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New single-number quantities for evaluation of impact sound insulation

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ABSTRACT

The standardized single-number quantities for evaluation of impact sound insulation do not correlate especially well with the subjective judgment of living impact sound sources directed to the floors. The aim of this study was to find new single-number quantities better associated with the subjective annoyance caused by different impact sounds. The new single-number quantities were developed on the bases of experimental data of laboratory measurements of impact sound insulation of floors and a psychoacoustic experiment. Five impact sound types were studied: walking with hard shoes, socks, and soft shoes, super ball bouncing, and chair moving. Basic requirement was that the new single-number quantities could be expressed as the sum of $L'_{n,w}$ or $L'_{nT,w}$ and new spectrum adaptation terms. Reference spectra for calculation of new spectrum adaptation terms for each sound type were derived by the means of a mathematical optimization method. In addition, an optimized reference spectrum based on all five sound types was derived. An optimized reference spectrum based on all five sound types explained the annoyance of the five sound types reasonably well.

Keywords: building acoustics, impact sound insulation, single-number quantity

1. INTRODUCTION

It has been long recognized (1–5) that the single-number quantities (SNQ) presented in the standard ISO 717-2 (6) do not correlate especially well with the subjective judgment of living impact sound sources directed to the floors. There have been two strategies for solving the problems. Firstly, modifying or replacing the standard tapping machine as a sound source has been suggested. There is, however, some evidence indicating that the alternative sound sources to the tapping machine do not necessarily lead into a better association between the objective SNQs and subjective rating (7). The second strategy for solving the problematics concerning the association between the SNQs and subjective rating is defining a new SNQ based on the tapping machine as a sound source (8). Several alternative SNQs for rating the impact sound insulation of floors have been suggested since the 1960s (2, 9–12).

A recent psychoacoustic experiment dealing with the impact sound insulation of concrete floors indicated that the standardized SNQs, $L'_{n,w}$, $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{-}2500}$ were not always well associated with subjectively perceived loudness or annoyance of different impact sound sources (13). This concerns also the four alternative SNQs (2, 10–12).

The aim of the study reported in this paper was to develop alternative SNQs for impact sound insulation that explain well the annoyance caused by various impact living sounds transmitted from the neighboring dwelling upstairs. Alternative SNQs concern five spectrally different impact sounds (walking with hard shoes, walking with socks, walking with soft shoes, superball bouncing, chair moving) experimentally investigated in (13). The object also was to develop a SNQ that explains well the annoyance caused by all five impact living sounds. This paper is based on a wider study reported in the reference (14).

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2. MATERIALS AND METHODS

2.1 Basic Requirements

It seems obvious that the tapping machine will remain as the primary impact sound source (15). Therefore, it was assumed that a new method for rating the impact sound insulation could be found by deriving a better SNQ or reference curve instead of replacing the tapping machine with some other sound source, such as Japanese ball used in ISO 16283-2 (16). In addition, basic requirement was that the new single-number quantities could be expressed as the sum of $L'_{n,w}$ or $L'_{nT,w}$ and new spectrum adaptation terms. The alternative SNQs are developed for the frequency range 50–2500 Hz.

2.2 Experimental Data

The experimental data utilized in the study originates from a psychoacoustic laboratory experiment concerning subjective loudness and annoyance of different impact sounds. The conduction of the psychoacoustical experiment has been reported in the reference (13). The recording of living impact sounds and measurements of the impact sound insulation of different floors has been reported in the reference (17).

The experiment involved 45 impact sounds. They were created by recording sounds of five different impact sound sources directed to nine different floor types in an impact sound insulation laboratory. The floor types consisted of nine floor constructions: a bare 265-mm-thick hollow core concrete slab (F1) and eight different floor coverings (F2–F9) installed on the top of F1. The normalized impact sound levels L'_n [dB] were measured according to ISO 140-7 (18) using the tapping machine. The floor coverings and the impact sound insulation measurements have been described in detail in the reference (17). The floor coverings of constructions F2–F9 were:

- F2: hard cushion vinyl (ΔL_w = 2 dB),
- F3: soft cushion vinyl ΔL_w = 21 dB),
- F4: parquet and soft underlayment ΔL_w = 20 dB),
- F5: hard wall-to-wall textile carpet (ΔL_w = 21 dB),
- F6: soft wall-to-wall textile carpet (ΔL_w = 37 dB),
- F7: F4 on top of a floating floor 1 (2 plasterboards and 13 mm mineral wool) ΔL_w = 29 dB),
- F8: F4 on top of a floating floor 2 (2 plasterboards and 50 mm mineral wool) ΔL_w = 36 dB),
- F9: F4 on top of a floating floor 3 (4 plasterboards and 50 mm mineral wool) ΔL_w = 38 dB).

