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A model based on loudness level to describe airborne sound insulation

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ABSTRACT

Sound transmission between units is one of the biggest complaints among apartment building residents today. Since living noise is an increasing problem particularly between dwellings there is a need for a method of assessing airborne sound insulation between rooms. In many practical cases, however, the objective measures of the airborne sound insulation using procedures in standards are not in agreement with the subjective assessment. This paper describes a calculation scheme based on loudness level linked with specific fluctuation strength, yielding a weighted normalized loudness level difference $L_{nor,w}$. By analysing the difference between standard airborne sound insulation values and the introduced weighted normalized loudness level difference, it is revealed that the sound pressure level that is transmitted through a partition contains important details concerning subjective assessments. It is shown, that a simple level difference does not exhibit the effect of a given signal to the frequency-dependent airborne sound insulation curve, while using $L_{nor,w}$, a significant effect can be observed, in terms of both computed and measured results.

Airborne sound insulation, Rating, Loudness I-INCE Classification of Subjects Number(s): 51.4

1. INTRODUCTION

The approach to designing for sound insulation in Europe and other countries pays insufficient attention to many important aspects of how sound is judged subjectively. The subjective perception aspect regarding building acoustics characterization values is an important topic and it is well known that the objective measures of the airborne sound insulation using procedures in standards are not in agreement with the subjective assessment. There is agreement among the building acoustics experts that the dweller's perception has to be included with appropriate approaches.

The sound insulation of a partition wall or a ceiling is generally measured using standardized methods. Standards in Europe and other countries consider only single number rating, which reduces the results at a number of frequencies to a single numerical value. A number of indexes have been defined; each offers various benefits for different situations. All have, however, in common that they have to be obtained using a steady-state sound signal, usually pink noise, and compared against a reference curve as defined e.g. in ISO 717-1 (1). This procedure results in a single number rating yielding a sound insulation index. As was shown e.g. in (2-6) people evaluate the sound signal differently if the sound signal which is transmitted through a partition shows varying time and frequency structure. The currently used descriptors for airborne sound insulation are based on steady-state signals. The effect using non-steady-state signals in describing airborne sound insulation was shown in (2). The authors discussed in (7, 8) a calculation scheme based on loudness level linked with specific fluctuation strength, yielding a weighted normalized loudness level difference ($L_{nor,w}$) as a function of frequency.

This paper designates the introduced calculation scheme of (7) and discusses the weighted normalised loudness level difference further. Results of measured and calculated airborne sound insulation values compared to the calculated weighted normalized loudness level difference are presented. Calculations of psychoacoustic parameters were performed using software ArtemiS V11.

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2. DESCRIPTION OF THE MODEL

The authors have shown that the airborne sound insulation has to be converted into a subjective related measure (2). The airborne sound insulation is essentially the level difference of a signal after being transmitted through a partition. The apparent sound reduction index *R*' is described in ISO 16283-1 (9) (nb: previous ISO 140-4). This standard specifies procedures to determine the airborne sound insulation between two rooms in a building using sound pressure measurements. These procedures are intended for room volumes in the range from 10 m^3 to 250 m^3 in the frequency range from 50 Hz to 5 kHz. Hence, the measured airborne sound insulation is frequency-dependent and can be converted into a single number quantity to characterize the acoustic performance using the rating procedures in ISO 717-1.

In free space with the partition separating two domains, the apparent sound reduction index *R*' is identical to the sound pressure level difference, *D*:

$$R' \equiv D = L_1 - L_2 \text{ dB} \tag{1}$$

with L_1 and L_2 denoting the energy-average sound pressure levels measured in a testing facility in the source and receiving room.

After transmission of L_1 through a structure or partition, the sound heard by a listener is L_2. The level of interest is therefore, L_2. This is the sound pressure level that is impinging on the ear of a resident, and thus, this level has to be judged correctly in an objective manner (7). The sensation that corresponds most closely to the sound intensity of the stimulus is loudness. That is, loudness describes the quality of a sound that is the primary psychological correlate of physical strength, i.e. the amplitude (10). Therefore, the perception of loudness is related to the sound pressure level (SPL) and is defined as a level of 40 dB of a 1-kHz tone referenced for loudness sensation, i.e. 1 sone (11).

In order to describe a sound there are other psychoacoustic properties such as roughness and fluctuation strength.

Roughness is often used for the subjective judgment of sound impression and for sound design (10). With increasing roughness, noise emissions are perceived as increasingly noticeable and usually as increasingly annoying. Fluctuation strength is also often used but the modulation frequency is around 4 Hz instead of 70 Hz as for the roughness. Since speech is related to a modulation frequency of about 4 Hz a sufficiently high modulation depth is necessary. Thus, it is assumed that the heard sound can be judged in terms of a loudness level L_N. To compute the loudness level, the sound pressure level has to be transformed into a loudness level. This transformation is accomplished using the standard procedure of ISO 226 (12). The loudness is determined by means of a hearing-related measurement procedure focused on the functioning of the human hearing. If it is assumed that frequency-dependent sound insulation should reflect any events in the frequency range, it is expressed in the ratio of the airborne sound insulation with a dip to the airborne sound insulation without a dip in the frequency depending sound insulation. Because loudness is a hearing-related measure, with temporal and spectral mask effects taken into account, it is preferable as a measure to describe sound insulation.

