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Airborne sound insulation in terms of a loudness model

Reinhard O. Neubauer*, Jian Kang

School of Architecture, University of Sheffield, Western Bank, Sheffield S10 2TN, United Kingdom

A B S T R A C T

One of the main goals of building acoustics is the prediction of airborne sound insulation between rooms to determine the quality of sound protection. 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, therefore, after reviewing the conventional model to calculate airborne sound insulation, introduces a calculation scheme based on loudness level linked with specific fluctuation strength, yielding a weighted normalised loudness level difference, $L_{nor,w}$. By analysing the difference between standard airborne sound insulation values and the introduced weighted normalised loudness level difference, it is revealed that the sound pressure level that is transmitted through a partition decreases with increasing frequency, and this is independent of the type of signal and of the airborne sound insulation values (R'_w-values), whereas if the transmitted signal is converted into a loudness level, it tends to rise with increasing frequency. Moreover, it is found that, whereas a simple level difference does not exhibit the effect of a given signal to the frequency-dependent airborne sound insulation curve, using $L_{nor,w}$, a significant change can be observed, in terms of both computed and measured results. Furthermore, the frequency-dependent results allow more details to be investigated for a certain sound insulation. A comparison between the measured and predicted airborne sound insulation with no obvious malfunction suggests that at some frequency ranges, a hypothetical subjective related failure might occur. Overall, the proposed $L_{nor,w}$ could reveal detailed insights into the in situ measured airborne sound insulation compared with standard airborne sound insulation values. The frequency-dependent values discussed in this paper form a basis for developing a single-number index.

1. Introduction

Airborne sound insulation is mandatory to ensure a healthy living environment in buildings. The measurement of airborne sound insulation is usually specified in terms of single numbers by means of the standard ISO 717 [1]. The quality of airborne sound insulation in buildings described as a single number rating of sound insulation in terms of a weighted apparent sound reduction index R'_w is, however, inadequate and requires improvement because of the significant difference between the standard rating of sound insulation and its subjective assessment [2, 3]. Various investigations have been published that rate airborne sound insulation with respect to their correlation with subjective ratings of sound insulation. Vian et al., for example, related subjective ratings of sound insulation to an A-weighted level difference [4], whereas Tachibana et al. investigated the loudness of sounds transmitted through walls with various sound insulation characteristics [5], and Park et al. published results concerning sound insulation ratings of the intelligibility of transmitted speech [6].

Recently, a replacement for ISO 717-1, designated as ISO 16717-1 [7], has been proposed [8], which includes changes to the frequency range included in the single number ratings [9, 10]. However, no evaluation has been introduced into the proposed new standard that classifies hearing sensation.

As a subjective experience of noise stress can lead to regulation health problems, as reported, for example, in [11, 12, 13, 14], it is important that a more specific requirement be established to quantify sound insulation to safeguard occupants from possible health effects.

To determine airborne sound insulation, a standard test with broadband noise signals as a source signal is used. In reality, music sounds from neighbours are, however, often said to be a prime cause of annoyance and complaints [15]. Currently, according to present standards, the influence of noise is mainly described by the A-weighted equivalent continuous sound pressure level ($L_{A,eq}$). This measure, however, takes into account too little the subjective perception and evaluation of sound [16, 17, 18] and is not a satisfactory descriptor of a sound event because it cannot describe many signal characteristics, such as time fluctuations [19], and furthermore, as shown in [20], an A-weighted level is not suitable to assess low-frequency noise events. The time fluctuations of a signal can be captured, for example, by psychoacoustic parameters, including roughness and fluctuation strength.

The investigations thus far indicate that the airborne sound insulation measured in accordance with present standards [21] does not correlate well with subjective impression [22, 23, 24, 25, 26, 27]. These results reveal that, in line with previous reports, the level difference measured tends to produce lower correlations than the corresponding transmission loss measures, and this contradicts suggestions that differences in sound level would correlate best with subjective responses [28]. In the meantime, it has been reported that loudness combined with roughness describes the correlation with subjective estimation of noise-induced discomfort better than the A-weighted sound level [29]. Moreover, as Jeon et al. [30, 31] noted, subjective response to noises, such as annoyance, depend upon the type of noise.

Therefore, the purpose of this study is to investigate the differences between the airborne sound insulation expressed as a sound pressure level difference (ΔL) and a loudness level difference (ΔL_N), effects of a frequency depending dip in the airborne sound insulation curve, which is realised as a drop of 6 dB in a certain frequency range, and the influence of a psychoacoustic measure based on the specific fluctuation strength of the normalised loudness level difference. This paper starts with a description of the calculation scheme used to derive the presented new term of a weighted normalised loudness level difference. It then presents measured and calculated results comparing airborne sound insulation and weighted normalised loudness level differences. The results of this paper are then summarised with a short discussion on measured and calculated level differences, which is followed by a conclusion concerning the need for consideration of psychoacoustic measures in the assessment of airborne sound insulation.

* Corresponding author. Tel.: +49 (0)84134173; fax: +49 (0)84135238.
  E-mail address: dr.neubauer@ibn.de (R.O. Neubauer).

2. Method

The drawback of a dB(A) assessment is illustrated in Fig. 1 and in Fig. 2, where the sound pressure level with an A-weighting is shown and compared to specific loudness and loudness levels, respectively. It can be seen that a broadband noise signal (pink noise), music type signal (rap music: Eminem), and a single ton (sinus) at 1 kHz, despite equal value in the dB(A) rating, loudness (sone) and loudness level (phon) are quite different. The *A*-weighted level and the loudness are therefore not sufficient to describe sounds. This is in agreement with the results presented in [32]. A measure that is more closely related to direct human perception of noise is the loudness level [33]. Therefore, the method of this study is to describe airborne sound insulation in terms of a sensation level related to a psychoacoustic measure, which means that in an imaginary manner of subjective regards the intrusive sound pressure level, which is an objective measure, will be linked with a psychoacoustic measure to describe the sensation of a perceived sound pressure level. This will be carried out using the transmitted or filtered sound signal. To distinguish results related to the type of signal, a steady-state signal and a non-steady-state signal are investigated. The intended perceived sound pressure level is calculated using a transfer function filtering the signal for the airborne sound insulation. The calculated psychoacoustic measure is intended to be a measure of a subjective related estimation of the hearing sensation.

2.1 Signal description

The steady-state signal used in this research was a broadband noise signal, so-called "pink noise". According to investigations published in [34], pink noise appears to most preferable as a substitute for music-type signals if a test signal has to be judged.

As indoor residential noise is judged differently with different noise types, as indicated for example in [31], in this study, in addition to the steady-state signal, we also investigated a non-steady-state signal as well for comparison purposes. The non-steady-state signal, i.e., the transient signal was a music sample, namely rap (Eminem, "Loose Yourself"). This music type was chosen because prior investigations have reported, e.g., in [25, 27], that this piece of music was judged in a preliminary study subjectively louder than other music samples compared, such as classic music (Beethoven), otherwise having the same sound pressure level. The preliminary study, although having a relatively small number of participants (i.e., nine subjects), demonstrated that when using a broadband noise type signal such as pink, white, or grey noise as a test signal compared to a music sound source, the subjectively estimated sound insulation was judged differently. This result confirms previous findings [10, 35].

In Fig. 3, the power spectral density of the used two signals is shown. Pink noise has equal strength over a logarithmic scale of frequencies. Pink noise displays a decreasing straight line over the frequency bandwidth, whereas the music type signal "Eminem" decreases with a certain fluctuation toward higher frequencies.

In this study, the used sound signals have a SPL of 85 dB and duration of 90 seconds. In Fig. 4, the sound pressure level of the test signals are shown at one-third octave-band centre frequencies.

2.2 Airborne Sound Insulation

2.2.1 Computed R-values

The airborne sound insulation is essentially the level difference of a signal after being transmitted through a partition. According to ISO 140-4, the sound reduction index *R'* is described as follows:

$$R' = L_1 - L_2 + 10\log\frac{S}{A} \text{ dB} \tag{1}$$

with L_1 and L_2 denoting the sound pressure levels measured in a testing facility in the source and receiving room, S denoting the area of the partition, and A the equivalent sound absorption area of the receiving room.

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

$$R' \equiv D = L_1 - L_2 \text{ dB} \tag{2}$$

The level of interest is then, 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. Previous studies [32, 36, 37] have demonstrated that the sound pressure level cannot be judged as an *A*-weighted sound level to represent a proper hearing sensation. Therefore, an *A*-weighted sound level is misleading when used as an indication of subjectively perceived loudness [38, 39].

First of all, airborne sound insulation has to be defined to investigate the sound pressure level of interest. In an idealised way, the frequency-dependent airborne sound insulation was chosen in accordance with the standard ISO 717-1. In the left panel of Fig. 5, the investigated idealised airborne sound insulation is shown exemplarily for the case of an *R*-value of 40 dB. Introducing a dip into the frequency depending airborne sound insulation, however, and letting the single number value (*R'*_w) remain constant is depicted in the middle and right panel, respectively. The frequency dip throughout this study was 6 dB, i.e., at a certain frequency the airborne sound insulation decreased by -6 dB.

