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AIRBORNE SOUND INSULATION BASED ON A MODEL OF LOUDNESS

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An objective description of airborne sound insulation between rooms still challenges house builders as well as house owners. In order to describe the measure of the quality of sound protection, different descriptors are used in different countries. This paper introduces a calculation scheme based on loudness level linked with specific fluctuation strength, yielding a weighted normalised loudness level difference. 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 which 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, while a simple level difference does not allow investigating a single frequency dip in an airborne sound insulation curve, using the weighted normalised loudness level difference a significant change can be observed. Furthermore, the frequency dependent results allow more details to be investigated for a certain sound insulation. In this paper it will be shown that an objective descriptor of airborne sound insulation based on psychoacoustic magnitudes like loudness level and specific fluctuation strength can largely account for different aspects, particularly if it is supposed to describe hearing sensation.

1. INTRODUCTION

In the field of building acoustics there is evidence that the currently applied requirements and descriptors do not sufficiently consider residents' experience of the building acoustic comfort. This study is a continuation of an ongoing study[1,2,3,4,5,6] and presents a calculation scheme based on loudness level linked with specific fluctuation strength, yielding a weighted normalised loudness level difference. The approach in this paper is a suggestion to find an appropriate sound insulation rating in regard to the dwellers' perception. It is expected that with the derived psychoacoustic concept of "weighted normalised loudness level difference", perception relevant sound insulation properties can be distinguished with a higher resolution than by applying the ISO 717-1[7] approach. The standard procedure to measure airborne sound insulation according to ISO 140-4[8] is based on the use of a broadband noise like pink noise. Since it is well known that many different types of sounds can be disturbing when transmitted through a partition and, especially, music sounds from neighbours are often said to be a main cause of annoyance and complaints,[9] and indoor residential noise is judged differently with different noise types, as indicated by Ryu et al.,[10] for example, a music type signals is investigated in addition. In contrast to the steady-state signal pink noise a non-steady-state signal is used. In analogy to previous studies[2,3,4] the rap type music Eminem with the song: “Loose Yourself” is used in this study as well.

2. AIRBORNE SOUND INSULATION

The airborne sound insulation is defined as 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:

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

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

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

Since the source signal is L_1 the level of interest is L_2. This is the sound pressure level which has to be judged. In order to investigate the airborne sound insulation a filter has to be applied to an unprocessed sound signal. In Figure 1 an example is shown, with a frequency dependent sound insulation without and with a dip of 6 dB at a frequency of 800 Hz. Both filters have the same *R*-value of 30 dB. The used standard procedure was ISO 717-1.

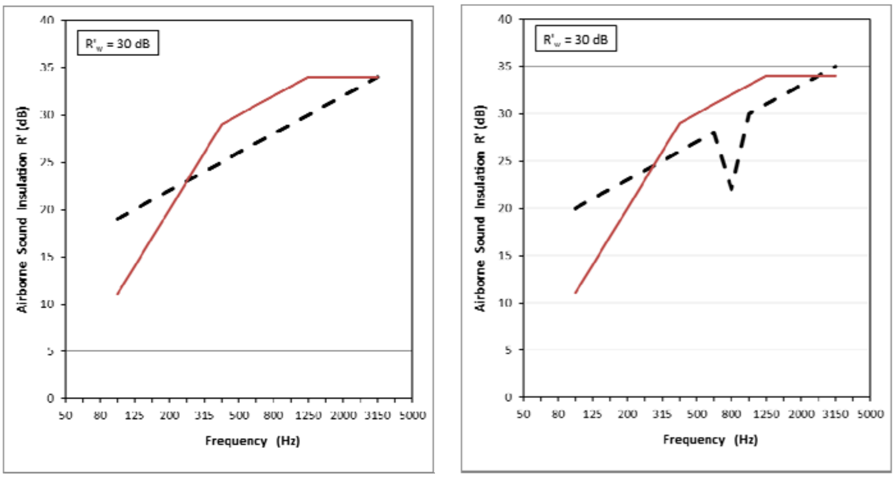

Figure 1. Idealised airborne sound insulation of R'_w = 30 dB without (left panel) and with a dip at 800 Hz (right panel). The solid line is the reference curve given in ISO 717-1.