The phon is a unit of perceived loudness level (L_N), which is a subjective measure of the strength of a sound. The measure of sound insulation may therefore be written in terms of a loudness level yielding a measure of airborne sound insulation strength. The transformation follows ISO 226:

$$L_{2(f)} \rightarrow L_{N(f)} \tag{3}$$

The filtered level (L_2) contains all information of the airborne sound insulation characterized by the weighted apparent sound reduction index (R'_w) as it is the transmitted sound signal. Thus, conversion of sound pressure level into loudness level yields a sensation level.

The level difference characterized by the weighted apparent sound reduction index (R'_w) as computed (L_0) and measured (L_m) provides a set of loudness level differences. The level difference of the idealized (i.e., hypothetical or computed) airborne sound insulation as *R*'-values for third-octave bands is given by eq. (4):

$$\Delta L_{0(f)} = L_{N1(f)} - L_{N2(f),0} \tag{4}$$

and the level difference of an actual (i.e., measured) airborne sound insulation as *R'*-values for third-octave bands is given by eq. (5):

$$\Delta L_{m(f)} = L_{N1(f)} - L_{N2(f),m} \tag{5}$$

The normalized level difference with respect to the idealized level difference for third-octave band values is written as follows:

$$L_{nor}(f) = \frac{\Delta L_{m}(f)}{\Delta L_{0}(f)} \quad (6)$$

It is assumed that an appropriate weighting has to be applied. The weighting will be judged as an awareness of noise, i.e., annoyance. Psychological effects like annoyance cannot be fully evaluated by the measurement of the sound pressure level (5). For this reason some psychoacoustic factors like roughness, fluctuation strength and tonality were in (4) investigated and discussed, where it was found that white noise yield a zero value for roughness and tonality for high sound insulation. This result led to the conclusion, that roughness and tonality are not suitable predictors for a rating procedure concerning sound insulation. In contrast to the psychoacoustic measure roughness, which has an envelope fluctuation between 20 Hz and 300 Hz, the specific fluctuation strength has modulation frequencies under 20 Hz. Fluctuation strength reaches a maximum for modulation frequencies around 4 Hz and plays a vital role in the assessment of human speech (11). This will be detected by a listener as time modifications and hence results in a perception of fluctuation strength. In general this measure is a psychoacoustic analysis of the human perception of a slowly varying modulation of the signal based on the hearing model (10). The weighted normalised loudness level difference, or airborne sound insulation strength, for third-octave band values is then written as follows:

$$L_{nor,w}(f) = L_{nor}(f) * w(f) \quad (7)$$

where w is a weighting factor.

From reasons discussed above and because the specific fluctuation strength, *Fls'* (vacil) relates to the temporal structure of the sounds (3, 13), this measure is chosen to be an appropriate weighting. This is in accordance with investigations concerning indoor acoustic comfort in (14). To complement the normalised loudness level the weighting must be normalized also. The level specified in eq. (4) yield the frequency depending specific fluctuation strength $Fls'_{(f),0}$ and the level specified in eq. (5) yield $Fls'_{(f),m}$, so the weighting for third-octave band values is:

$$w(f) = \frac{Fls'_{(f),m}}{Fls'_{(f),0}} \quad (8)$$

The total specific fluctuation strength is calculated as the sum of all partial fluctuation strength yielding *Fls'*. The single number quantity or the weighting w is:

$$w = \frac{Fls'_{m}}{Fls'_{0}} \quad (9)$$

A method for determining a single numerical value of a given sound in terms of a loudness level was developed by Zwicker (15) and the calculation method is given in ISO 532 B (16), DIN 45631 (17), respectively, and this is based on spectrum analyses in one-third octave bands. The single number quantity for the normalized loudness level difference L_{nor} is then written as the quotient of the differences of the total loudness levels, yielding:

$$L_{nor} = \frac{L_{N1} - L_{N2,m}}{L_{N1} - L_{N2,0}} \quad (10)$$

Combining eq. (9) and eq. (10) yield the single number quantity for the weighted normalized loudness level difference $L_{nor,w}$ and is written as:

$$L_{nor,w} = L_{nor} * w \quad (11)$$

3. Signal description

In order to investigate the effect using different signals there are two types of signal compared, including steady-state and non-steady-state signals. The steady-state signals are the broadband noise signals, “pink noise” (PN) and “white noise (WN). These signals are chosen due to the fact that they are recommended in the Standards for measuring airborne sound insulation like ISO 16283-1. The non-steady-state signals, i.e., the transient signals, were music samples, namely rap (Eminem: “Loose Yourself”) (E) and a classic music (Beethoven: Symphony Nr. 9: Poco Allegro, Stringendo Il Tempo, Sempre Piu Allegro - Prestissimo) (B). Additionally, a sound sample was used considering people speaking combined with pop music (Party-Sound) (PS).