2.2.2 Measured R-values

A field measurement of sound insulation was performed. The partition investigated in-situ was a concrete wall of thickness $d = 220$ mm in a massive construction building. The measured procedure applied was according to ISO 140-4 using pink noise as the source signal. A second measurement was conducted to obtain records of signals. The used sound signals were pink noise and rap music. The measured procedure to obtain the records in a wav format was according to EN ISO 10052 [40]. The results are shown in Fig. 6.
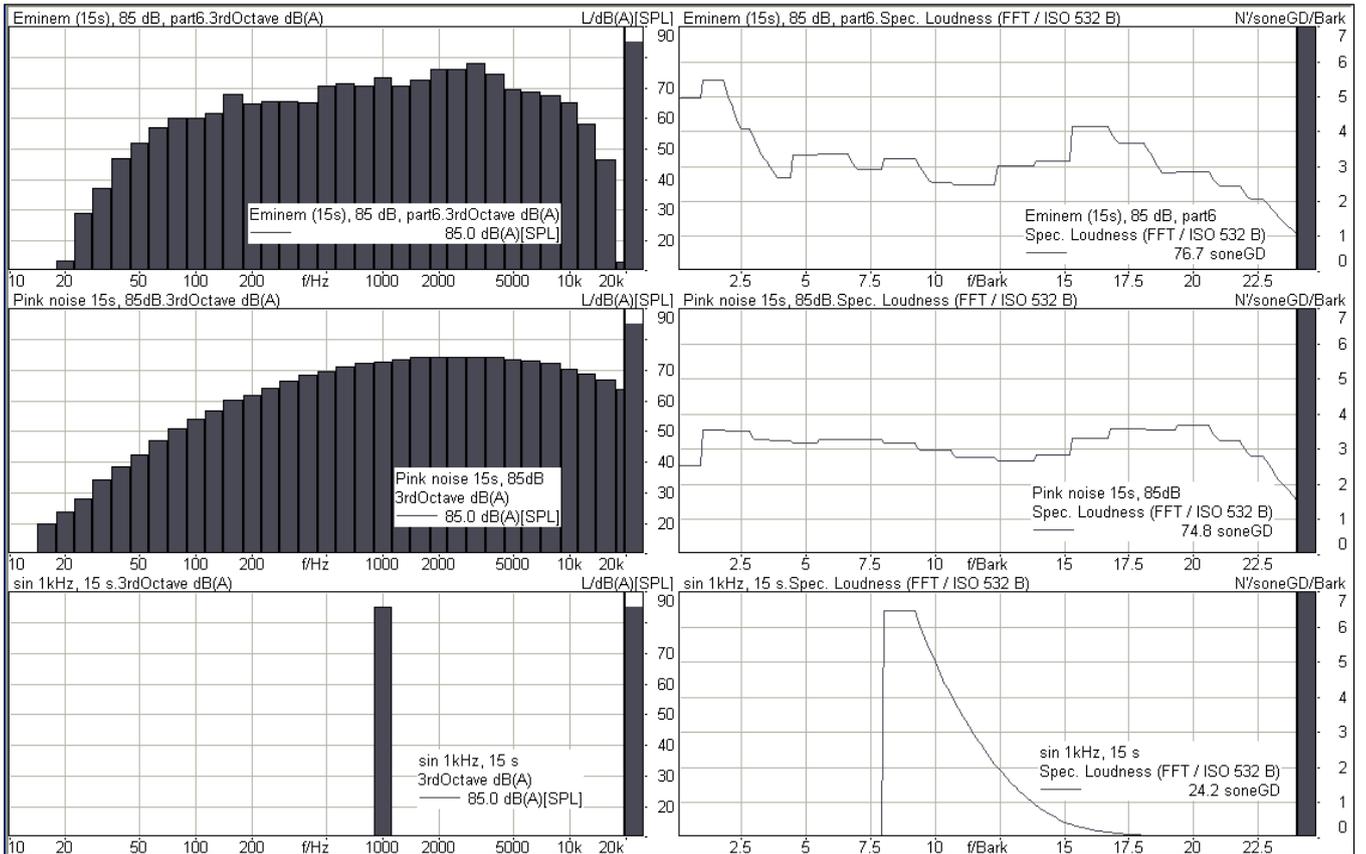
Fig. 1. Three different sound signals (music type signal, broadband noise, tone) with equally weighted sound pressure level of 85 dB(A) but different loudness (sone).
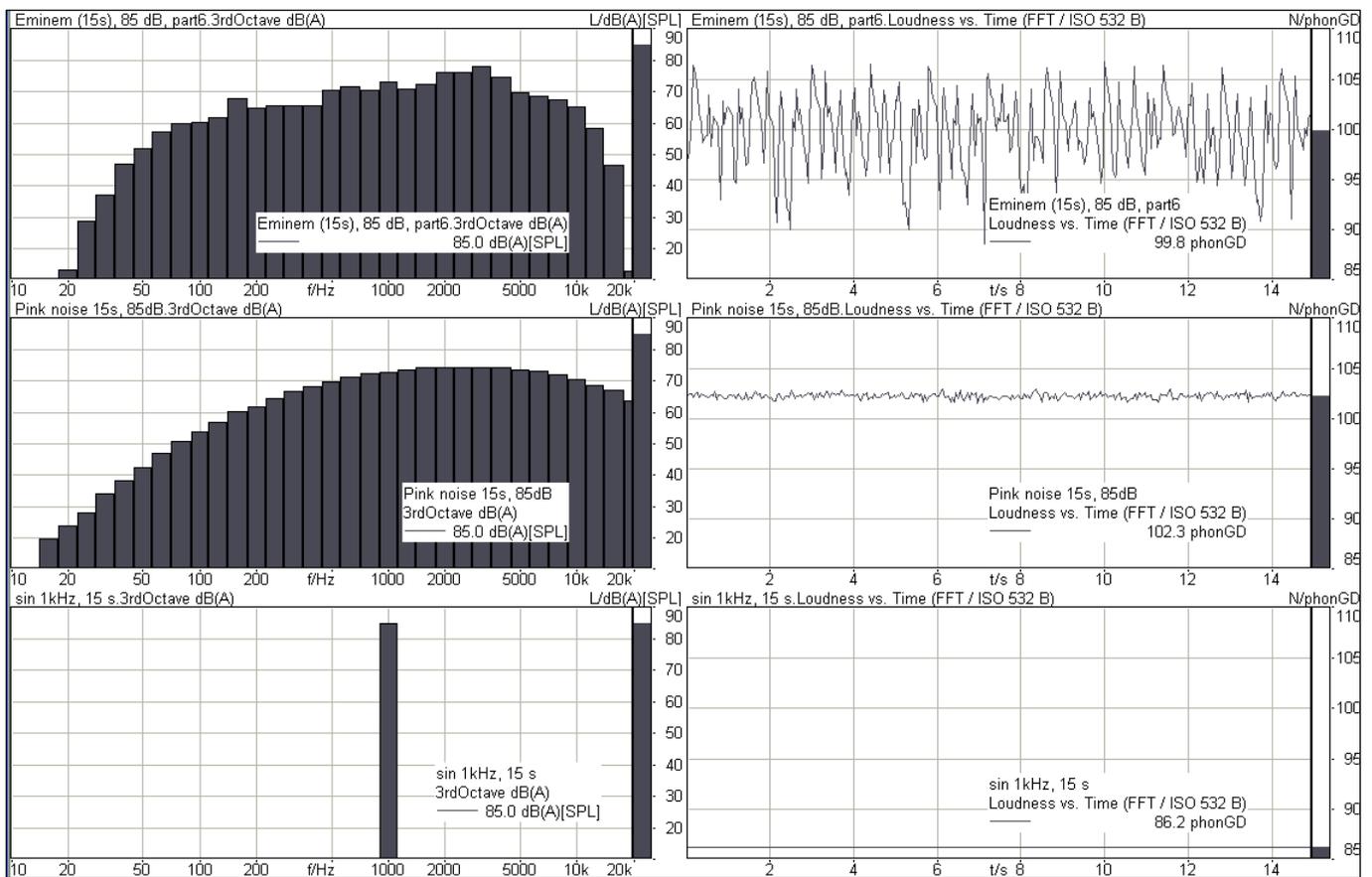
Fig. 2. Three different sound signals with SPL of 85 dB(A) but different loudness level (phon).
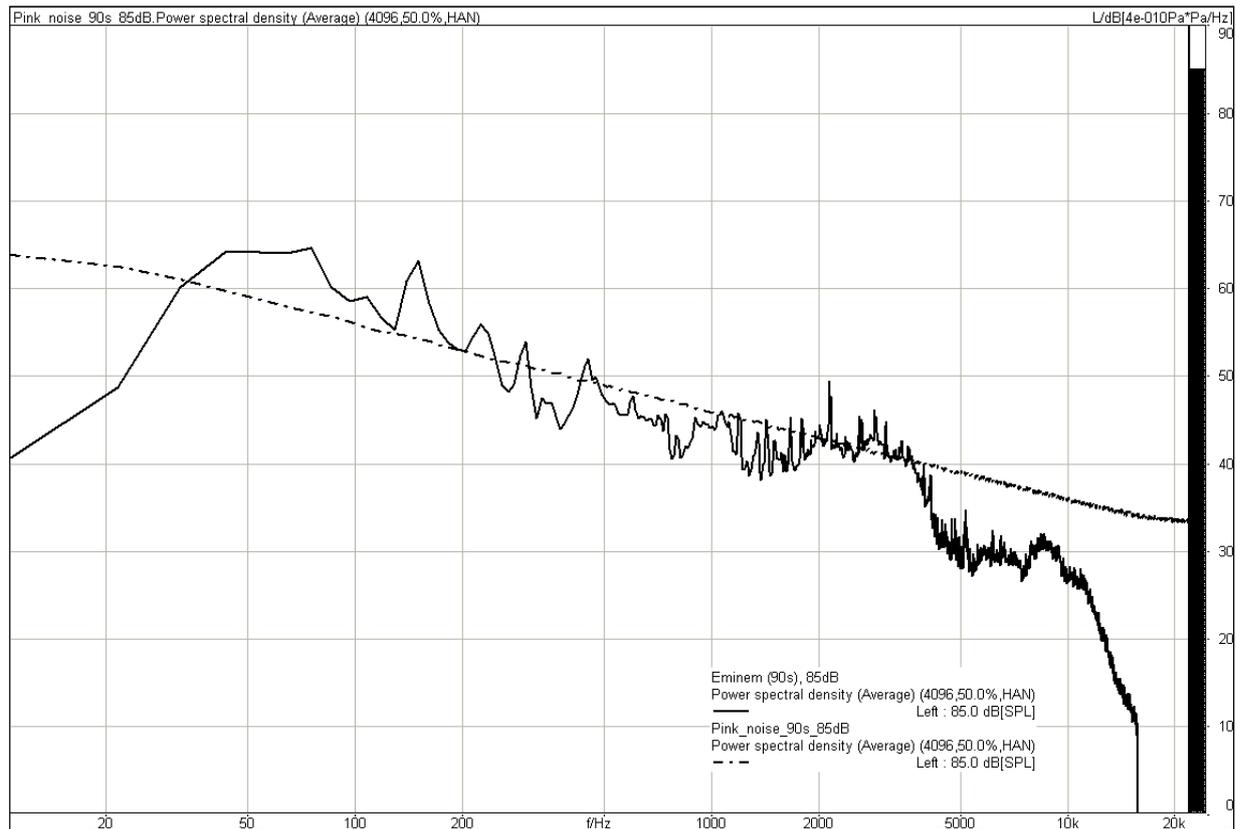
Fig. 3. Power spectral density (PSD) of the used sound signals pink noise and rap music "Eminem" as a function of frequency having sound pressure level of 85 dB and duration of 90 s.