In the impact sound insulation laboratory, five different impact *sound types* S1–S5 were recorded in for each floor type F1–F9. The sound types were:

- S1: walking with hard shoes
- S2: walking with socks
- S3: walking with soft shoes
- S4: super ball bouncing
- S5: chair moving

There were fifty-five voluntary people (25 male, 30 female) participating in the experiment. Their age varied between 20 and 57 years. The impact sounds were played from several loudspeakers installed above the suspended ceiling so that the impact sounds seemed natural. The participants judged the *annoyance* of each impact sound. The judgment for annoyance was given on a scale from 0 to 10, value 10 indicating that the sound is "extremely annoying" and 0 "not at all annoying because the sound could not be heard". The mean values of subjective annoyance (Figure 1) as a subjective variable were used in the optimization problem since annoyance is closely related to health effects of noise and acoustic comfort. The measured normalized impact sound pressure levels L'_n are shown in Figure 2.

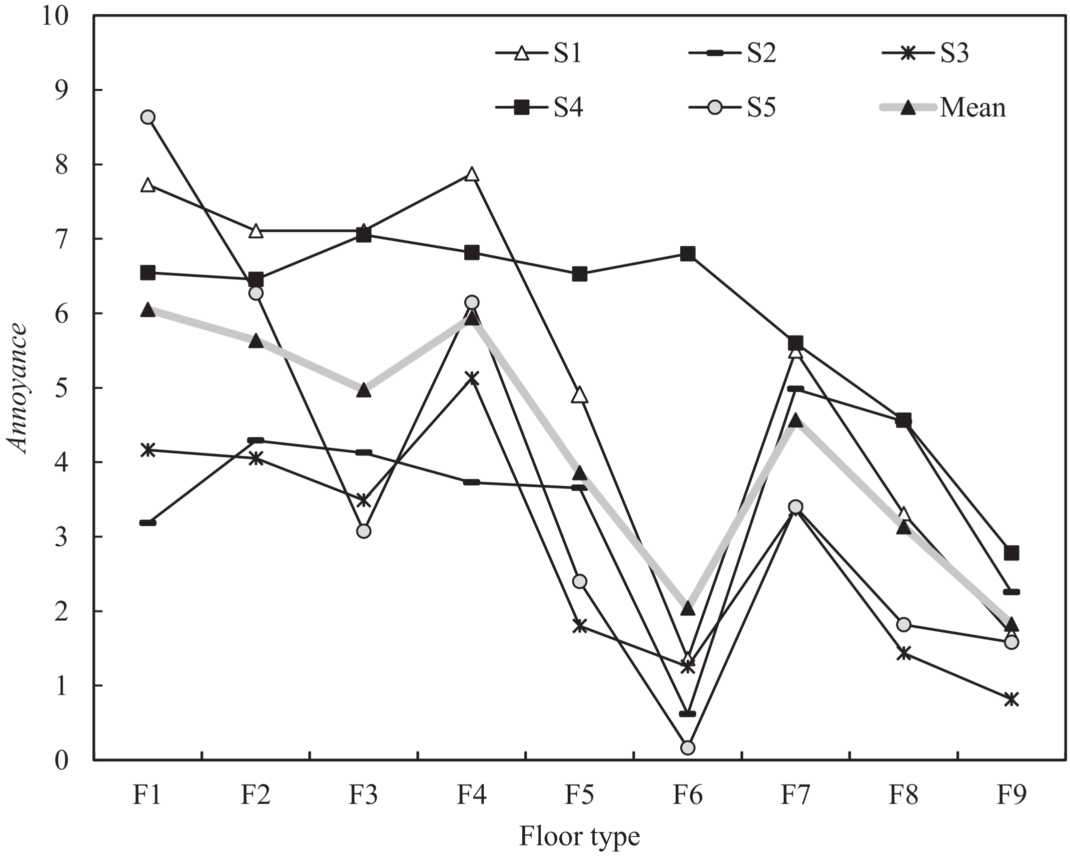

Figure 1 – Mean values of subjective annoyance for each combination of impact sound types S1–S5 and floor types F1–F9. In addition, the mean over all five sound types (Mean) is shown. The variable on the X-axis is categorical. Lines are used to facilitate the reading of data.