In Figure 1, the power spectral densities of the used signals are shown. Pink noise, also known as 1/f-noise, is a signal with a frequency spectrum such that the power spectral density is proportional to the reciprocal of the frequency. There is equal energy in all octaves. In terms of power at a constant bandwidth, 1/f-noise falls off at 3 dB per octave. White noise on the other hand, is a random signal with a flat power spectral density. The signal contains equal power within a fixed bandwidth at any centre frequency. Pink noise displays a decreasing straight line over the frequency bandwidth and white nose displays a straight line, whereas the music type signals decreases with a certain fluctuation toward higher frequencies.

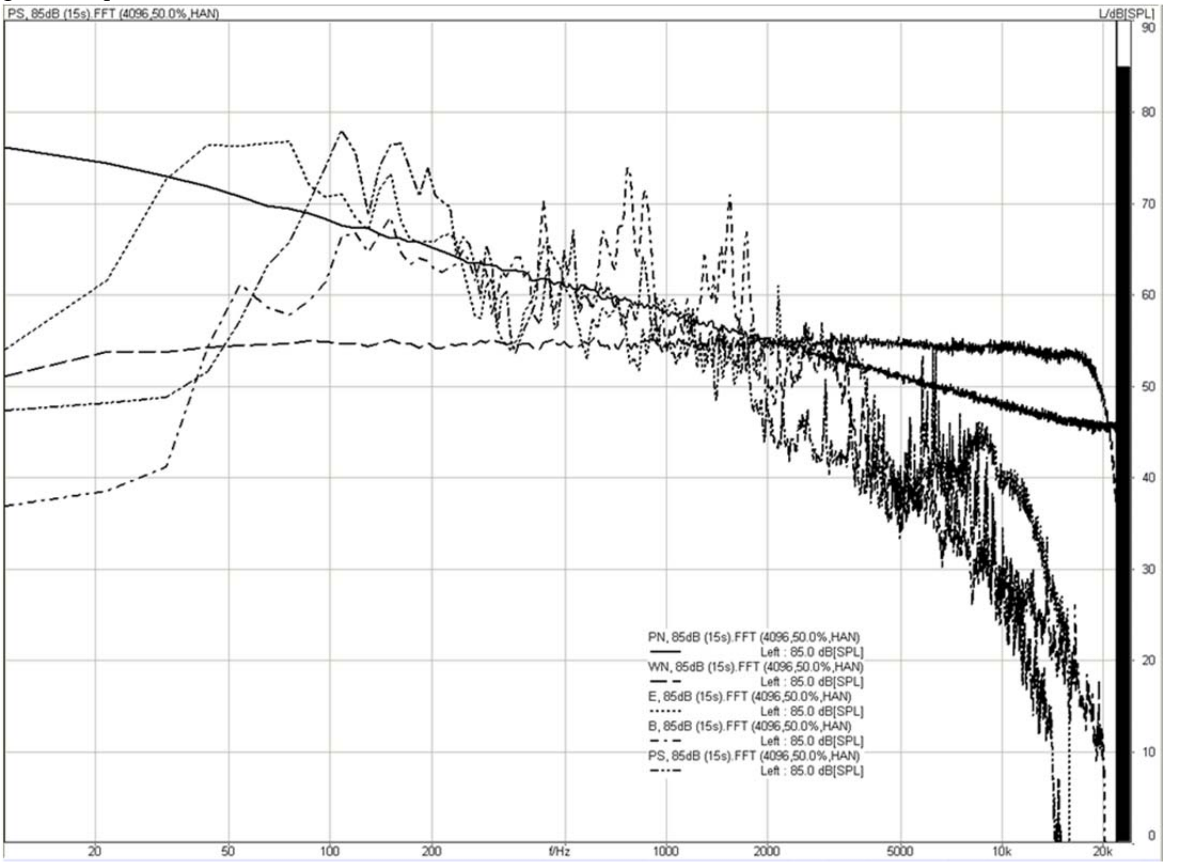

Figure 1 – Power spectral density (*PSD*) of the five sound signals used in the test as a function of frequency having sound pressure level of 85 dB SPL and duration of 15 s.

The specific fluctuation strength (*Fls'*) of the five sound signals used in the test for different sound pressure level (*SPL*) is shown in Figure 2.