2.2.3 Predicted R-values

An estimation of the airborne sound insulation was performed for the partition investigated. The prediction procedure applied was according to EN12354-1 [41]. The result of the frequency-dependent airborne sound insulation is shown in Fig. 6, together with the results of the measurement to obtain a direct comparison. There, the calculated airborne sound insulation is depicted as a solid line.

2.3 Transformation of sound pressure level into loudness level

To compute the loudness level difference, the sound pressure level has to be transformed into a loudness level. This transformation is accomplished using the standard procedure of ISO 226 [42]. In Fig. 7, the computed sound pressure level and the corresponding loudness level for different R'_w-values are depicted. Computing the level difference of both measures, i.e., the difference of the sound pressure level ($L_1 - L_2$) and the difference of the loudness level ($L_{N1} - L_{N2}$), yield results that are depicted in Fig. 8. The level differences are shown for the pink noise and Eminem sound signals. In the filter function for simulating the airborne sound insulation, no dip was introduced.

2.4 Loudness concept

After transmission of L_1 through a structure or partition, the sound heard by a listener is L_2. Thus, it is assumed that the heard sound can be judged in terms of a loudness level L_N.

The loudness is determined by means of a hearing-related measurement procedure focused on the functioning of the human hearing. Here, the signal processing units of the human hearing (critical bands) as well as the temporal and spectral mask effect is taken into account [38]. 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.

2.4.1 Loudness level

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 characterised 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.
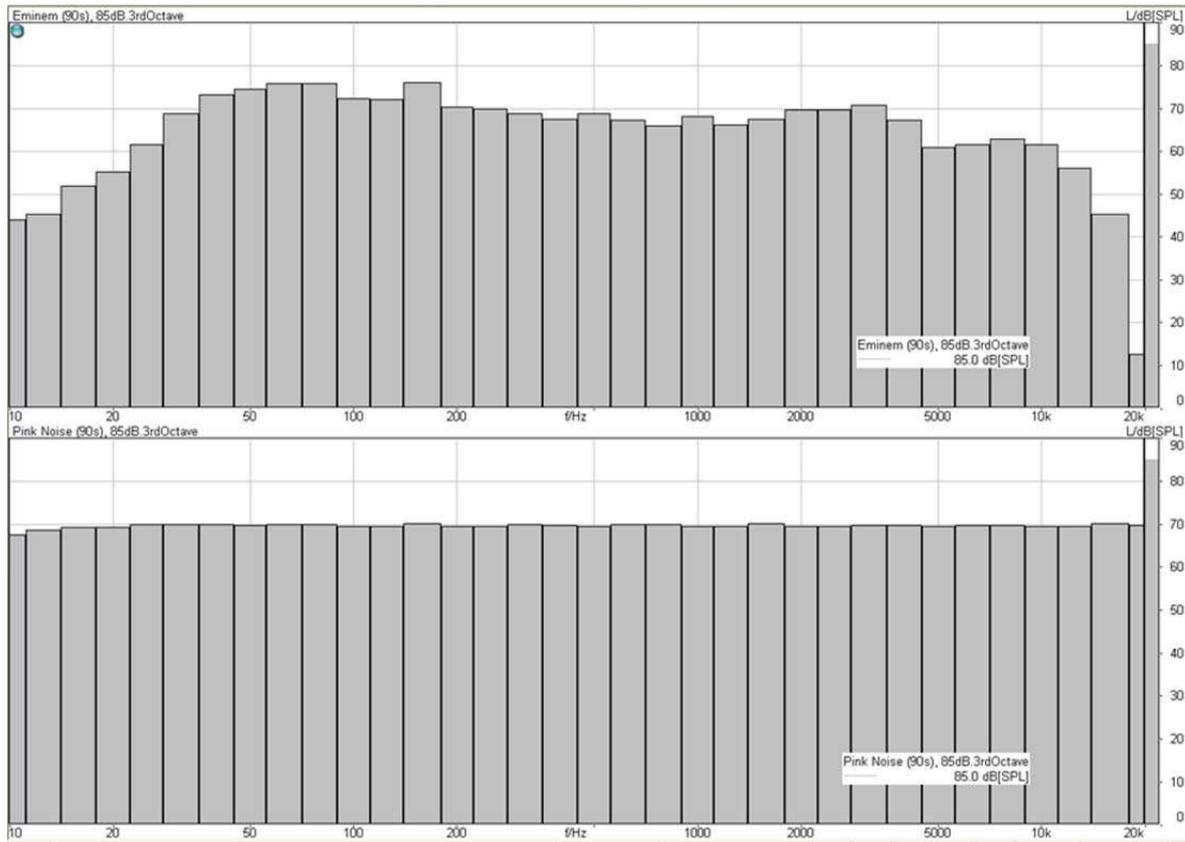
Fig. 4. Sound pressure level of the used sound signals as a function of frequency in a one third octave band spectrum. All signals have a sound pressure level of 85 dB SPL and duration of 90 s.
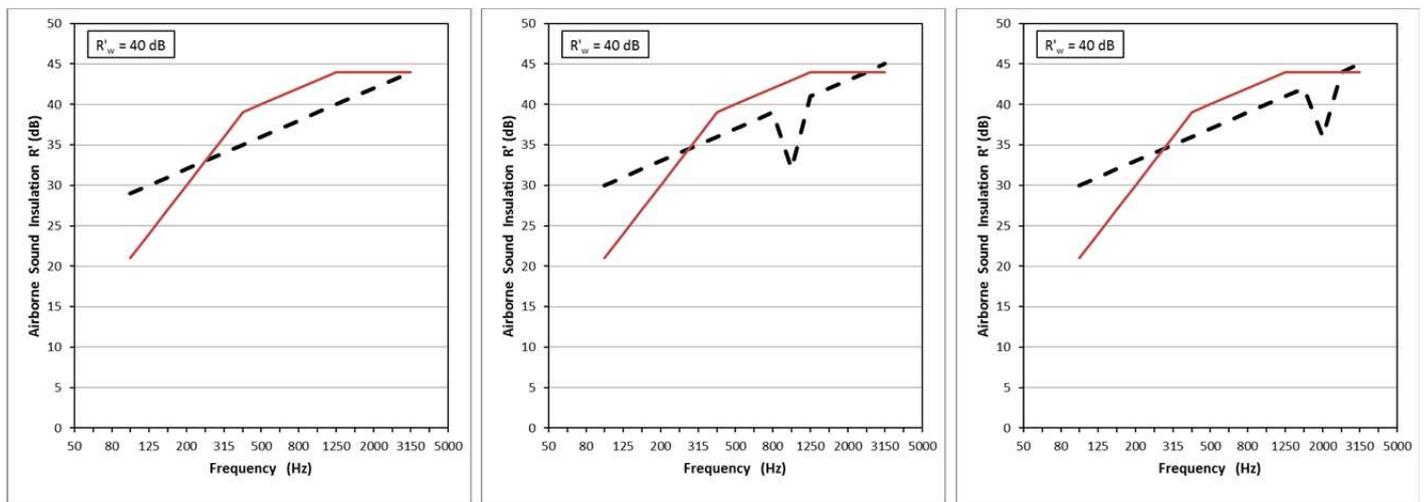
Fig. 5. Idealized airborne sound insulation of $R'_w = 40$ dB without (left panel) and with a dip of 6 dB at frequency of 1 kHz (middle panel) and 2 kHz (right panel). The solid line is the reference curve given in ISO 717-1.