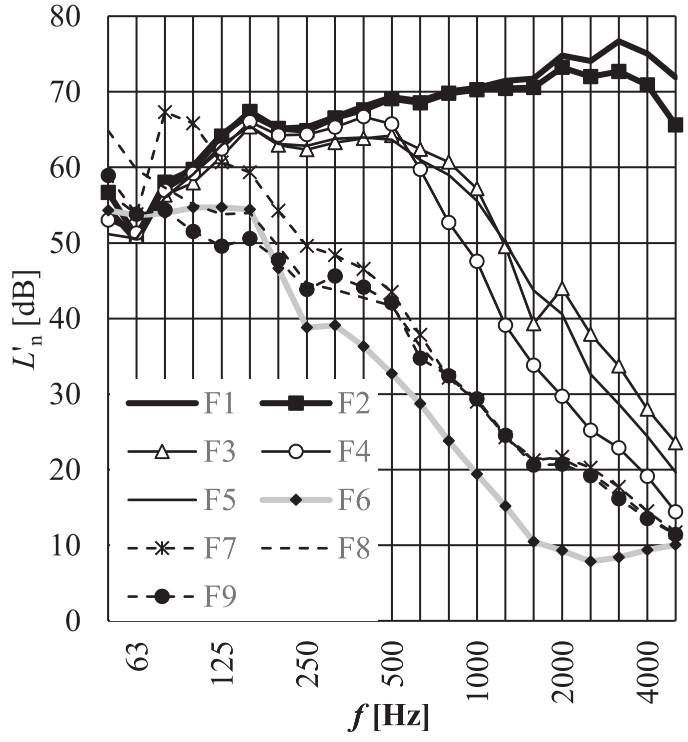

Figure 2 – Measured normalized impact sound pressure levels L'_n of the nine floor types F1–F9.

2.3 Mathematical Optimization

Mathematical optimization was used to solve our problem instead of using sophisticated guess method although both methods may end up to very similar outcomes. Reference spectra for calculation of new spectrum adaptation terms for each *sound type* were derived by the means of a mathematical optimization method. In addition, an optimized reference spectrum based on all five sound types was derived. Virjonen et al. (19) have already developed optimized reference spectra for airborne sound insulation by applying mathematical optimization to experimental data presented in the reference (20). The mathematical optimization method is an effective and quick method for the derivation of a scientifically justified SNQ.

The formulation of the optimization is presented in detail in the reference (14). The subjective variable for each floor type and sound type was defined as the mean of the ratings of annoyance given by the 55 participants. It was assumed that the subjective variable depends linearly on the SNQ.

The goal was to find an optimal reference spectrum for each impact *sound type* S1–S5. The optimized reference spectrum for impact *sound type* S1 was called L_{S1}. For each impact sound type, such a reference spectrum was sought, that the subjective annoyance had the best achievable least-squares fit with the resulting SNQs. The optimal reference spectrum was determined by formulating the problem as a non-linear optimization problem with constraints, and solving it numerically.

The optimized SNQ can be expressed as a sum of the weighted normalized impact SPLs $L'_{n,w}$ and a spectrum adaptation term. E.g. spectrum adaptation term for impact sound S1, $C_{I,S1}$, can be expressed as

$$C_{I,S1} = 10\lg \sum_{j=1}^{K} 10^{0,1(L_{S1,j} - 78,2 - 10\lg f_j + L_{n,j})} - 18,9 - L'_{n,w} \quad (1)$$

In addition to *sound type* optimized reference spectra derived above, an optimized reference spectrum over all five sound type was also derived. This is meaningful since the construction performances are declared using a single SNQ which is expected to represent all impact sound types sufficiently well. The optimized reference spectrum was called L_{opt} and the SNQ calculated from it $L'_{n,w} + C_{I,opt}$. This reference spectrum was derived by adding all 45 experimental sounds (9 floor types times 5 sound types) into the same pool.