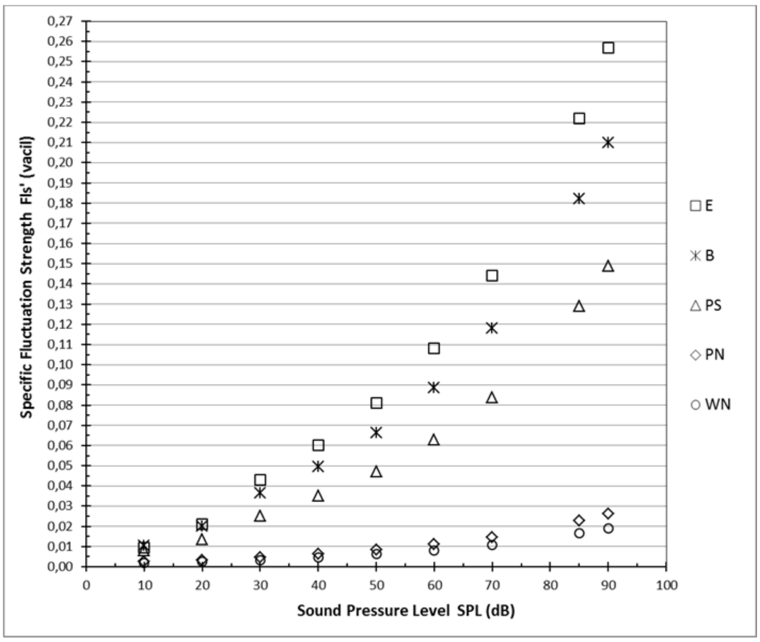

Figure 2 – Specific fluctuation strength for different sound signals over sound pressure level.

4. Airborne Sound Insulation

In this study the airborne sound insulation of three partitions has been measured in situ due to complain of residents. Two samples were lightweight constructions and one sample was a heavyweight construction. The measurement was according to ISO 16283-1.

The frequency depending airborne sound insulation was converted in a single number rating using the Standard ISO 717-1. In general this procedure uses a reference curve shifted against the frequency dependent values.

Figure 3 shows the measured frequency depending airborne sound insulation and the shifted reference curve according to ISO 717-1. In the left panel the airborne sound insulation of a lightweight ceiling (wood ceiling) having R'_{w} =36 dB is shown. In the mid panel of Figure 3 a gypsum board wall having R'_{w} =51 dB and in the right panel a masonry wall having R'_{w} =54 dB are shown.

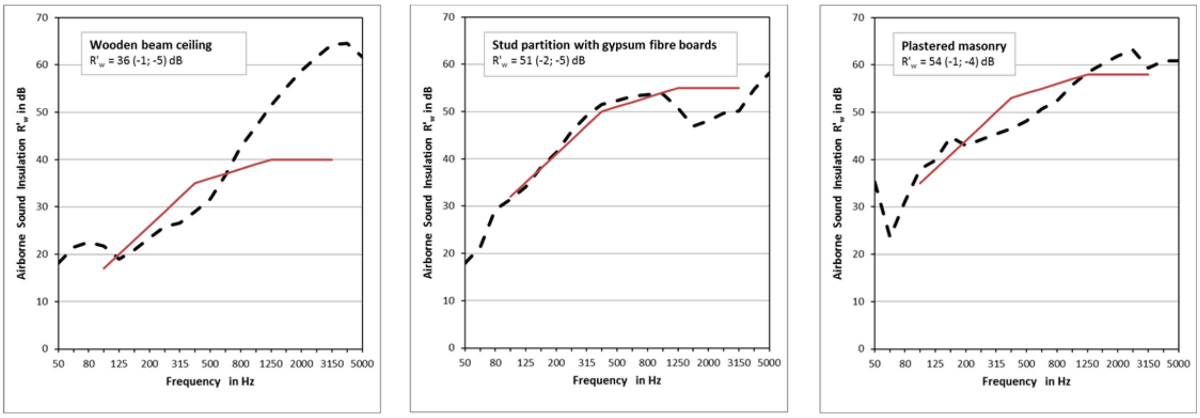

Figure 3 – Measured airborne sound insulations. The solid line is the reference curve given in ISO 717-1.

As an example Figure 4 shows the measured sound pressure level and the corresponding computed loudness level for different sound signals after transmission through a wall having an R'_{w} = 54 dB.