2.4.2 Loudness level difference

The level difference characterised by the weighted apparent sound reduction index (R'_w) without a dip (L_0) and with a dip (L_m) provides a set of loudness level differences. The level difference of the idealised (i.e., hypothetical) 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).

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

In evaluating a sound event, the rule of absolute level or loudness is often insignificant [42]. Temporal structures and spectral patterns are more important factors in determining whether a sound makes an annoying or disturbing impression [43]. Therefore, it

is suggested to normalise the level difference with respect to the idealised level difference. The normalised loudness level difference for third-octave band values is then written as follows:

$$L_{nor}(f) = \frac{\Delta L_{m(f)}}{\Delta L_{0}(f)} \qquad (6)$$
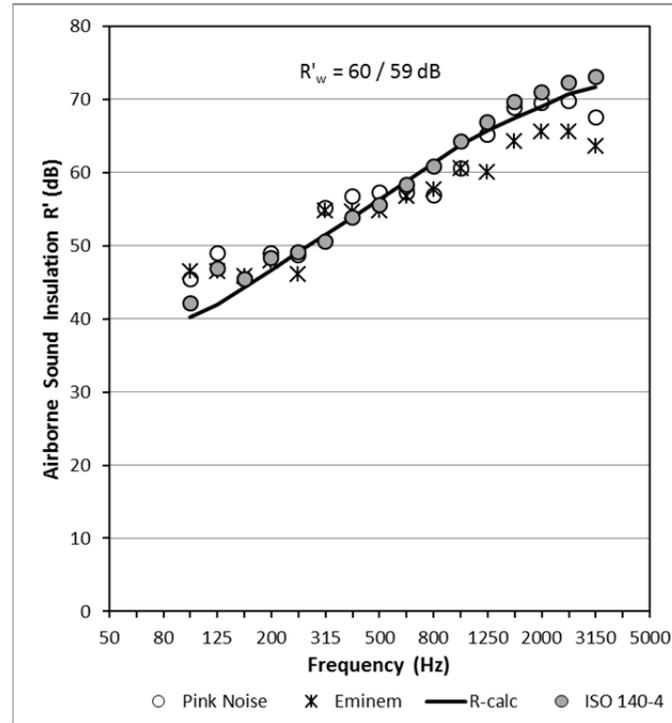
Fig. 6. Results of field measurements using standard procedure of EN ISO 10052 and ISO 140-4. Airborne sound insulation measured according to ISO 140-4, $R'_w(C; C_{tr}) = 60$ (-1; -5) dB and predicted according to EN 12354-1, $R'_w(C; C_{tr}) = 60$ (-1; -6) dB. Airborne sound insulation measured according to EN ISO 10052 using pink noise yield $R'_w = 60$ dB and using rap music yield $R'_w = 59$ dB.

The calculated normalised loudness level difference as a function of frequency is shown in Fig. 9. For comparison, the sound pressure level difference ($L_1 - L_2$) over frequency is depicted in Fig. 10.

2.4.3 The normalised specific fluctuation strength as a weighting function

It is assumed that an appropriate weighting that reflects the event of a frequency-dependent dip has to be applied. The weighting will be judged as an awareness of noise, i.e., annoyance. Therefore, the value is highlighted according to its importance for the comparator or weakened. The weighted normalised loudness level difference, or airborne sound insulation strength, for third-octave band values is then written as follows:

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

where w is a weighting factor.

To differentiate the signal in terms of psychoacoustic measures, investigations of music type signals were focused on specific fluctuation strength as was suggested, e.g., in [25, 44]. This is in accordance with investigations concerning indoor acoustic comfort by Jeon et al. [45].

As a distinction criterion, the envelope of the specific fluctuation strength was chosen. In Fig. 11, the chosen music-type signal and the broadband noise signal are shown, where the specific fluctuation strength of the respective signal is shown before filtering. The unprocessed Eminem signal has a specific fluctuation strength of 0.36 vacil, and pink noise has a value of approximately 0.011 vacil. From the comparison, it can be seen that the envelope of the specific fluctuation strength of pink noise falls off with increasing frequency, and for the signal "Eminem", the envelope first falls off and rises again with increasing frequency. The calculated values of the investigated unprocessed signals are listed in Table 1.

For the weighting, it is assumed that two psychoacoustic parameters can be applied, namely, the specific fluctuation strength, *Fls'* (vacil), and the specific roughness, *R'* (asper), because they are related to the temporal structure of the sounds. The calculation was performed using software ArtemiS V11. For roughness, ArtemiS calculates the partial roughness from the modulation depths of partial signal bands and adds them up to determine the total roughness. The calculation method of the fluctuation strength is, on the other hand, similar to the algorithm for the calculation of the roughness in the way that the maximum of the fluctuation strength is obtained at 4 Hz instead of 70 Hz [46]. In Table 2, the results taken from [25] are shown, where comparisons of calculated results are presented for different damping values, i.e., receiving level (L_2), loudness (N), specific fluctuation strength (*Fls'*), and specific roughness (*R'*). It can be seen that the calculated specific roughness yields zero for damping values of 50 dB and 60 dB. Therefore, roughness is not believed to be an appropriate measure because of the fact it provides a zero value for the high sound insulation