3. RESULTS

The optimized reference spectra are presented in Fig. 3. The squared correlation coefficients between the standardized and optimized SNQs and the mean annoyance are given in Table I.

Table 1 – Squared Pearson's correlation coefficients r^2 of the optimized and standardized SNQs for each impact *sound type* S1…S5. The best acquired value per sound type is underlined.

SNQ	S1	S2	S3	S4	S5
$L'_{n,w} + C_{I,S1}$	<u>0,93</u>	0,38	0,75	0,35	0,73
$L'_{n,w} + C_{I,S2}$	0,41	<u>0,87</u>	0,30	0,01	0,31
$L'_{n,w} + C_{I,S3}$	0,91	0,35	<u>0,77</u>	0,42	0,69
$L'_{n,w} + C_{I,S4}$	0,87	0,24	0,71	<u>0,56</u>	0,59
$L'_{n,w} + C_{I,S5}$	0,75	0,26	0,61	0,20	<u>0,87</u>
$L'_{n,w} + C_{I,opt}$	0,92	0,40	0,75	0,35	0,74
$L'_{n,w}$	0,68	0,09	0,54	0,30	0,80
$L'_{n,w} + C_I$	0,83	0,17	0,68	0,44	0,75
$L'_{n,w} + C_{I,50\text{-}2500}$	0,82	0,27	0,65	0,29	0,82