3. LOUDNESS CONCEPT

The perceived loudness is a psycho-acoustic quantity that depends on the sound pressure level, the frequency spectrum, and the time behaviour of the signal. If it is assumed that a frequency dependent sound insulation should reflect any events in the frequency range it is expressed in the ratio of undisturbed to disturbed sound insulation, i.e. without and with a dip in the frequency dependent sound insulation. Since loudness is a hearing-related measurement taken as well temporal and spectral masking effects into account, it is preferable as a measure to describe sound insulation.

3.1 TRANSFORMATION OF SOUND PRESSURE LEVEL INTO LOUDNESS LEVEL

In order to compute the loudness level difference the sound pressure level has to be transformed into a loudness level. This transformation is done using the method of ISO 226.[11]

3.1.1 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 is made according to ISO 226:

$$L_2(f) \rightarrow L_{N2}(f) \tag{3}$$

The filtered sound pressure level (L_2) contains all information of the airborne sound insulation (R'_w) since it is the transmitted sound signal. Hence conversion of sound pressure level (L) into loudness level (L_N) yields a sensation level.

3.1.2 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):

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

where $L_{N1(f)}$ is the loudness level of the source signal.

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 normalised loudness level difference for third-octave band values is then written as:

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

An example of a calculated normalised loudness level difference as a function of frequency is shown in Figure 2, using an airborne sound insulation of 30 dB with a dip of 6 dB at 800 Hz.

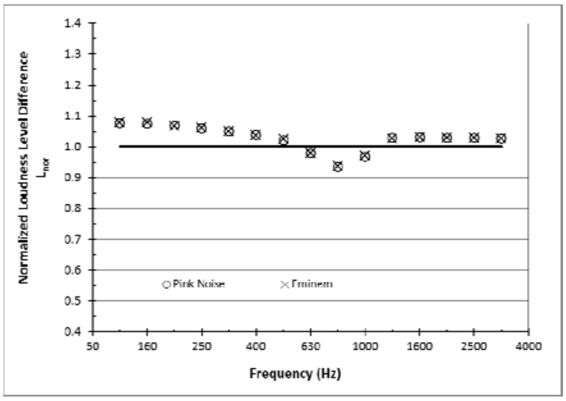

Figure 2. Normalised loudness level difference over frequency according to Eq. (6) for pink noise and Eminem. Investigated airborne sound insulation value is 30 dB with a dip of 6 dB at 800 Hz.

A method for determining a single numerical value of a given sound in terms of a loudness level was developed by Zwicker[12] and the calculation method is given in ISO 532 B[13], DIN 45631[14], respectively, and this is based on spectrum analyses in one-third octave bands. The single number quantity for the normalised loudness level difference L_{nor} is then written as the quotient of the differences of the total loudness levels, yielding:

$$L_{nor} = \frac{L_{N1} - L_{N2,m}}{L_{N1} - L_{N2,0}} \tag{7}$$

3.1.3 THE NORMALISED SPECIFIC FLUCTUATION STRENGTH AS A WEIGHTING FUNCTION

An appropriate weighting which 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. The weighted normalised loudness level difference, or airborne sound insulation strength, for third-octave band values is then written as:

$$L_{nor,\,w}(f) = L_{nor(f)} * w(f) \tag{8}$$

where *w* is a weighting factor.

To differentiate the signal in terms of psychoacoustic measures, the fluctuation of the signal was investigated. For the weighting, it is assumed that the psychoacoustic parameters, specific fluctuation strength, *Fls'* (vacil), or the specific roughness, *R'* (asper), can be applied, because they are related to the temporal structure of the sounds.[15] The calculation was carried out 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[16]. From earlier results[2,3] it was found that fluctuation strength is a suitable magnitude to describe the signal in terms of psychoacoustic quantity. Assume that for the level specified in Eq. (4) the specific fluctuation strength is $Fls'_{(f),0}$ and for the level specified in Eq. (5) the specific fluctuation strength is $Fls'_{(f),m}$ the unknown weighting for third-octave band values may be written as:

$$w_{(f)} = \frac{Fls'_{(f),\,m}}{Fls'_{(f),0}} \tag{9}$$

The computed weighting coefficient as a function of frequency is shown in Figure 3.