value using white noise. This agrees with findings in [47, 48], which show that the examined unmodulated white noise has no or only negligible roughness. Furthermore, Daniel and Weber demonstrated [47] for small frequency bandwidths, the random envelope fluctuation is approximately 6 Hz, yielding a calculated roughness of approximately 0 asper. For that, Zwicker and Fastl stated [38] that subjects will have difficulties in differentiating between roughness and fluctuation strength. This means that in the overlapping area of smaller modulation depth, fluctuation strength is a prime measure. Therefore, it is assumed that fluctuation strength is an appropriate magnitude to describe the signal in terms of psychoacoustic quantity.
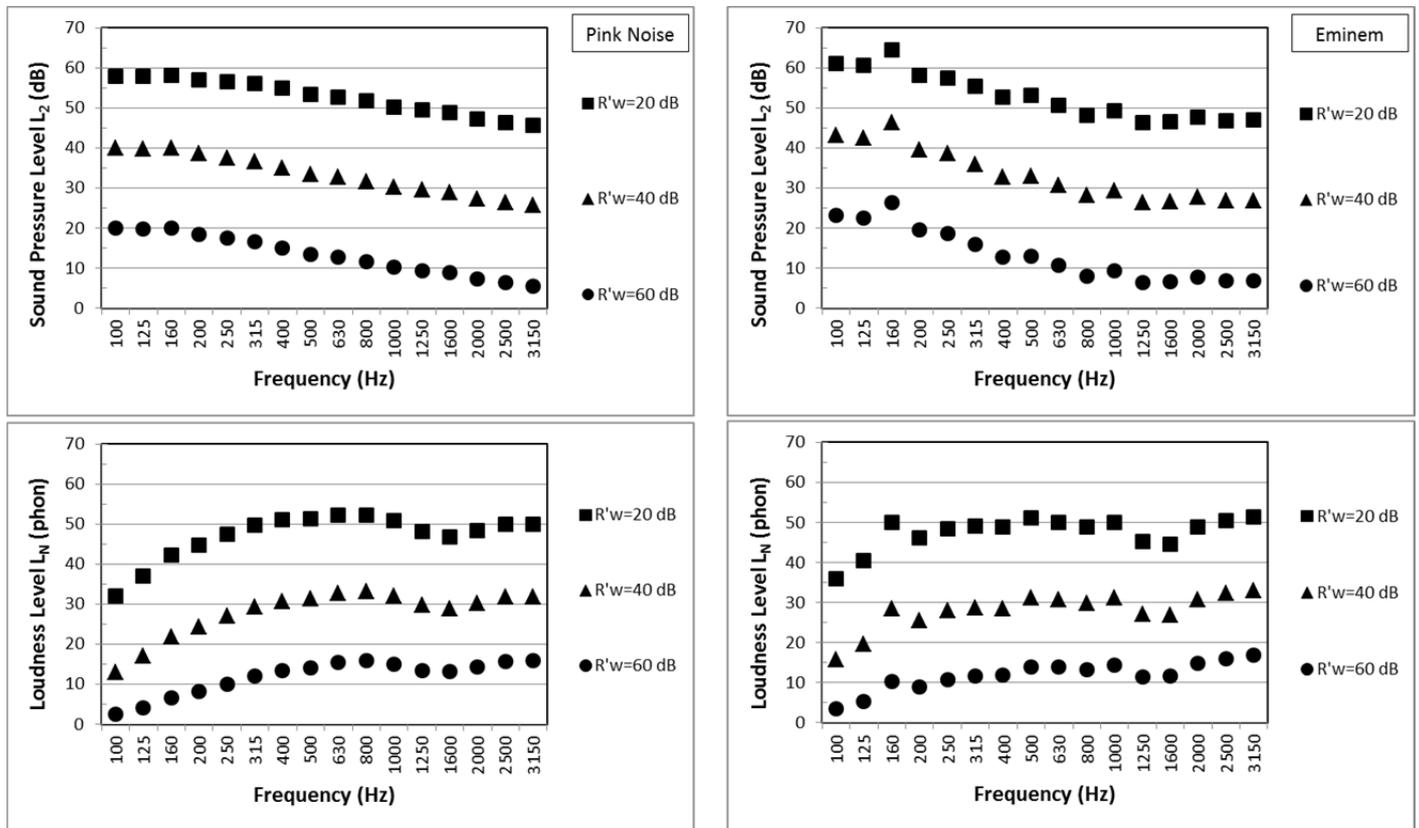
Fig. 7. Comparison of calculated level after transmission for different R'_w-values of 20, 40, and 60 dB using sound pressure level (L_2) and loudness level (L_N). Filter function without a dip.
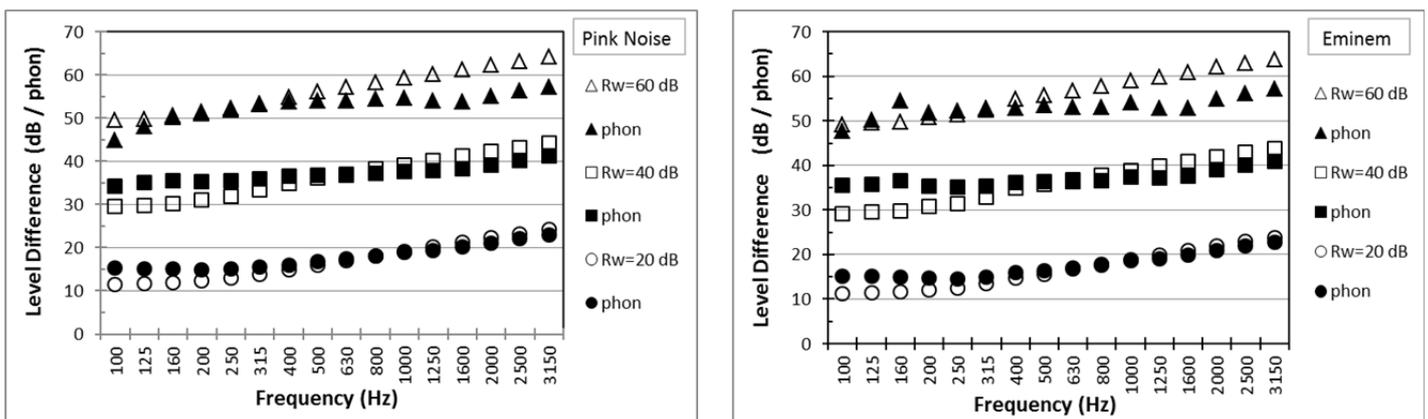
Fig. 8. The calculated sound pressure level difference ($L_1 - L_2$) and loudness level difference ($L_{N1} - L_{N2}$) over frequency for two types of test signals and various R'_w-values without a dip. Shown is the music type signal "Eminem" and the broadband noise type signal "pink noise".

Assume that for the level $L_{N2(f),0}$ specified in Eq. (4), the specific fluctuation strength is $Fls'_{(f),0}$ and for the level $L_{N2(f),m}$ specified in Eq. (5), the specific fluctuation strength is $Fls'_{(f),m}$, and the unknown weighting for third-octave band values may be written as follows:

$$W_{(f)} = \frac{Fls'_{(f),m}}{Fls'_{(f),0}} \tag{8}$$
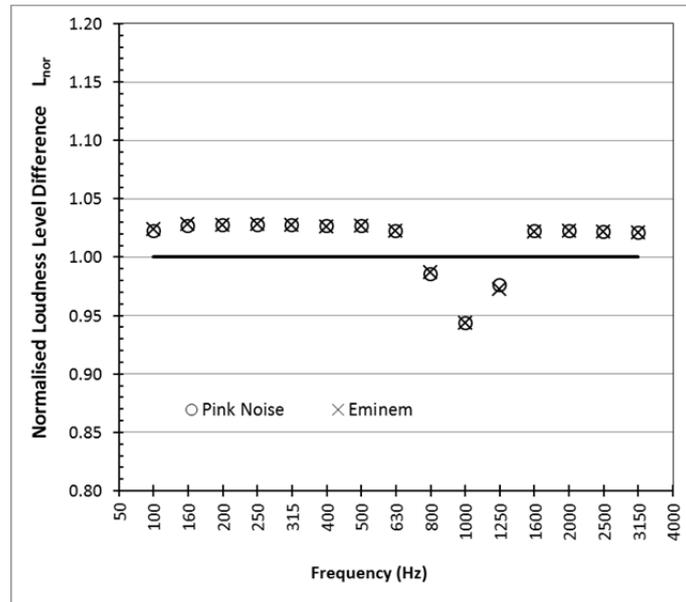
Fig. 9. Normalised loudness level difference over frequency according to Eq. (6) for two types of test signals. Investigated airborne sound insulation with a weighted apparent sound insulation value $R'_w = 40$ dB with a dip of 6 dB at a frequency of 1 kHz.
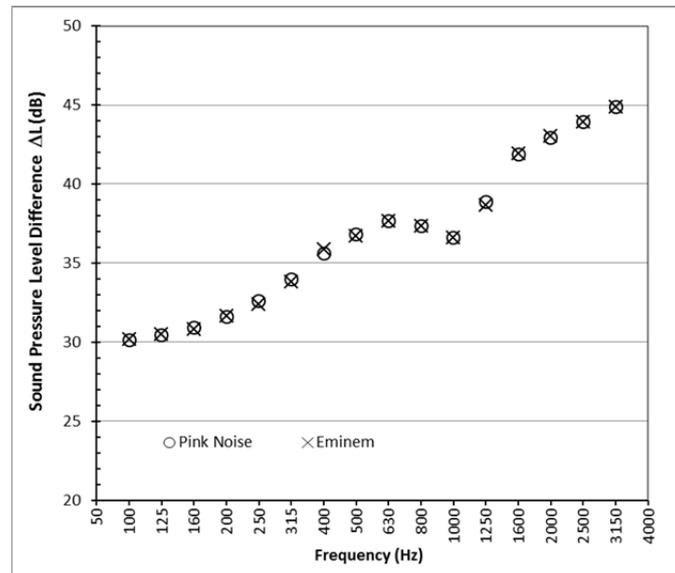
Fig. 10. Sound pressure level difference over frequency for two types of test signals. Investigated airborne sound insulation with a weighted apparent sound insulation value $R'_w = 40$ dB with a dip of 6 dB at a frequency of 1 kHz.

It is noted that Eq. (8), as well as Eq. (6), are normalised using the level difference characterised by the weighted apparent sound reduction index (R'_w) without a dip in the airborne sound insulation curve. The computed weighting coefficients as a function of frequency are shown in Fig. 12. There, two types of test signals are exemplarily investigated with a weighted apparent sound insulation value of $R'_w = 40$ dB having a dip of 6 dB at a frequency of 1 kHz.

