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Annoyance penalty of broad-band steady-state noise due to the spectrum shape

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Abstract

Many noise measurement guidelines involve a penalty procedure where a constant number, k [dB], that is added to the measured sound level, L_{Aeq} [dB], if the sound is tonal or impulsive. The adjusted value, $L_{\mathrm{Aeq}}+k$, should then describe noise annoyance better than L_{Aeq} alone. However, many sounds in our environment are broadband steady-state (BBSS) sounds. Our purpose is to summarize psychoacoustic research, which developed a simple model to calculate the annoyance penalty of a BBSS sound from the measured 1/3-octave band spectrum. The model is based on psychoacoustic experiment of Kuusinen et al. (2023) who investigated the annoyance of 23 spectrally different BBSS sounds. They reported annoyance penalty values within 0 and +12 dB. In the follow-up study, Kuusinen & Hongisto (2026) developed a regression model, which predicted the annoyance penalty obtained in the experiment with high reliability (R^2=0.79). The input variable of the model spectral centroid, which is calculated from the 1/3-octave band spectrum of BBSS sound. The model may have broad applications in the assessment of noise annoyance of various BBSS sound scenarios both outdoors and indoors.

Keywords: *broadband noise, noise annoyance, penalty, sanction, psychoacoustics*

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1. Introduction

Many noise measurement guidelines involve sound level adjustment (also known as penalty, sanction, or surplus), if the noise carries specific, and objectively measurable features, such as impulsivity or tonality. In most guidelines, the penalty is constant, k [dB], that is added to the measured sound level, L_{Aeq} [dB]. The adjusted value, $L_{\mathrm{Aeq}}+k$, should then describe noise annoyance better than L_{Aeq} alone.

Noise annoyance is usually measured using 11-step numerical scale where 0 denotes "Not at all annoyed" and 10 denotes "Extremely annoyed". Many psychoacoustic experiments have proven that noise annoyance penalty due to sounds carrying abovementioned specific properties cannot be explained using constant penalty models. Instead, the annoyance penalty varies between 0–12 dB for tonal sounds [1, 2] 0–8 dB for normal impulsive sounds [3, 4], and even 20 dB for impulsive shooting sounds [5]. The annoyance penalty strongly depends on the physical measurable properties of the specific feature. For tonal sounds, such properties are tonal audibility and tonal frequency [1, 2]. For impulsive sounds such properties are onset rate and level difference or variability of sound level [3, 4].

Many sounds in our environment, both indoors and outdoors, are **broadband steady-state** (**BBSS**) sounds, which lack temporal variations and tonal features. A recent psychoacoustic experiment [6] found that BBSSs deserve annoyance penalty if the spectrum fulfils certain criteria. The annoyance penalty was even 12 dB for sounds which have strong high frequency content [6].

A follow-up study of Ref. [6] provided a prediction model [7], which showed how the annoyance penalty could be calculated from the sound pressure levels (SPL) measured using one-third octave band analysis.

The purpose is to summarize the psychoacoustic research of Ref. [7], which developed a simple model to calculate the penalty of a BBSS sound, when spectrum is measured using 1/3-octave band analysis within 100–10 000 Hz.

2. Psychoacoustic experiment

This section summarizes the experiment [6], which was used in the development of the penalty model in Ref. [7].

The psychoacoustic experiment involved 40 participants. Each participant rated the annoyance of 78 stimuli which all were BBSS sounds. The sounds were played via headphones, and the listening time was 10 seconds before the rating was possible. The rating was made using abovementioned 11-step numerical response scale. The number of actual research stimulus was 69. They involved 23 different spectral shapes, which were presented at three L_{Aeq} levels (32, 40, 48 dB). In addition, the stimuli involved 9 reference sounds played at 28–60 dB L_{Aeq} in 4-dB steps. Reference sounds had a constant spectrum shape. The chosen spectrum shape was Brown noise (-9 dB per octave increment) as a previous study found it to be among the most pleasant ones [8]. Therefore, it was expected that the spectra of the studied 23 BBSSs should be more annoying than the spectrum of reference sound. The annoyance of reference sounds depended linearly on L_{Aeq}. This linear relationship was used to determine the penalty for the 69 BBSSs.

The spectrum shapes of the experiment are summarized in Figure 1.

The penalty derivation method is clarified in Figure 2. The penalty values of the spectra are shown in Table 1. Penalty of a specific BBSS spectrum did not strongly depend on L_{Aeq} within 32–48 dB. Therefore, it was justified to develop a calculation model, which could be used to predict the annoyance penalty of any kind of spectrum.

3. Prediction model

The development of the prediction model is explained in detail in Ref. [7]. The work started with the inspection of all previously published models which have been used for the rating of BBSS sounds. First, we studied level-dependent descriptors: Unweighted sound level ($L_{Z,eq}$), A-weighted sound level (L_{Aeq}), Speech Interference Level (SIL), Noise Criterion (NC), Preferred Noise Criterion (PNC), Noise Rating (NR), Balanced Noise Criterion (BNC), Room Criterion (RC), Room Noise Criterion (RNC), Loudness level (LL), and Loudness level with Sharpness. Thereafter, we studied spectral shape descriptors: spectral centroid (SC), spectral spread (SS), sharpness (SH), level difference of low and high frequency bands (LAlohi), Nratio, Nlow, and Quality Assessment Index (QAI).

