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Tonal Annoyance vs. Tonal Loudness and Tonality

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ABSTRACT

Quantifying tonalities in technical sounds according to human perception is a task of growing importance. The psychoacoustic tonality method, published in the 15th edition of the ECMA-74 standard, is a new method based on a model of human hearing according to Sottek that can calculate the perceived tonality of a signal.
In the past, many listening experiments have been performed asking for the tonality of the presented sounds. The results showed that participants may evaluate tonal annoyance instead of tonal loudness; there is a distinction between these two perceptions. In general, tonal loudness is regarded as strongly correlated with tonality. It could be assumed that the tonal annoyance will increase at higher frequencies for equal-loudness tones, e. g., due to higher sharpness values.
New listening experiments were performed to compare the frequency-dependent differences between equal-tonal-loudness contours and equal-tonal-annoyance contours for different phon values. This article describes the results of the listening experiments and explains how the hearing model can be used to predict the experimental data. This is an essential step for the definition of targets with respect to tonality.

Keywords: Tonality, Loudness, Annoyance, Psychoacoustics
I-INCE Classification of Subject Number: 61

1. INTRODUCTION

Technical sounds containing tonal components are often perceived as rather annoying. For this reason, the quantification of tonal sounds has been an important challenge in the field of psychoacoustics for a long time [1, 2, 3], resulting in metrics such as the tone-to-noise ratio [4], the prominence ratio [5] or the German DIN standard for tonality [6]. Recently, the topic of tonality has received increasing attention due to the tonal character of sounds in electric vehicles. A new method for the quantification of tonal sounds, the

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psychoacoustic tonality, has recently be standardized in the 15th edition of the ECMA-74 standard [7]. In contrast to other existing metrics, this method is completely based on psychoacoustics because it is based on a model of human hearing [8]. Therefore, it is able to model the human perception of tonality closely [9]. This method, just as other existing metrics, only deals with the perception of tonality but not with the question how annoying tonal sounds are perceived. The annoyance of the tonal sound is surely one of the most important questions for manufacturers of electric vehicles or other products emitting tonal sounds. However, the topic of tonal annoyance is yet rather unexplored. Tonal annoyance was recently studied in the context of automotive electric vehicles [10].

As a first step in basic research about tonal annoyance, it is important to know, how tonal annoyance is related to the loudness of tonal sounds. This paper aims on finding first answers to this question. Listening experiments were conducted with the aim of measuring the 50 phon equal-tonal-loudness contour and the corresponding equal-tonal-annoyance contour. These contours can be compared to investigate relationships between the two. The listening experiments were conducted using an adaptive two-alternative forced-choice (2AFC) method [11]. In another listening experiment, the 50 phon and 70 phon equal-loudness and equal-annoyance contours were measured with an adjustment procedure: participants adjusted the sound pressure level of tones of various frequencies using a slider in order to match the perception of a 1 kHz tone.

The results show that tonal annoyance is mainly influenced by the perceived loudness of the tone for frequencies below 1 kHz. For higher frequencies, the annoyance increases with increasing frequency.

The analysis of the results of the listening experiments include a study of the ECMA-74 tonality metric which shows, that the results fit very well to the perception of equal loudness with a minor modification of the metric for lower frequencies. It is also shown how the tonality metric could further be modified to model the perception of tonal annoyance.

In Section 2, the listening experiments are described. The results are presented in Section 3. Subsequently, the comparison with the ECMA-74 standard is presented in Section 4 and finally conclusions are drawn in Section 5.

2. LISTENING EXPERIMENTS

The listening experiments were conducted to evaluate the loudness perception of tones of different frequencies and the annoyance of the same tones. First experiments were conducted using the 2AFC method. Further experiments were performed using a method of adjustment. Twenty participants (four females and sixteen males) took part in the listening experiments. An audiometry was conducted to confirm normal hearing with less than 20 dB hearing loss at any tested frequency. The age of the participants ranged between 23 and 40 years. Eight out of the 20 participants were students and the rest were experienced in taking part in listening experiments. In the following, the listening experiments are described in detail.