3. Results and discussion

In this section, theoretical and experimental results are compared. The differences of sound pressure level and loudness level and the influence of the weighting coefficient are discussed.

3.1 Airborne sound insulation

3.1.1 Measurement
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.
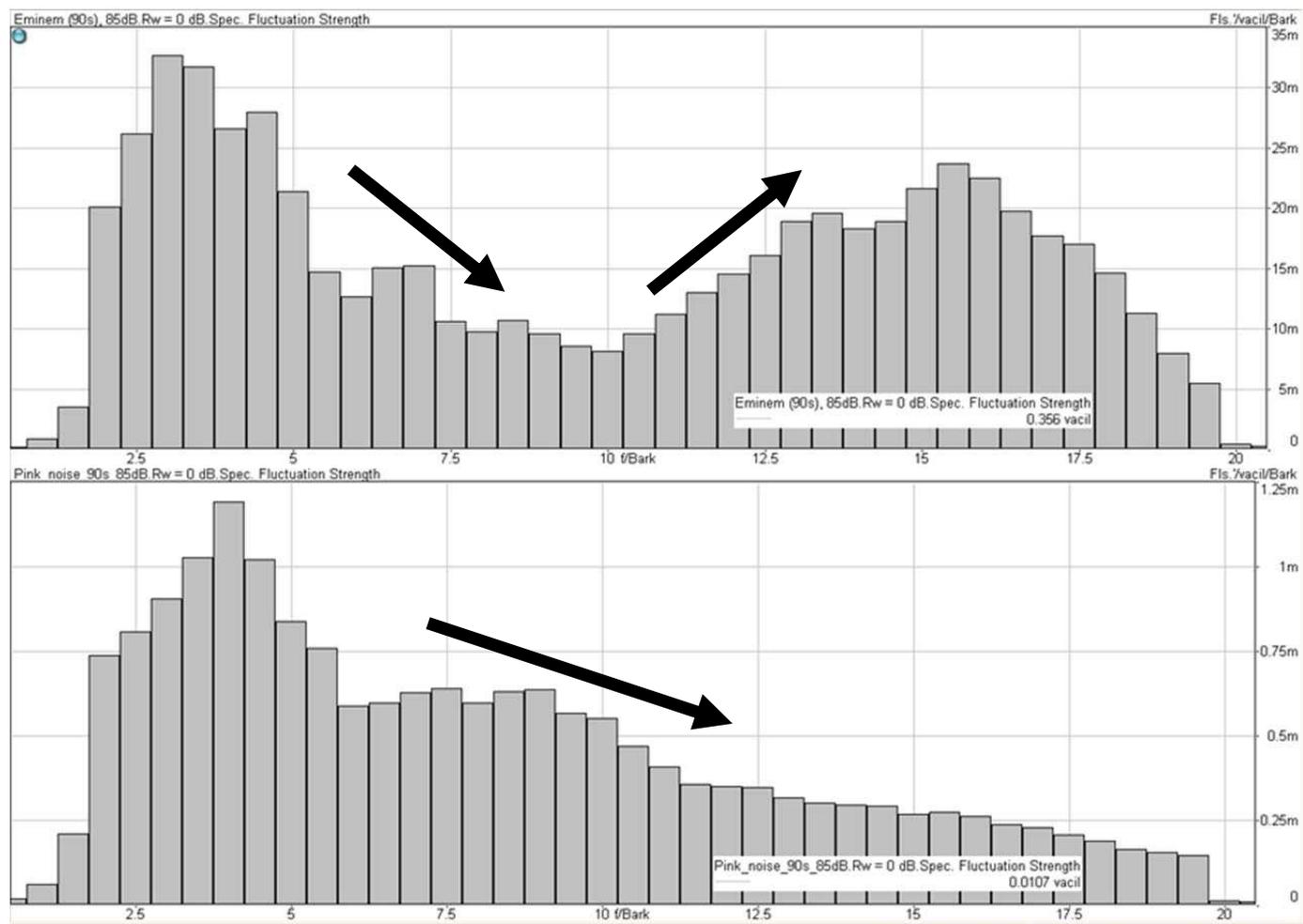
Fig. 11. Specific fluctuation strength of the unprocessed test signal "Eminem" and "pink noise".

Table 1
Acoustic factors of the unprocessed signal ($R'_w = 0$ dB): sound pressure level (*SPL*), loudness level (L_N), sharpness (*S*), specific roughness (*R'*), tonality (*Ton*) and specific fluctuation strength (*Fls'*).

Sound sample	SPL [dB]	L_N [phon]	S [acum]	R' [asper]	Ton [tu]	Fls' [vacil]
Pink noise	85.0	99.0	2.15	3.95	0.018	0.0107
Eminem	85.0	90.3	1.32	3.27	0.361	0.3560

Table 2
Comparison of calculated results, receiving level (L_2), loudness (*N*), specific fluctuation strength (*Fls'*), and specific roughness (*R'*), respectively. Results taken from Ref. [25].

Filter R'_w (dB)	0	20	30	40	50	60	
Pink noise $L_2 =$	85.0	72.1	62.1	52.1	42.1	32.1	dB SPL
$N =$	60.5	18.20	9.24	4.27	1.59	0.323	sone GD
$Fls' =$	0.0223	0.0146	0.0109	0.00819	0.00614	0.00461	vacil
$R' =$	3.94	2.06	1.45	0.816	0.138	0.0185	asper
White noise $L_2 =$	85.0	62.3	52.3	42.3	32.3	22.3	dB SPL
$N =$	57.6	15.50	7.79	3.54	1.25	0.205	sone GD
$Fls' =$	0.0166	0.0120	0.00903	0.00677	0.00508	0.00381	vacil
$R' =$	3.59	1.83	1.29	0.614	0.0	0.0	asper
Eminem $L_2 =$	85.0	73.8	63.8	53.8	43.8	33.8	dB SPL
$N =$	38.5	12.30	6.07	2.74	1.01	0.238	sone GD
$Fls' =$	0.356	0.217	0.163	0.122	0.0917	0.0688	vacil
$R' =$	3.26	1.49	0.897	0.349	0.0850	0.0202	asper
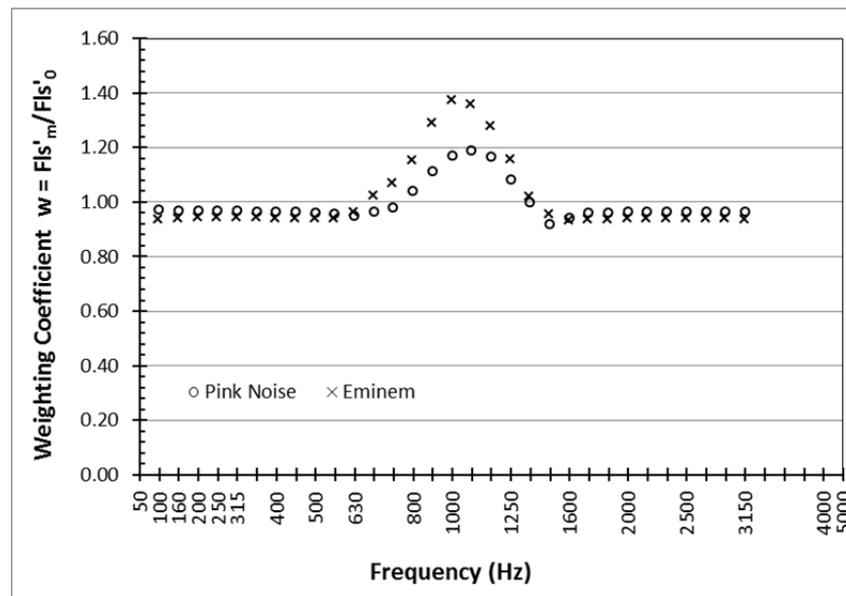
Fig. 12. Function of the weighting coefficient (w) over frequency for two types of test signals. Shown is the music type signal "Eminem" and the broadband noise type signal "pink noise" for a weighted apparent sound insulation value $R'_w = 40$ dB with a dip of 6 dB at a frequency of 1 kHz.

The measurements results are shown in Fig. 6. It can be seen that the results using the survey method of EN ISO 10052 yield only small deviations except at higher frequencies. There, a maximum deviation between pink noise and rap music (Eminem) is approximately 5 dB at a frequency of 1.25 kHz. Overall, the difference of the obtained single number rating is 1 dB. The single value obtained using pink noise was $R'_w = 60$ dB, and using rap music (Eminem), $R'_w = 59$ dB. Applying the standard procedure according to ISO 140-4 using pink noise yield a single value of $R'_w(C; C_{tr}) = 60$ (-1; -5) dB. That is, both methods using pink noise yield same a single value of the airborne sound insulation of 60 dB. A deviation was observed using a music-type signal as a source signal to measure the airborne sound insulation. The observed deviation was 1 dB. Overall, the measured results reveal good agreement between the applied two standard methods using pink noise as a source signal.