The functioning of these descriptors was investigated using correlation analysis. Since Ref. [6] found that the penalty was independent on L_{Aeq} within 32–48 dB, our main interest was towards spectral shape descriptors.

Sharpness and Spectral centroid were the best objective descriptors for predicting the annoyance penalty. However, the recommended descriptor for practical noise measurements is SC.

We defined a simplified SC which is not calculated from narrow-band SPL spectrum but from one-third octave spectrum by Eq. (1):

$$SC = \frac{\sum_{n=1}^{N} f_n \cdot L_n}{\sum_{n=1}^{N} L_n} \tag{1}$$

where f_n [Hz] is the middle frequency of one-third octave band n, and L_n [dB] is the unweighted SPL at the one-third octave band n. In our study, N=21, since the stimuli of Ref. [6] was limited to 100–10 000 Hz.

It should be noted that L_n is set to 0 dB that at such bands, where the SPL is either below the hearing threshold level, HTL [9], or below the threshold of irrelevance, T. It was defined to be T=15 dB in our study.

Annoyance penalty is calculated by Eq. (2):

$$k = 6.9 * log_{10}(SC) - 16.3 \tag{2}$$

The prediction accuracy of the model in Equations (1–2) was very good (R^2=0.79). The association between SC and annoyance penalty is illustrated in Figure 3.

An example of the calculation procedure is shown in Figure 4 for one of the BBSS sounds. The predicted penalty (8.3 dB) is very close to the subjective penalty of Table 1 (8.8 dB).

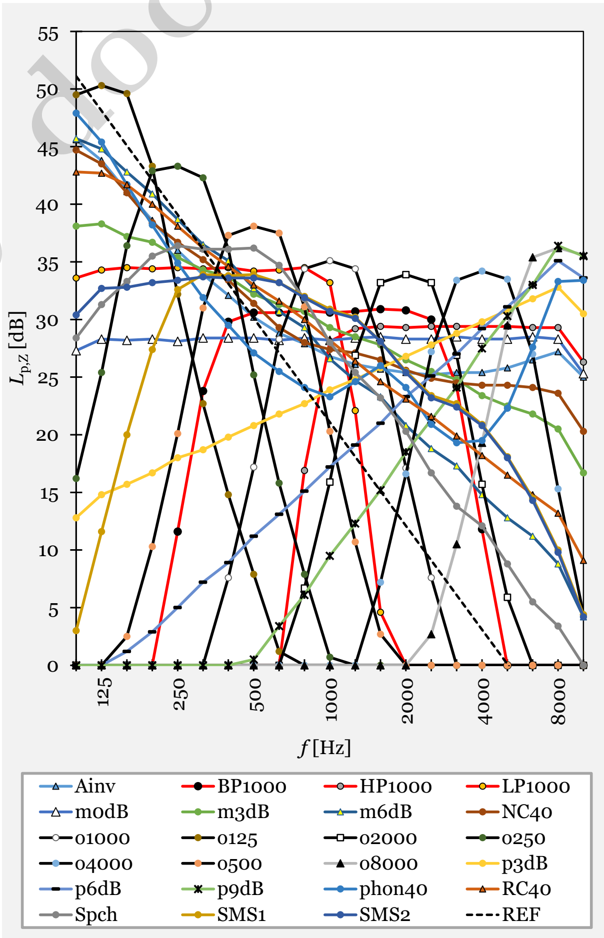

Figure 1. The spectra of the 23 BBSS sounds of Ref. [6] and the reference sound (REF). All levels are shown at 40 dB L_{Aeq}.

Table 1. The mean subjective penalties of the studied spectra of Figure 1. These values are the mean penalties of the sounds presented at three levels (32, 40, and 48 dB L_{Aeq}).

Sound	k [dB]	Sound	k [dB]
REF	0.0	o1000	4.4
Ainv	6.6	o2000	7.3
BP1000	7.1	o4000	7.1
HP1000	9.4	o8000	10.4
LP1000	2.3	p3dB	8.1
m0dB	5.9	p6dB	8.8
m3dB	5.3	p9dB	9.0
m6dB	2.8	phon40	6.8
NC40	6.2	RC40	3.2
o125	0.2	SMS1	3.4
o250	-0.7	SMS2	2.9
o500	3.9	Spch	2.0