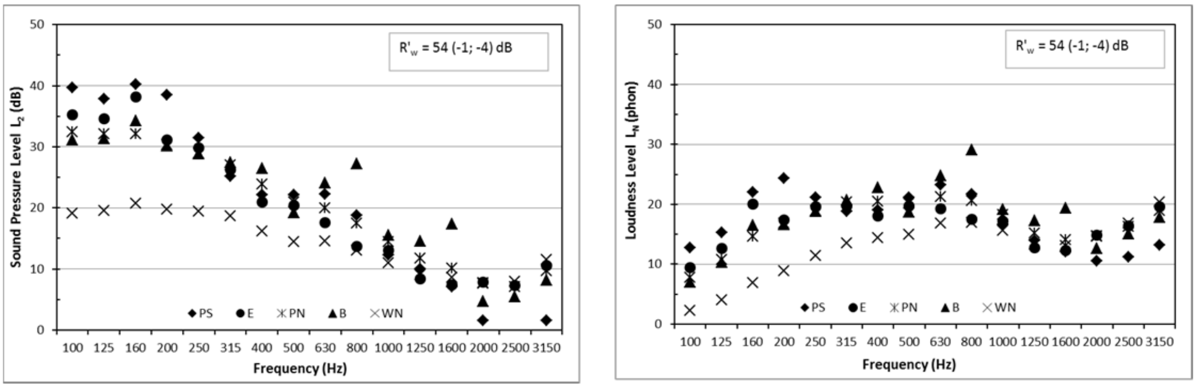

Figure 4 – Comparison of measured sound pressure level (L_2) and calculated loudness level (L_N)

5. Subjective Test

Results from an earlier experiment which are presented in (2) demonstrated that different sound samples are differently judged in loudness.

In a new experiment one hundred subjects were asked to listen to the sound samples presented in section 3 and to judge the sound level with regard to the perceived loudness. The subjects were presented two sound signals one after the other, with both signals having the same sound pressure level. The duration of one sound sample was 5 s.

In the listening test the used method was a bipolar 11-point scale providing a midpoint and has labels only at the endpoints of the scale.

The subjects were asked to decide if the last heard sound was louder or quieter as the first one. They had to mark in a range from -5 to +5. That means, they had to choose a number from -5 to +5 in single steps, where -5 stands for: “much quieter”, zero: “equally loud” and +5: “much louder”.

In the experiment the following response scale was used.

	Was the second sound sample when compared to the first …?										
	much louder					equally loud					much quieter
	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
1	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
…	…	…	…	…	…	…	…	…	…	…	…
30	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑

Figure 5 – Response scale used in the listening test.

The first set of test signals had an unweighted sound pressure level of 50 dB.

The second set had an unweighted sound pressure level of 40 dB and the last set had an unweighted sound pressure level of 60 dB.

Each sound sample was tested against each other. That is, three groups of volume levels (40, 50, 60 dB) and five sound samples (WN, PN, E, B, PS). In total all 5 sounds with 12 pair comparisons were compiled in the experiment (such as WN: WN vs. PN, WN vs. E, WN vs. B and WN vs. PS; at 40 dB, 50 dB to 60 dB).

All responses made from the subject of the survey were collected and sorted for consequent statistical analysis.

For the comparison of two paired samples, if there is a scale variable and normal distribution of the differences of the pair of variants, the paired t-test is used.

When comparing two paired samples regarding a metrical variable, the Wilcoxon test is used if the differences of the pairs of variants are not normally distributed. In other words, the Wilcoxon test is a non-parametric test. It compares the distributions of the two variables by means of the differences between the pairs of variants.

The 5 noise variables calculated in accordance with above scheme (points average from 12 pair comparisons) have been compared using t-test for related samples and Wilcoxon test, respectively, to determine whether the mean differences between the sounds (if quieter or louder) are significant, i.e. whether the differences can be generalized and thus related to a larger population.

Preliminary, the difference of the two variables using the Kolmogorov-Smirnov test for normality has been tested.

If there is a normal distribution of the difference the t-test for related samples is appropriate, otherwise the non-parametric Wilcoxon test is applied.

The analyses have shown that with regard to the significance ($p < 0.05$) of the differences between the sounds the t-test and Wilcoxon test lead to the same result.

The test revealed WN was highly significantly ($p < 0.001$) perceived quieter compared to other sound samples.

The results of the listening test are shown in Table 1 and graphically in Figure 6 as a box plot.

Table 1 – Results of the subjective test for comparing all test samples. Total, all 5 sounds in 12 pair comparisons (3 groups times 4 signals) are joined in the experiment yielding 1.200 pair comparisons.

	WN	PS	PN	B	E
Mean	-0.8883	-0.3608	-0.2117	0.4525	1.0083
Standard deviation	0.79598	0.66772	0.70536	0.71561	0.67404
Standard error of the mean	0.07960	0.06677	0.07054	0.07156	0.06740
Minimum	-3.67	-2.33	-2.33	-1.25	-0.33
Maximum	0.75	1.50	1.42	3.00	3.00
Median	-0.8333	-0.3333	-0.1667	0.3333	1.0000
N	100	100	100	100	100