3.1.2 Prediction of airborne sound insulation according to the standard

The calculated airborne sound insulation using the method of the European standard EN 12354-1 for the investigated concrete wall of thickness d = 220 mm is $R'_w(C; C_{tr}) = 60$ (-1; -6) dB. In Fig. 6, the predicted airborne sound insulation over frequency is depicted as a solid line. No significant deviation is observed in that frequency-dependent airborne sound insulation curve. Considering, however, the spectrum adaptation terms C, and C_{tr}, the impression is created that there is a less sound protection quality present than the single value R'_w might imply. That is, for the considered sound spectra (living noise or A-weighted pink noise and traffic noise spectrum), the sound insulation is actually ($R'_w + C$) or ($R'_w + C_{tr}$) and hence, the airborne sound insulation is less if these particular spectra are applied.

The comparison of the calculated airborne sound insulation using EN 12354-1 and the measured airborne sound insulation using ISO 140-4 reveals that the prediction is very close to the in-situ measured airborne sound insulation. At a frequency of 125 Hz, the measured value, however, shows a peak compared with the predicted value, where the deviation is approximately 5 dB. No difference in the single number rating was observed, but there were differences in the spectrum adaptation terms C, and C_{tr}, which is for both terms is 1 dB. Overall, the comparison of measured results using pink noise as a source signal and the calculated results reveal good agreement except at a frequency of 125 Hz, where in this case, a deviation of 5 dB was observed.

3.2 Sound pressure level and loudness level

A comparison of calculated level after transmission for different sound insulation values is shown in Fig. 7. The investigated frequency-dependent sound insulation contains no dip (see Fig. 5, left panel). It is seen, as expected, that the sound pressure level after transmission falls off with increasing frequency. This is seen independent of the type of signal and of the R'_w-values. 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 and increasing airborne sound insulation, the loudness level rises, which was not expected.

Computing the level difference according to Eq. (2) using sound pressure level ($L_1 - L_2$) and loudness level ($L_{N1} - L_{N2}$) yield the results depicted in Fig. 8. As seen, the smallest difference is observed for airborne sound insulation at mid frequencies. This means that at mid frequencies, the airborne sound insulation expressed as a sound pressure level difference and the airborne sound insulation expressed as a loudness level difference is small. It is notable that for high frequency and high airborne sound insulation ($R'_w = 60$ dB), the level difference spreads as the frequency rises. For small and medium levels of airborne sound insulation, the opposite pattern is observed, i.e., at low frequency the difference between both values are greater, and for higher frequencies, the differences become smaller. This is independent of the type of signal. In addition it is seen from Fig. 8 that at 100 Hz for high sound insulation ($R'_w = 60$ dB) the loudness level difference is lower than the sound pressure level difference. This is because the loudness function becomes much steeper at low levels [38] than that at mid and high levels. At high airborne sound insulations the loudness level becomes smaller and hence the loudness level difference becomes greater than that for low airborne sound insulation.

If a dip in the frequency depending airborne sound insulation is introduced, the normalised loudness level difference (L_{nor}) according to Eq. (6) provides a picture of this event. As an example, in Fig. 9, the normalised loudness level difference for an airborne sound insulation of $R'_w = 40$ dB, having a frequency dip of 6 dB at 1 kHz using "pink noise" and "Eminem" as test signals, is shown. The graph displays a strong peak at the frequency where the dip was introduced in the airborne sound insulation. At frequencies below and above this dip, the normalised loudness level difference is close to 1. Both test signals reveal similar results at 1 kHz. The event of the dip is independent of the type of signal. In both cases, the average value (i.e. arithmetic mean) of the normalised loudness level difference is 1.01 with a standard deviation for pink noise of 0.02 and 0.03 for Eminem. In the vicinity of the frequency dip (800 Hz - 1.25 kHz) the average value of both signals is 0.97 ± 0.02. That means that at the ambit of the dip of 6 dB the normalised loudness level difference drops in average about 4%.

It is interesting to compare the level difference using the sound pressure level. This was performed for the forgoing example, and the results are presented in Fig. 10, where it can be seen that the sound pressure level difference provides a picture of this event, i.e., the frequency dip of 6 dB at 1 kHz is clearly seen.

3.3 Specific fluctuation strength as a weighting function

The designed weighting (w) as described in Eq. (8) is shown in Fig. 12 for an example of an airborne sound insulation of $R'_w = 40$ dB having a frequency dip of 6 dB at 1 kHz using "pink noise" and "Eminem" as test signals. It can be seen that the weighting function indicates an introduced dip in the airborne sound insulation. For the transient signal, the peak of the function is more formed than for the broadband noise signal. It is noted, however, that the signal "Eminem" compared with the broadband signal "pink noise" displays a higher peak value. Furthermore, it is noted that the signal of the broadband noise displays slightly higher values than the transient signal outside the circle of influence of the dip. That is, the weighting coefficient of the broadband noise is closer to 1 than that of the transient signal. This is in line with the basic theory of fluctuation strength which states that unmodulated broadband noise does not have high fluctuation strength.

The circle of influence of the dip at 1 kHz is in the range of 630 Hz to 1.6 kHz. The pink noise signal is shown to be up to approximately 2% above the value of the transient signal "Eminem". At the ambit of the dip at 1 kHz, the transient signal is approximately 9% higher than the broadband noise signal. This makes it clear that the signal type affects the weighting coefficient. It is interesting to see that the signal "Eminem" reaches an approximately 15% higher maximum at the dip event than the signal "pink noise". To summarise the results for this point, it is understood that the weighting coefficient reflects the frequency-dependent event in the frequency-dependent airborne sound insulation, and it differs for different types of signals.

3.4 Weighted normalised loudness level difference

Introducing Eq. (8) into Eq. (7) yields the weighted normalised loudness level difference ($L_{nor,w}$). A calculation example for an airborne sound insulation of 40 dB with a dip at 1 kHz is presented in Fig. 13. The introduced dip at a frequency of 1 kHz is clearly seen, and for the transient signal, the peak is more formed than for the broadband noise signal. Both signals on the other hand yield similar results outside the ambit of the dip at 1 kHz, i.e., at frequencies below and above that dip, $L_{nor,w}$ is close to 1. In fact, the pink noise signal is up to less than 3% above the value of the transient signal "Eminem". That is, no substantial difference is observed in the frequencies of at least one-third octave band off the introduced dip compared to the event of the frequency dip. The circle of influence of the dip at 1 kHz is again between 630 Hz and 1.6 kHz. It is clearly seen that $L_{nor,w}$ is constant and close to 1 except at frequencies around the ambit of the introduced dip. In the case of Fig. 13, this is approximately 1 kHz with a spread of approximately one-third octave bands. The music type signal reveals again a higher peak value than the broadband noise signal. The signal "Eminem" reaches approximately 15% higher maximum value at the dip event than the signal "pink noise". The average value of $L_{nor,w}$ for the Eminem signal is 1.01 with a standard deviation of 0.10, and for pink noise the average is 1.00 with a standard deviation of 0.04. From Figs. 9 and 10, it is clear that simple level differences display no difference between the results. This proves that describing airborne sound insulation in terms of sound pressure level difference is not sufficient to demonstrate a frequency dependent event in the airborne sound insulation property. This is in accordance to previous investigations reported, e.g., in [4]. This holds also for the loudness level difference.

The results illustrate in detail that the calculation scheme of a weighted normalised loudness level difference allows the revelation of a single frequency event and distinguishes between the stimuli, i.e., source signal. The fact that both measures, i.e., the loudness level and the specific fluctuation strength, need to be considered becomes clear, for example, when comparing the results in Figs. 9 and 13.

Because this calculation scheme is linked by psychoacoustic measures described in terms of loudness level and fluctuation strength, it is supposed that the airborne sound insulation strength, as a method to describe the quality of a certain sound protection in terms of an airborne sound insulation, is more related to the real impression of an experienced airborne sound insulation in-situ.