To ensure calibrated playback, the sounds were presented diotically via a digital equalizer (HEAD acoustics LabP2 frontend), ArtemiS Suite software and Sennheiser HD 650 headphones in a sound-attenuated listening studio. To reproduce the scenario of a listener in free field conditions, the playback was equalized using the HRTF of an artificial head (HMS IV) for frontal incidence in the horizontal plane and the inverted transfer function of the HD 650 headphones measured with the in-ear microphones of the HMS IV wearing the headphones. With this equalization, it was ensured that a defined sound pressure level was present at the ear canal entrance.

2.1 Adaptive two-alternative forced-choice experiments

The 2AFC method was used for the first experiment. The stimuli were pure sine tones of different frequencies. Two sounds were played to each participant. One sound was a fixed reference tone with a frequency of 1000 Hz and a sound pressure level of 50 dB and the other was the test signal. The order of test and reference sound was randomly changed. The test sounds had different frequencies between 80 Hz and 8000 Hz. In total, 17 different test sounds were used. The complete session consisted of four experiments. The first experiment covered five frequencies; the remaining experiments covered four frequencies each, thereby completing 17 frequencies. The order of the test signals was chosen randomly from the 17 signals.

For the tonal loudness experiment, the participant were asked to indicate which sound was perceived louder to her or him. For the experiment evaluating tonal annoyance the participant was respectively asked to indicate which sound was perceived more annoying. The sound pressure level of the reference signal was unchanged. The sound pressure level of the test signal was increased or decreased based on the participant's response. If the test signal was perceived as louder (resp. more annoying), then its sound pressure level was reduced in the next iteration, and increased if it was perceived as less loud (resp. less annoying). A reversal in the direction of change of the test signal is known as a 'turnaround'. Each test signal was played until eight turnarounds were completed. However, the test signals were played interleaved in each iteration in order to reduce bias effects. Step sizes used were 8 dB (for the first two turnarounds), 4 dB (for the next two turnarounds), and 2 dB (for the last four turnarounds). The mean dB SPL value of the last four turnarounds was considered as the result. The starting levels of the signals were randomized, based on average levels of established equal loudness contours with a random offset in the range of ±20 dB for the loudness experiment and in the range of ±10 dB for the annoyance experiment. During the experiment, the sound pressure level of the test signal was not allowed to exceed ±20 dB of this average value for the loudness experiment and ±50 dB for the annoyance experiment. Each session took between 30 to 45 minutes depending on how many interactions a participant needed.

2.2 Adjustment experiments

The method of adjustment was used for this experiment. The stimuli were pure sine tones of different frequencies. Two sounds were played to each participant. One sound was a fixed reference tone with a frequency of 1000 Hz and a sound pressure level of 50 dB in a first experiment and 70 dB in a second one. The other was the test signal. The test sounds had different frequencies between 80 Hz and 8000 Hz. In total, 21 different test sounds were used. The order of the test signals was chosen randomly from the 21 signals.

For the loudness experiment, the participant was asked to adjust the sound pressure level of the test sound using a slider such that the test sound was perceived as equally loud as the reference signal. The starting sound pressure levels of the signals were randomized, based on average sound pressure levels of established equal loudness contours with a random offset in the range of ±10 dB. The range of the slider was also based on average sound pressure levels of established equal loudness contours. During the experiment, the sound pressure level of the test signal was not allowed to exceed ±40 dB of this average value for the loudness experiment and ±50 dB for the annoyance experiment.

3. RESULTS OF LISTENING EXPERIMENTS

3.1 Results of 2AFC method

In a first step, the results of the 2AFC listening experiment rating the equal loudness are analyzed. The average sound pressure levels that were rated as equally loud are shown in Figure 1 together with the 95% confidence intervals. Additionally, the 50 phon equal loudness contours as defined in ISO 226:2003 and ISO 226:1987 are given.