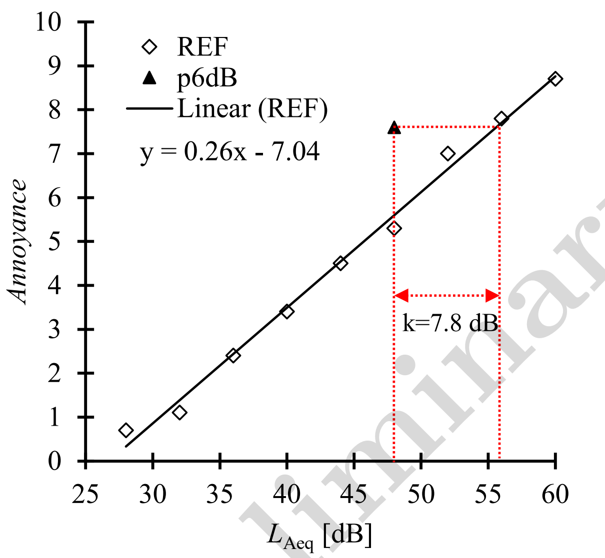

Figure 2. The penalty value for a specific stimulus was determined by projecting the annoyance of the stimulus to the linear fit of the mean annoyance of reference sounds. The example stimulus here is p6dB at 48 dB L_{Aeq}. The mean annoyance was 7.6. The same annoyance would be achieved by a reference sound played at 55.8 dB. The outcoming penalty is k=7.8 dB.

4. Discussion

The experimental work and the outcoming prediction model are unique because there are no previous studies which have investigated the annoyance penalty of BBSS sounds in similar depth.

Most noise measurements apply one-third octave band frequency analysis, our model can be easily applied in, e.g., the assessment of building service and environmental sounds indoors or outdoors, development of product sounds, and assessment of soundscapes.

Although the threshold of T=15 dB was justified by the analysis of Ref. [7], further research may be needed about the threshold where audible SPLs do not elicit annoyance responses.

The experiment of Kuusinen et al. [6] was limited within 100–10 000 Hz. It is still possible that the model may be applicable to a broader frequency range. However, the model should not be applied to tonal sounds.

The experimental work of Kuusinen et al. [6] was limited to sound level range 32–48 dB L_{Aeq}. Because the annoyance penalty did not depend on sound level within that range, it is probably safe to apply the model within 25–55 dB. However, uncertainties may appear beyond that range.

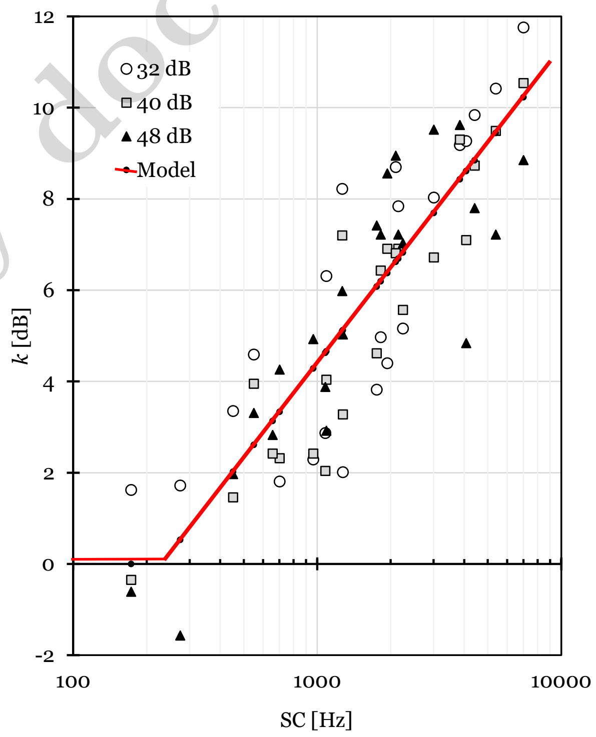

Figure 3. The association between spectral centroid measured for the stimuli, SC, and penalty, k. Symbols represent the subjective penalties obtained for the 69 stimuli of Kuusinen et al. [6] and line represents the penalty given by the prediction model of Equations (1–2).

f [Hz]	p6dB	HTL
100	3.9	26.5
125	7.1	22.1
160	9.2	17.9
200	10.9	14.4
250	13.0	11.4
315	15.2	8.4
400	16.9	5.8
500	19.2	3.8
630	21.1	2.1
800	23.1	1.0
1000	25.2	0.8
1250	27.1	1.9
1600	29.0	0.5
2000	31.3	-1.5
2500	33.1	-3.1
3150	35.0	-4.0
4000	37.2	-3.8
5000	39.1	-1.8
6300	41.0	2.5
8000	43.1	6.8
10000	41.6	9.8

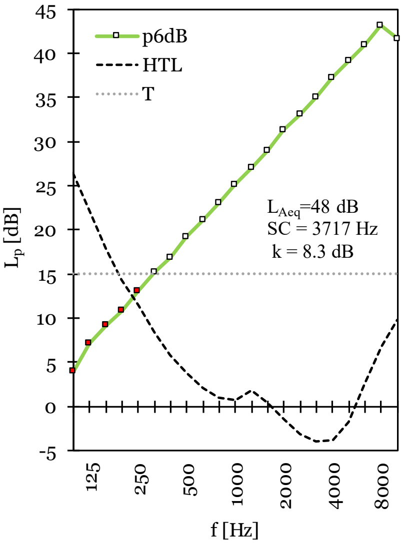

Figure 4. Example of the calculation process of spectral centroid and annoyance penalty for sound p6dB at L_{Aeq}=48 dB. HTL is the hearing threshold level according to ISO 389-7 [9].

5. Acknowledgements

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