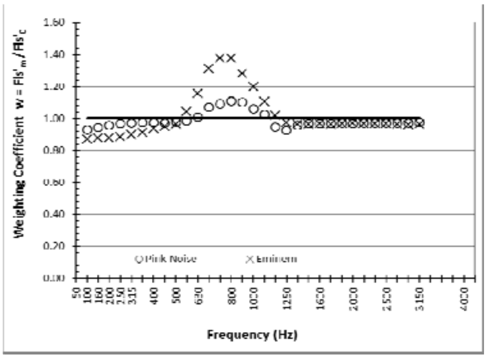

Figure 3. Weighting coefficient (*w*) over frequency for the test signals pink noise and Eminem according to Eq. (9), based on a *R'*-value of 30 dB with a dip of 6 dB at 800 Hz.

Using the function for the weighting in Eq. (8) the computed results are shown in Figure 4.

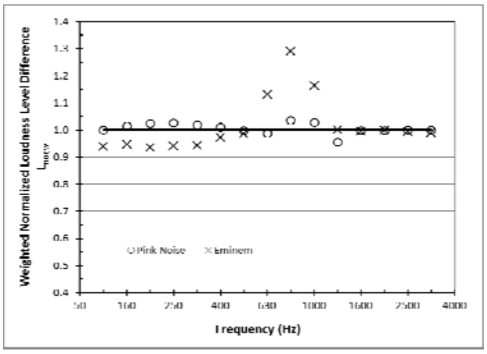

Figure 4. Weighted normalised loudness level difference ($L_{nor,w}$) for the test signals pink noise and Eminem according to Eq. (8), based on a *R'*-value of 30 dB with a dip of 6 dB at 800 Hz.

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

$$w = \frac{Fls'_{,m}}{Fls'_{,0}} \tag{10}$$

Combining Eq. (10) and Eq. (7) yield the single number quantity for the weighted normalised loudness level difference $L_{nor,w}$ and can be written as:

$$L_{nor,w} = L_{nor} * w \tag{11}$$

For the investigated signals the computed weighted normalised loudness level difference as a function of frequency is shown in Figure 4.

4. Results and Discussion

The computed normalised loudness level difference as a function of frequency was shown in Figure 2. It can be seen that negligible variance between the investigated two different sound signals based on level difference occur. Indeed, this holds for sound pressure level differences too, which confirm results e.g. in.[17] This is seen in Figure 5 where the sound pressure level difference is depicted for an *R'*-value of 30 dB with a dip at 800 Hz. The dip is certainly seen for both signal types, but the sound pressure level differences of both signals do not differ much.

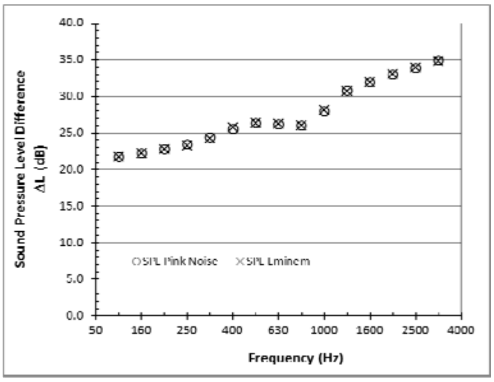

Figure 5. Sound pressure level difference over frequency for pink noise and Eminem, where the airborne sound insulation value is 30 dB with a dip of 6 dB at 800 Hz.

A comparison of calculated sound pressure level (L_2) and loudness level (L_N) after transmission for different sound insulation values is shown in Figure 6. The investigated frequency-dependent sound insulation contains no dip (see Fig. 1 left panel).