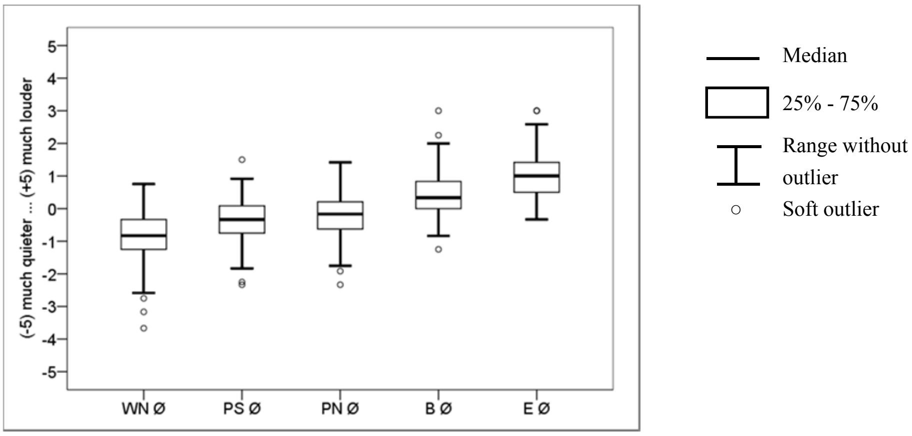

Figure 6 – Box plots of data comparing all results.

The interpretation of the results in Figure 6 is that the lower the value decreases the lower the particular sound will be perceived of all test persons about perceived attempts.

White noise is overall judged to be quietest. Eminem is the loudest. It is interesting to mention that overall statistically the evaluation result of “party-sound” and “pink noise” is equal.

6. Calculated Parameters

The concept for the evaluation of airborne sound insulation as defined in ISO 717-1, which is the single-number rating method, uses a standard reference curve to determine the weighted value of airborne sound insulation and introduces the spectrum adaptation terms C and C_{tr}.

The spectrum adaptation terms C and C_{tr} are evaluated in order to take into account different source spectra.

The spectrum adaptation term C corresponds to an A-weighted pink noise spectrum, while C_{tr} corresponds to an A-weighted urban traffic noise spectrum.

A method to obtain a calculated airborne sound insulation value is presented in the Standard EN12354-1 (18).

The calculation results of the airborne sound insulation for the investigated partitions are compared with the measured values, as presented in Table 2.

Table 2 – Calculated and measured airborne sound insulation.

Measured (ISO 16283-1)	Calculated (EN 12354-1)	Construction
R'_w = 36 (-1; -5) dB	R'_w = 36 (-1; -5) dB	Wooden beam ceiling
R'_w = 51 (-2; -5) dB	R'_w = 55 (-3; -10) dB	Gypsum fibre board wall
R'_w = 54 (-1; -4) dB	R'_w = 54 (-2; -6) dB	Masonry wall plastered

Figure 7 shows the computed normalized loudness level difference (L_{nor}) for the three investigated constructions having different airborne sound insulations. Applying the weighting (w) according to Eq. (8) yields the weighted normalized loudness level difference ($L_{nor,w}$).

The computed weighting coefficients as a function of frequency are shown in Figure 8.

The weighted normalized loudness level difference is shown in Figure 9.

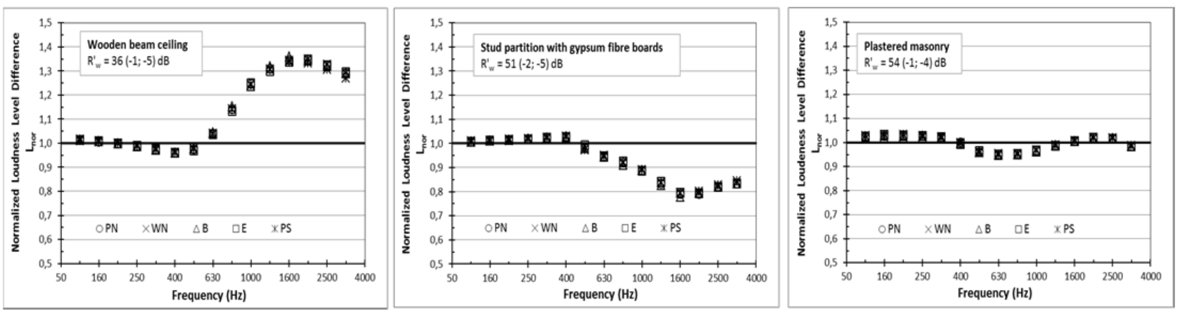

Figure 7 – Calculated normalized loudness level difference over frequency according to Eq. (6).