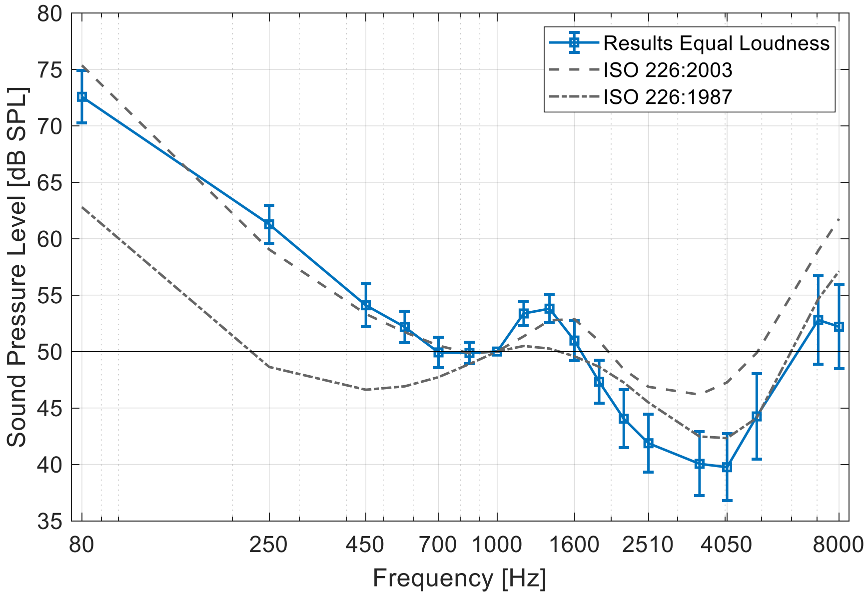

Fig. 1 – Results for the equal loudness 2AFC experiment

For frequencies below 1 kHz, the results fit very well to the equal loudness contour of ISO 226:2003. For higher frequencies, the uncertainty of the data gets higher and the results rather follow the equal loudness contour of ISO 226:1987 for frequencies above 2 kHz.

In Figure 2, the average sound pressure levels that were rated as equally annoying together with the 95% confidence intervals are added for comparison.

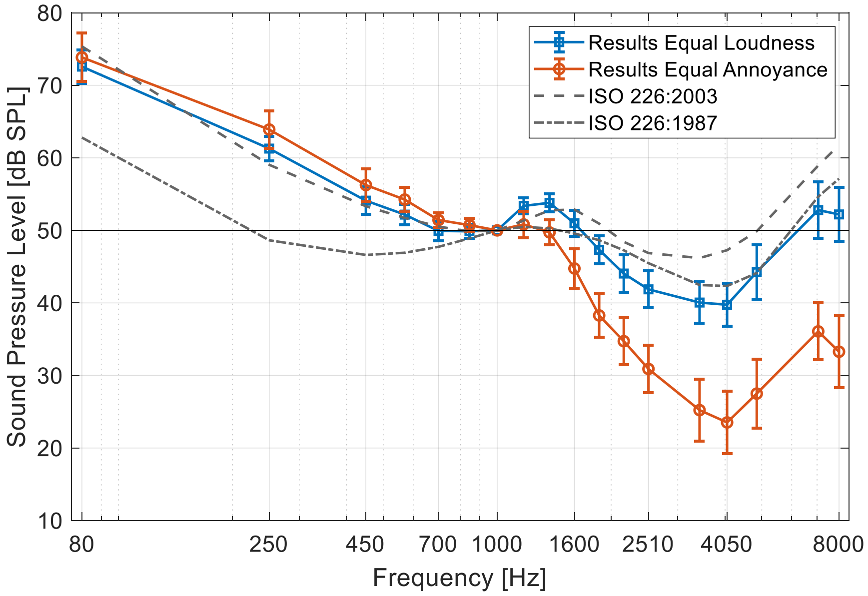

Fig. 2 – Results for the equal loudness and the equal annoyance 2AFC experiment

It can be observed, that this curve is very close to the values of equal loudness for frequencies below 1 kHz. Thus, it can be assumed that tonal annoyance is mainly influenced by the tonal loudness in this frequency range. For higher frequencies, however, the sound pressure levels for equal annoyance decrease compared to equal loudness, indicating that the annoyance of high frequent sounds is not only influenced by the loudness of the tone, but also by the frequency due to, e. g., higher sharpness of the tones with increasing frequency. For better interpretation, the difference between the average sound pressure levels of the equal loudness and the equal annoyance curve is shown in Figure 3.