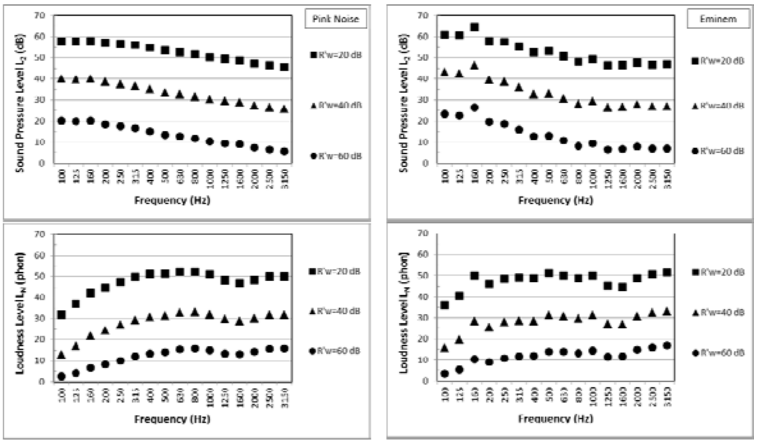

Figure 6. Comparison of calculated sound pressure level (L_2) and loudness level (L_N) after transmission for different *R'*-values of 20, 40, and 60 dB using a filter function without a dip.

It is seen from Figure 6, 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’*-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 noted that although the sound pressure level falls off with increasing frequency and increasing airborne sound insulation, the loudness level rises, which was not expected. To distinguish the signal the fluctuation of the signal was investigated, which was demonstrated in Figure 3, where the specific fluctuation strength as a weighting coefficient over frequency is shown. The introduced dip at 800 Hz in Figure 3 is clearly seen.

In Figure 4, the weighted normalised loudness level difference is depicted showing results according to Eq. (8). These results show clearly, that pink noise is close to 1 with small fluctuations, but with the influence of the dip at 800 Hz. On the contrary, the non-steady-state signal Eminem shows in the ambit of the dip at 800 Hz a clear peak. That is, for the transient signal the peak is more formed than for the broadband noise signal. The results illustrate that the calculation scheme of a normalised weighted loudness level difference allows an identification of a single frequency event and distinguishes between the stimuli, i.e., source signal.

In order to compare the single number quantities, the normalised loudness level difference (L_{nor}), the weighting coefficient (w), and the weighted normalised loudness level difference ($L_{nor,w}$) are calculated for different airborne sound insulation values. Table 1 shows calculated results using pink noise and Eminem as source signals and filter functions having damping values of 20, 40, 60 dB, respectively, and a dip of 6 dB at 500, 800, and 1k Hz.

Table 1. Single number quantities using pink noise and Eminem as source signal, having a SPL of 85 dB with an applied damping of 20, 40, and 60 dB, respectively, and a dip of 6 dB at 500, 800, and 1k Hz.

Dip at 500 Hz	Pink Noise, L_{N1} = 99.3 phon			Eminem, L_{N1} = 90.3 phon		
	R’ = 20 dB	R’ = 40 dB	R’ = 60 dB	R’ = 20 dB	R’ = 40 dB	R’ = 60 dB
$L_{N2,0}$ (phon)	81.5	61.0	27.2	73.2	51.5	21.6
$L_{N2,m}$ (phon)	81.1	60.3	25.1	72.7	50.9	20.5
Fls'_0 (vacil)	0.00676	0.00385	0.00216	0.215	0.123	0.0692
Fls'_m (vacil)	0.00688	0.00387	0.00217	0.215	0.122	0.0684
w (-)	1.018	1.005	1.005	1.000	0.992	0.988
L_{nor} (-)	1.022	1.018	1.029	1.029	1.015	1.016
$L_{nor,w}$ (-)	1.041	1.024	1.034	1.029	1.007	1.004
Dip at 800 Hz						
$L_{N2,0}$ (phon)	81.5	61.0	27.2	73.2	51.5	21.6
$L_{N2,m}$ (phon)	81.1	60.5	26.2	72.7	50.6	20.1
Fls'_0 (vacil)	0.00676	0.00385	0.00216	0.215	0.123	0.0692
Fls'_m (vacil)	0.00672	0.00379	0.00212	0.212	0.120	0.0671
w (-)	0.994	0.984	0.981	0.986	0.976	0.970
L_{nor} (-)	1.022	1.013	1.014	1.029	1.023	1.022
$L_{nor,w}$ (-)	1.016	0.997	0.995	1.015	0.998	0.991
Dip at 1 kHz						
$L_{N2,0}$ (phon)	81.5	61.0	27.2	73.2	51.5	21.6
$L_{N2,m}$ (phon)	81.1	60.4	25.9	72.7	50.8	20.5
Fls'_0 (vacil)	0.00676	0.00385	0.00216	0.215	0.123	0.0692
Fls'_m (vacil)	0.00672	0.00382	0.00217	0.210	0.120	0.0671
w (-)	0.994	0.992	1.005	0.977	0.976	0.970
L_{nor} (-)	1.022	1.016	1.018	1.029	1.018	1.016
$L_{nor,w}$ (-)	1.016	1.008	1.023	1.005	0.993	0.985