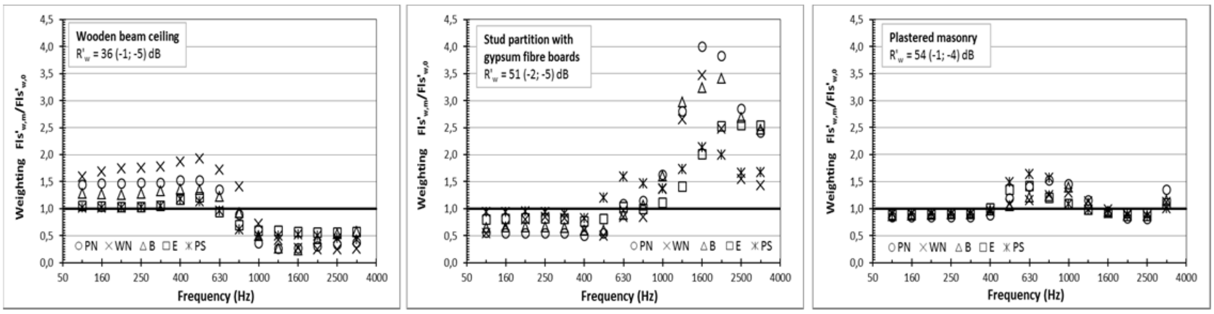

Figure 8 – Calculated weighting over frequency according to Eq. (8).

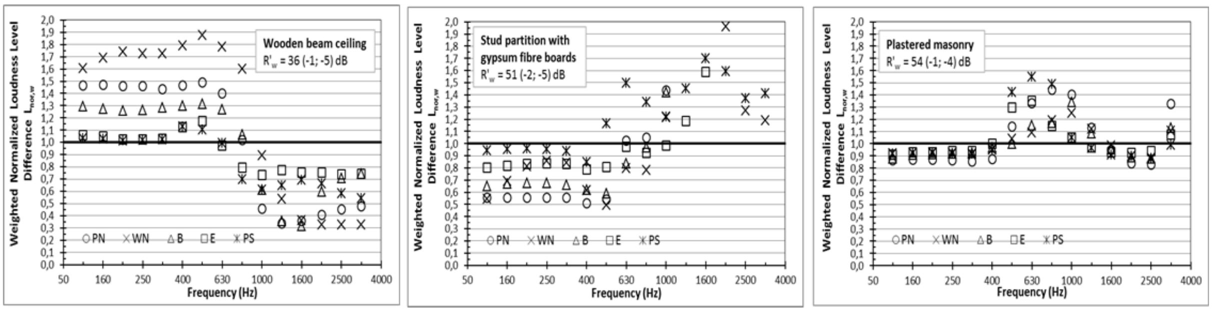

Figure 9 – Calculated weighted normalized loudness level difference over frequency according to Eq. (7).

Calculating the single number quantity of the normalized loudness level difference (L_{nor}) using Eq. (10) and the single number quantity for the weighting (w) using Eq. (9), yield the single number quantity of the weighted normalized loudness level difference ($L_{nor,w}$) according to Eq. (11). Results are depicted in Table 3.

Table 3 – Single number values for the investigated sound insulations and sound samples

Sound	R'$_w$ = 36 (-1; -5) dB			R'$_w$ = 51 (-2; -5) dB			R'$_w$ = 54 (-1; -4) dB		
Sample	L_{nor}	w	**$L_{nor,w}$**	L_{nor}	w	**$L_{nor,w}$**	L_{nor}	w	**$L_{nor,w}$**
PN	1.13	1.11	**1.25**	1.03	0.83	**0.85**	0.99	0.99	**0.98**
WN	1.18	1.21	**1.43**	1.07	1.06	**1.13**	0.98	1.01	**0.99**
B	1.11	0.92	**1.02**	1.03	1.13	**1.16**	0.99	1.01	**1.00**
E	1.09	0.96	**1.05**	0.99	1.06	**1.05**	1.01	0.99	**1.00**
PS	1.07	0.97	**1.04**	1.00	1.00	**1.00**	1.00	0.95	**0.95**

The single number values, i.e. the normalized loudness level differences, the weighting and the weighted normalized loudness level differences, respectively, as reported in Table 2 are shown in Figure 10.

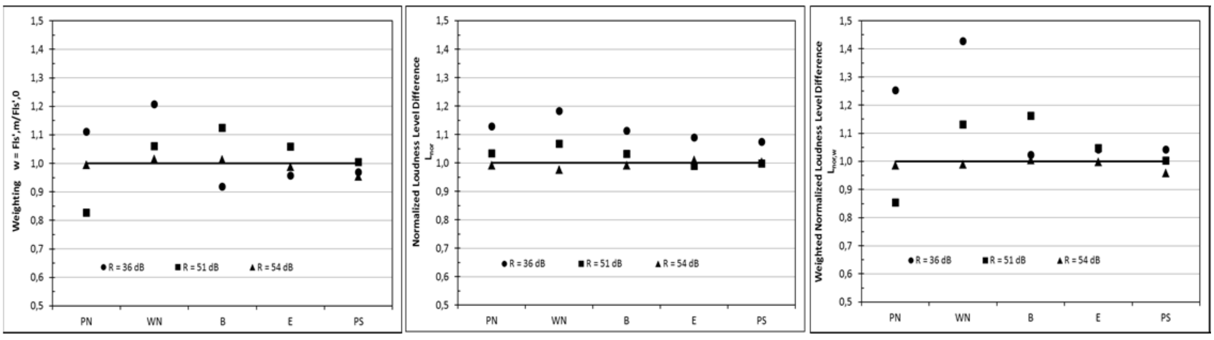

Figure 10 – Calculated single values according to Eq. (9), (10), and (11), respectively.

