in loudness ratings. Thus, laboratory data may be more reliable, when different sound types are concerned, and reference spectrum is being developed. Field surveys are more appropriate for studying the ultimate residential acoustic satisfaction.

The width of the uncertainty limits vary according to sound type. It seems that the optimal reference spectrum is quite sensitive to the variation of the subjective variable. The number of the subjects should not be greatly decreased for this type of studies.

All sound types encountered in living activities cannot be taken into account by using a distinctive spectrum adaptation term. Therefore, the target is to form a compromising reference spectra, suitable for most common living sound types. We suggest the consideration of R_{opt} for sounds originated from normal living activities. Another SNQ, $R_W+C_{50\text{–}5000}$, could be applied for amplified music with strong bass content, such as the sound type S2 of our study. The latter could be applied for e.g. dwellings located near to music clubs.

5. Conclusions

A new reference spectrum was developed using data of the psychoacoustic experiment of Hongisto et al. (6), and mathematical optimization to form a new single-number quantity R_{opt}, which could be used to rate airborne sound insulation in residential context. The reference spectrum of R_{opt} deviates significantly from that of $C_{50–5000}$ below 315 Hz (Figure 3). The new optimized single-number quantity correlates better with the subjective loudness caused by neighbor sounds than any of the present standardized single-number quantities of ISO 717-1.

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