The calculation results of the normalised loudness level difference according to Eq. (7) for different airborne sound insulation and different frequency dips are summarized in Figure 7. It is seen that all values do not spread much around 1. The calculated mean of L_{nor} is 1.016 ± 0.002. From Figure 7 it can be seen that there is no strong variance at the different airborne sound insulations along the frequencies. Both, the broadband noise signal as well as the transient signal yield level differences which lie very close together. The results shown in Figure 7 verify the assumption that there is no use looking at pure level differences.

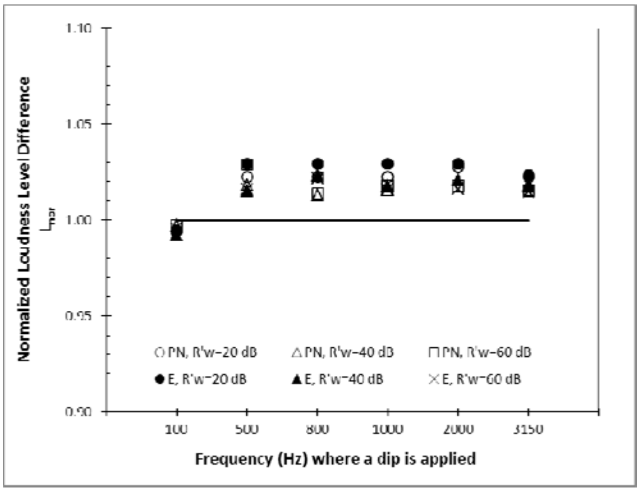

Figure 7. Normalised loudness level differences according to Eq. (6) over frequency where a dip of 6 dB is applied, and the investigated airborne sound insulation values are 20, 40, and 60 dB.

With the weighting coefficient (*w*) according to Eq. (10) is introduced, the results are shown in Figure 8, where the weighted normalised loudness level difference ($L_{nor,w}$) according to Eq. (11) shows greatest deviations at 500 Hz. Smallest variances are observed at 100 Hz. It is observed that at 1 kHz pink noise yield higher levels than the music type signal. Above 1 kHz the music type signal yields higher level. This may lead to the assumption that at high frequencies ($f > 1$ kHz) music type signals have more impact in terms of psychoacoustic measure than a broadband noise signal. The calculated mean of $L_{nor,w}$ for both signals is 1.01 ± 0.01.

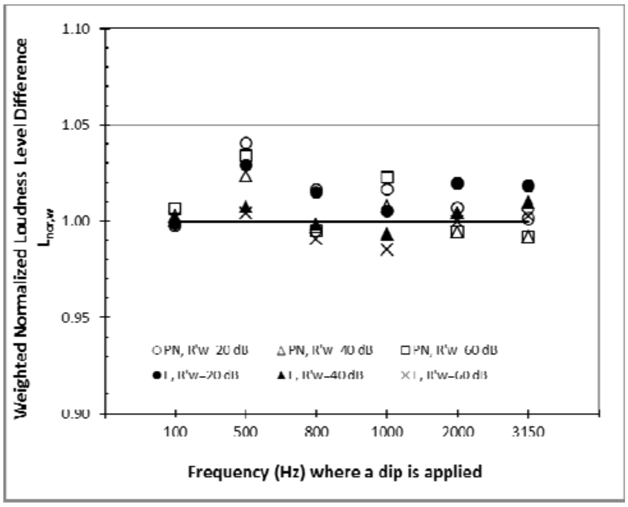

Figure 8. Weighted normalised loudness level differences according to Eq. (11) over frequency, where a dip of 6 dB is applied, and the investigated airborne sound insulation values are 20, 40, and 60 dB.