3.5 Comparison between measured and calculated level

From the measurements, as presented in Fig. 6, the transmitted sound pressure level (L_2) was obtained and according to Eq. (3) converted into a loudness level (L_{N2}). For the measured sound pressure level L_2, the related psychoacoustic measures were calculated, and the results are listed in Table 3. The calculated normalised loudness level difference (L_{nor}) of the measured and calculated airborne sound insulation is shown in Fig. 14. The comparison shows good agreement between the calculated normalised loudness level differences over frequency for both types of signal investigated. Applying the weighting (w) according to Eq. (7) yields the weighted normalised loudness level difference ($L_{nor,w}$).
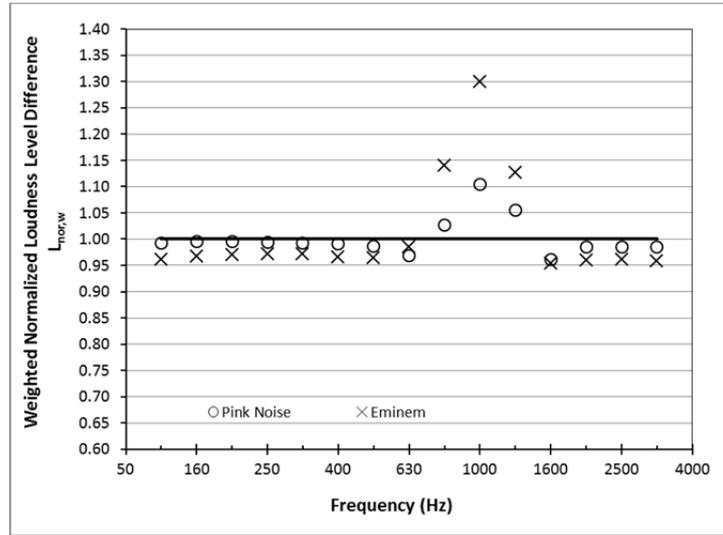
Fig. 13. Function of the weighted normalised loudness level difference ($L_{nor,w}$) over frequency according to Eq. (7). Shown is the music type signal "Eminem" and the broadband noise type signal "pink noise" for a weighted apparent sound insulation value $R'_w = 40$ dB with a dip of 6 dB at a frequency of 1 kHz.

The results are shown in Fig. 15. The results reveal a completely different picture as might be assumed, comparing results shown in Fig. 14, where it is seen that the normalised loudness level difference yields close results. No significant difference is observed for the results shown in Fig. 14. For both, the steady state signal (pink noise) and the transient signal (rap music: Eminem), the mean of the normalised loudness level difference is 1.00 with a standard deviation of 0.03. If the weighted normalised loudness level difference ($L_{nor,w}$) as depicted in Fig. 15 is compared, the pink noise shows a mean of 0.96 with a standard deviation of 0.29, whereas using music (Eminem) as a test signal, a mean of 1.01 with a standard deviation of 0.14 was obtained.

Table 3

Acoustic factors of the measured sound signal in the receiving room after transmission ($R'_w = 60$ dB): sound pressure level (SPL), loudness level (L_N), sharpness (S), specific roughness (R'), tonality (Ton) and specific fluctuation strength (Fls').

Sound sample	SPL [dB]	L_N [phon]	S [acum]	R' [asper]	Ton [tu]	Fls' [vacil]
Pink noise	56.4	54.1	1.91	0.1430	0.110	0.00501
Eminem	54.1	43.7	1.05	0.0932	0.176	0.00939
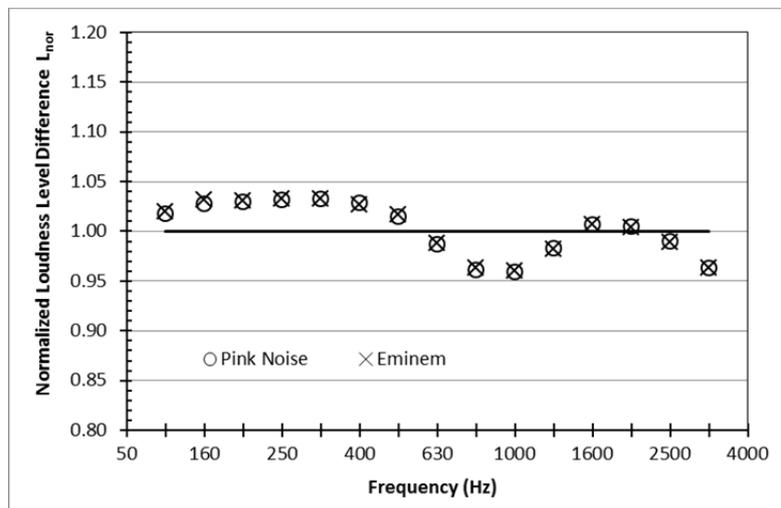
Fig. 14. Calculated normalised loudness level difference over frequency. Shown is the music type signal "Eminem" and the broadband noise type signal "pink noise". The L_{nor}-values refer to R'-values from measurement where reference values are calculated after EN 12354-1 (see Fig. 6). Airborne sound insulation measured according to ISO 140-1, $R'_w(C; C_{tr}) = 60$ (-1; -5) dB and predicted according to EN 12354-1, $R'_w(C; C_{tr}) = 60$ (-1; -6) dB.

It can be seen in Fig. 6 that the measured and predicted airborne sound insulation (R'_w) does not display a significant change. On the other hand, when comparing the results in Fig. 15, it can be seen that the transient signal (music type signal) differs greatly from the results obtained using a steady-state signal (broadband noise). It is interesting to compare results obtained using the standard procedures of ISO 717-1 and EN 12354-1. The results of $R'_w(C; C_{tr}) = 60$ (-1; -5) dB for the measured value and $R'_w(C; C_{tr}) = 60$ (-1; -6) dB for the predicted value do not describe, in detail, where the airborne sound insulation leads to a rated lower value than measured or predicted. The lowest value is the ($R'_w + C_{tr}$)-value, yielding 55 dB and 54 dB, respectively.
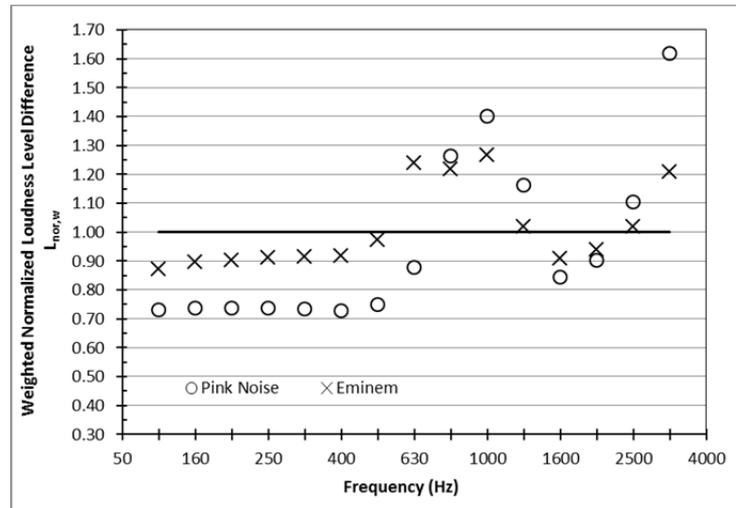
Fig. 15. Calculated weighted normalised loudness level difference ($L_{nor,w}$) according to Eq. (7). The $L_{nor,w}$-values refer to R'-values from measurement, the reference values are calculated after EN 12354-1 (see Fig. 6). Airborne sound insulation measured according to ISO 140-1, $R'_w(C; C_{tr}) = 60$ (-1; -5) dB and predicted according to EN 12354-1, $R'_w(C; C_{tr}) = 60$ (-1; -6) dB.

This means that although an airborne sound insulation was measured and predicted as 60 dB, it is supposed that for a certain spectrum, the real airborne sound insulation will be judged differently. The normalised loudness level difference (L_{nor}) as depicted in Fig. 14 does not distinguish between these two types of signals.

The introduced weighting (w) does alter the amplitude of the level difference. This confirms that a level difference does not display failures or weak points, respectively, in an airborne sound insulation curve. Therefore, it is essential to introduce a psychoacoustics-related weighting to estimate the airborne sound insulation in a more subjective-related manner.

In particular, the results indicate that the valuation of airborne sound insulation using the concept of a reference curve as in the standard ISO 717 described hardly allows determination of detailed frequency-dependent irregularities. Although the standard method of ISO 717 does distinguish different spectra using different adaptation terms C, and C_{tr}, the single number rating does not reveal the frequency range affected. This becomes clear by comparing results in Fig. 6 and results in Fig. 15 where both figures contain the same base information, i.e., the sound pressure level of the source signal and the sound pressure level of the processed signal after transmission through the wall. Therefore, it is believed that the presented calculation scheme describing airborne sound insulation in terms of a weighted normalised loudness level difference allows deeper insight into the sound protection in-situ and for characterising the sound insulation properties of building elements.

4. Conclusions

In this study, a calculation scheme for the loudness level was introduced and examined, and a comparison of calculated and measured airborne sound insulation linked with a psychoacoustic measure was performed.

The outcomes of the present study justify the assumption that level differences cannot reveal the influence of the type of signal on the airborne sound insulation. It was 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 normalised loudness level difference better relates to the hearing sensation of a transmitted sound signal and is very promising. Moreover, it is concluded that even if the sound pressure level lowers with frequency, the loudness level increases. This is in agreement with the results found in [36, 49, 50]. The use of fluctuation strength as an appropriate measure to describe an auditory judgment is in agreement with results published in [45].

Future studies using more controlled stimuli and comparisons with subjects may support the need to use psychoacoustic factors to describe the airborne sound insulation judgment. Though the present study was not concerned with single number ratings, it is important to consider this in further research, in addition to the investigation into the relationships between subjective and objective measures.

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