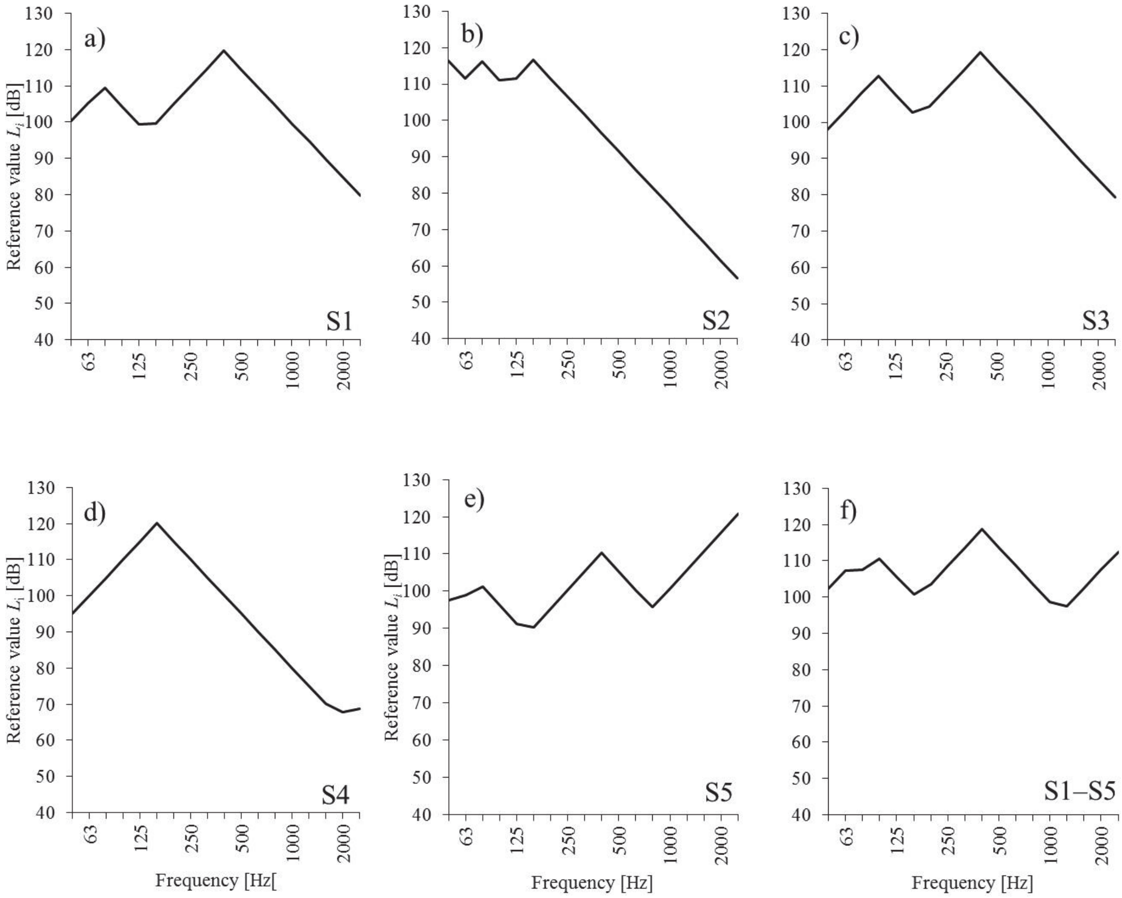

Figure 3 – The sound type optimized reference spectra $L_{S1}…L_{S5}$ for the impact *sound types* S1–S5 (panels a–e) and the optimized reference spectrum L_{opt} for all sound types S1–S5 (panel f).

4. DISCUSSION

The standardized SNQs $L'_{n,w}$, $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{-}2500}$ correlated relatively well with annoyance for sound types S1 (walking with hard shoes), S3 (walking with soft shoes) and S5 (chair moving). The correlation was poor for sound types S2 (walking with socks) and S4 (super ball bouncing).

An optimized reference spectrum yielding a high correlation with annoyance could be derived for each sound type S1–S5. Compared with the SNQs presented in the standard ISO 717-2 (6), each optimized reference spectrum produced a higher squared correlation coefficient between the optimized SNQ and annoyance. Virjonen et al. (19) developed optimized SNQs for airborne sound insulation using the same mathematical method and the resulting SNQs also explained annoyance much better than any of the standardized SNQs. This shows that the mathematical optimization is a consistent and justified method in striving for SNQs associating the physical measurement results to the subjective experience of the impact or other sounds.

Walking with socks (sound type S2) is among the most important residential impact sounds (7, 17, 20). Thus, the standardized SNQ should be well associated with the annoyance of this sound type. None of the studied standardized SNQs correlated well with the experienced annoyance of walking with socks.

A reference spectrum with a high correlation with annoyance also for sound type S2 (walking with socks) could be found using the optimization method because this sound type is among the most prevalent neighbor sounds in residential environments (22). The squared correlation coefficient 0.87 was significantly higher than those of the standardized SNQs $L'_{n,w}$, $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{-}2500}$ (r^2 values within 0.09–0.27). All the sound type optimized reference spectra gave better squared correlation coefficients than any of the standardized SNQs.

The optimized reference spectrum for sound type S4 (super ball bouncing) produced a better correlation (r^2 = 0.56) than the standardized single-number quantities $L'_{n,w}$, $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50-2500}$. The squared correlation of sound type S4 is, however, clearly lower than for the other sound types. One reason might be the narrow spread of annoyance responses. However, this cannot be the only reason since equally narrow spread was observed also for sound types S2 and S3. The reason for low correlation seems to be floor type F6 involving a very soft wall-to-wall carpet. It produces a low SNQ value but the sound type S4 is judged quite annoying. The soft wall-to-wall carpet leads to the lowest SPLs from walking (S1–S3) and chair moving (S5), but S4 is an exception. This sound type S4 with wall-to-wall carpet generates similar impact sound spectrum as this sound type with floors F1–F5 (17) which explains this exception.

It was found important to derive a single reference spectrum that would explain the annoyance responses reasonably for all five sound types simultaneously. Therefore, an optimized reference spectrum, L_{opt} was derived to predict the annoyance of all five sound types. According to Table I, the optimized reference spectrum is relatively good since it produced higher r^2 values than any of the standardized SNQs for sound types S1–S3. The values were also reasonably high for sound types S4–S5. Thus, the reference spectrum serves the original purpose of being better than any of the standardized SNQs.

5. CONCLUSIONS

Reference spectra for rating impact sound insulation of floors were derived by the means of a mathematical optimization method. An optimized reference spectrum could be developed for each five sound types. Each of them correlates better with the subjective annoyance of the impact sounds than any of the single-number quantities presented in the standard ISO 717-2 (6). In addition, an optimized reference spectrum could be derived which explained the annoyance of all five sound types reasonably well.

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