5. Conclusions

In this study a calculation scheme of a loudness level concept was introduced and examined, and a comparison of calculated airborne sound insulation linked with a psychoacoustic measure was carried out. It has been shown that using loudness level instead of 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. From the results obtained it is very promising that the calculation scheme of describing the airborne sound insulation in terms of a weighted normalised loudness level difference could be better related to the hearing sensation of a transmitted sound signal. The use of fluctuation strength as an appropriate measure to describe an auditory judgment is in agreement with results published previously.[18]

Future studies using more controlled stimuli and comparison with subjects may support the need to use psychoacoustic factors in order to describe the airborne sound insulation judgment.

REFERENCES

[1] Neubauer, R.O. "Airborne Sound Insulation in Dwellings and its Subjective Estimation", Proc. 12th *International Congress on Acoustics* - ICSV 12, Lisbon, Portugal, (2005).
[2] Neubauer, R.O., Kang, J. What Describes the Airborne sound Insulation in Technical and Subjective Regard? Proc. *Forum Acusticum*, Aalborg, Denmark, (2011).
[3] Neubauer, R.O., Kang, J. Time Structure of the Signal in Airborne Sound Insulation. Proc. *EURONOISE*, Prague, Czech Republic, (2012).
[4] Neubauer, R.O., Kang, J. Rating Airborne Sound Insulation in Terms of Time Structure of the Signal, Proc. *INTER-NOISE*, New York, USA, (2012).
[5] Neubauer, R.O., Kang, J. Subjective Evaluation of Airborne Sound Insulation below 100 Hz. Joint Conference on Acoustics - *AIA-DAGA* 2013, Merano, Italy, (2013).
[6] Neubauer, R.O., Kang, J. Airborne sound insulation as a measure for noise annoyance, Proc. 21st *International Congress on Acoustics*, ICA 21, Montreal, Canada, (2013).
[7] ISO 717-1: 2013, Acoustics – Rating of sound insulation in buildings and of building elements– Part 1: Airborne sound insulation, Int. Organization for Standardization, Geneva.
[8] ISO 140-4:1998, Acoustics - Measurement of sound insulation in buildings and of building elements. Field measurements of airborne sound insulation between rooms. Int. Organization for Standardization, Geneva.
[9] Park, H.K., Bradley, J.S. Evaluating standard airborne sound insulation measures in terms of annoyance, loudness, and audibility ratings. *J. Acoust. Soc. Am.* **126** (1), (2009).
[10] Ryu, J.K. and Jeon, J. Y. Influence of noise sensitivity on annoyance of indoor and outdoor noises in residential buildings, *Appl. Acoust*. **72**, 336 - 340, (2011).
[11] ISO 226:2003, Acoustics - Normal equal-loudness-level contours. Int. Organization for Standardization, Geneva.
[12] Zwicker, E. Ein Verfahren zur Berechnung der Lautstärke (in German). Acustica **10**, (1960)
[13] ISO 532/R, Acoustics- Method for Calculating Loudness Level (1975). Int. Organization for Standardization, Geneva. (This standard has been reviewed and confirmed in 2012).
[14] DIN 45631/A1: 2010-03, Berechnung des Lautstärkepegels und der Lautheit aus dem Geräuschspektrum - Verfahren nach E. Zwicker - Änderung 1: Berechnung der Lautheit zeitvarianter Geräusche. Beuth Verlag GmbH, Berlin.
[15] Zwicker, E., Fastl, H. Psychoacoustics. *Facts and Models*, third ed., Springer, Berlin, 2007.
[16] HEAD Acoustics GmbH. "Psychoacoustic analyses in ArtemiS II," available at: head-acoustics.de/downloads/eng/application_notes/PsychoacousticAnalysesII_06_11e.pdf
[17] Vian, J.-P., Danner, W.F. and Bauer, J.W. Assessment of significant acoustical parameters for rating sound insulation of party walls, *J. Acoust. Soc. Am.* **73** (4), 1236 - 1243, (1983).
[18] Jeon, J.Y., You, J., Jeong, C.I., Kim, S.Y., Jho, M.J. Varying the spectral envelope of air-conditioning sounds to enhance indoor acoustic comfort, *Building and Environment* **46**, 739 - 746, (2011).