7. Discussions

The measured airborne sound insulation of three partitions is depicted in Figure 3 which shows that with increasing frequency the sound insulation increases.

A comparison of level after transmission for different sound insulation values is shown in Figure 4. There the measured transmitted sound pressure level (L_2) and the calculated loudness level (L_N) is shown. It is seen, as expected, that the sound pressure level after transmission falls off with increasing frequency (see left panel in Figure 4). This is seen independent of the type of signal.

Comparing the loudness level of the same signal, however, the opposite pattern is observed where with increasing frequency, the loudness level tends to rise. It is interesting to note that although the sound pressure level falls off with increasing frequency, the loudness level rises, which was not expected. This is in agreement with results published in (8).

Comparing the specific fluctuation strength *Fls'* for different sound samples over frequency as shown in Figure 2 reveal, that the transient signal lead to higher fluctuation strength than the steady-state signal. This result was expected.

The study evaluating the sound signals with regard to the perceived loudness led to results which are summarized in Figure 6. There it is seen the response distribution for the different requests presenting the median and standard deviations. The statistical analysis of the data revealed that white noise was highly significant ($p < 0.001$) perceived quieter as all compared sound samples. From comparison it is seen in Figure 6 that Eminem was judged "louder" than Beethoven.

In general the results show that the noise samples (i.e. white and pink noise) are judged not as loud as music sound samples. This is in agreement with results presented in (2).

It is unexpected that the response for "party-sound" is statistically equivalent to pink noise. The reason for this would need further investigation. One explanation could be that the type of music that was used in the sound sample of "party-sound" lastingly influenced the results. It is therefore concluded, that the judgment is depending on the characteristic of the test sound.

Comparing results of Figure 2 were the specific fluctuation strength for the different sound signals are shown and the results outlined in Figure 6 were the listening test results are shown reveals that there is a similarity of both results. Figure 2 exposes that Eminem and Beethoven yield higher values than white noise and pink noise. Party-sound yield results between pink noise and Beethoven. Figure 6 illustrates in a similar way that Eminem is perceived louder than all the other compared sound samples, followed by Beethoven. The results for white noise state that it is judged as the quietest noise, followed by pink noise, and party-sound, respectively.

Thus, it can be summarized, that the steady-state signals yield lowest *Fls'*-values and were judged to be quietest. The non-steady-state signals on the other hand contrasting results showed, i.e. the *Fls'*-values were highest and were judged as the loudest.

The computed normalized loudness level difference over frequency, as shown in Figure 7, suggests that there is no significant difference for the normalized loudness level difference for different signal types. It is concluded that the normalized loudness level difference is independent of the type of signal used. Introducing, however, the weighting according to Eq. (8) a significant change is observed.

The weighted normalized loudness level difference as shown in Figure 9 reveal a completely different picture comparing results as shown in Figure 8, where it is seen that the normalized loudness level difference yields close results. Obviously the weighting has a dominant influence on the result in calculating the weighted normalized loudness level difference. This is in line with theory to describe an auditory judgment using a psycho-acoustic measure like the specific fluctuation strength.

In the left panel of Figure 10 the single number of the weighting is shown for different sound signals and different R'_w-values. The smallest deviation of the weighting coefficient is seen for party-sound followed by Eminem and Beethoven.

In general it is seen that for the weighting coefficient the music type signals have smallest deviations for different R'_w-values. White noise and pink noise on the other hand showed maximum deviation.

It is noted that by comparing results shown in Figure 3 and Figure 6 and remembering that statistically the test result of "party-sound" and "pink noise" was equal, the results correlate well. That means the result of the listening test is well represented using the specific fluctuation strength in connection with the normalized loudness level difference.

In the mid panel of Figure 10 it is seen that the music type signals revealed again smallest deviation for the different sound signals. In the right panel of Figure 10 it can be seen that the weighted normalized loudness level difference is most influenced by the weighting coefficient. It is also noted that the deviation of the respective measure is depending on the airborne sound insulation.

8. Conclusions

This study shows that level differences cannot reveal the influence of the type of signal on the airborne sound insulation. It has been demonstrated that using the loudness level instead of the sound pressure level in combination with the weighting by introducing the specific fluctuation strength leads to a detailed measure of an airborne sound insulation in the frequency domain. The results obtained indicate that the calculation scheme of describing the airborne sound insulation in terms of a weighted normalized loudness level difference better relates to the hearing sensation of a transmitted sound signal. Moreover, it is concluded that even if the sound pressure level lowers with frequency, the loudness level increases. The use of specific fluctuation strength as a measure to describe an auditory judgment has been demonstrated comparing subjective test results.

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