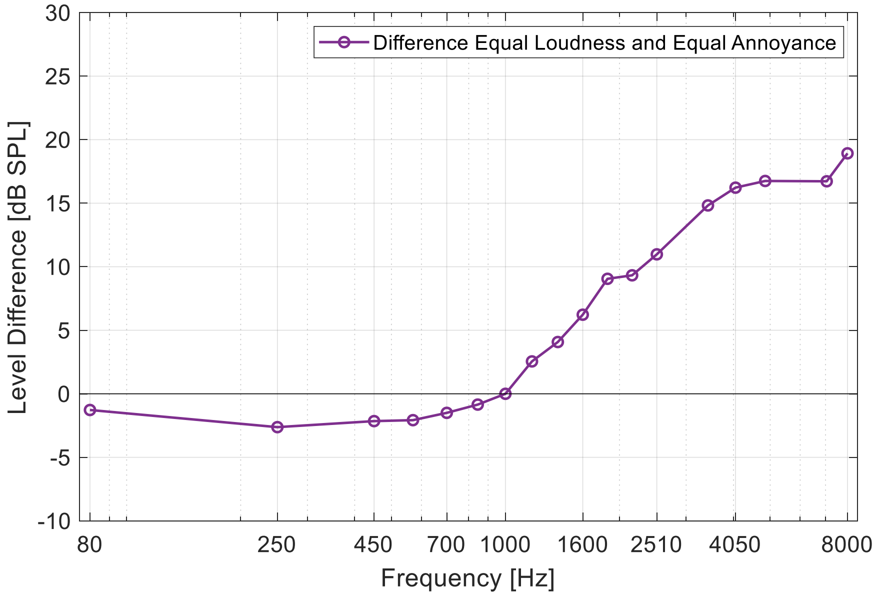

Fig. 3 – Difference between sound pressure *levels of equal loudness and equal annoyance of the 2AFC experiment*

The difference is close to zero up to 1 kHz. Starting from this frequency, the difference increases approximately logarithmically with frequency, leading to a linear increase in the plot using a logarithmic frequency axis.

3.2 Results of adjustment method

In the following, the results of the adjustment experiment are analyzed. The average sound pressure levels that were adjusted as equally loud or equally annoying as the 50 dB reference sound are shown in Figure 4 together with the 95% confidence intervals. Additionally, the 50 phon equal loudness contours as defined in ISO 226:2003 and ISO 226:1987 are given.

The results for the loudness are very similar to the results of the 2AFC experiment. For frequencies below 1 kHz, the results of the equal annoyance are also similar to the 2AFC experiment.

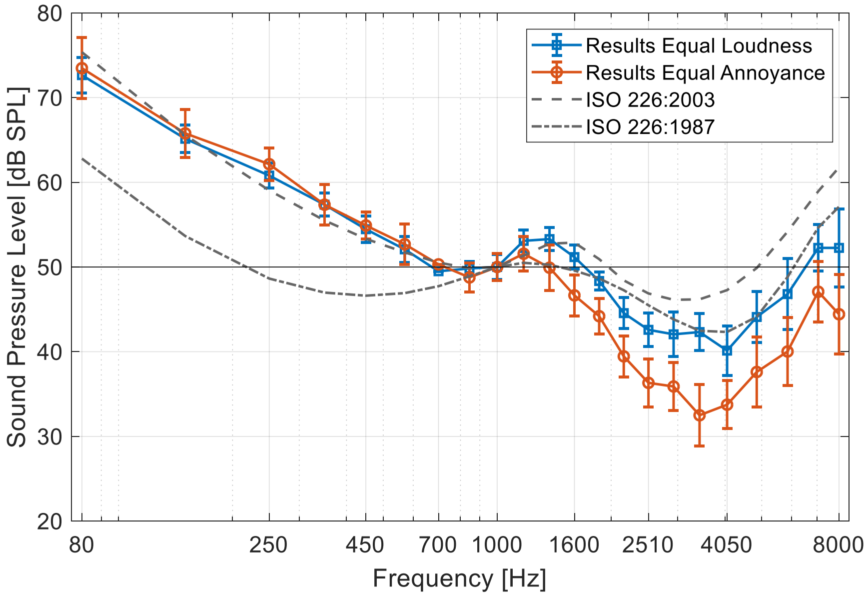

Fig. 4 – Results for the equal loudness and the equal annoyance adjustment experiment for 50 phon

For higher frequencies, the sound pressure levels for equal annoyance decrease compared to equal loudness just as in the 2AFC experiment. However, the difference is smaller in the adjustment experiment. The result confirms the assumption that the annoyance of high frequent sounds is not only influenced by the loudness of the tone, but also by the frequency.

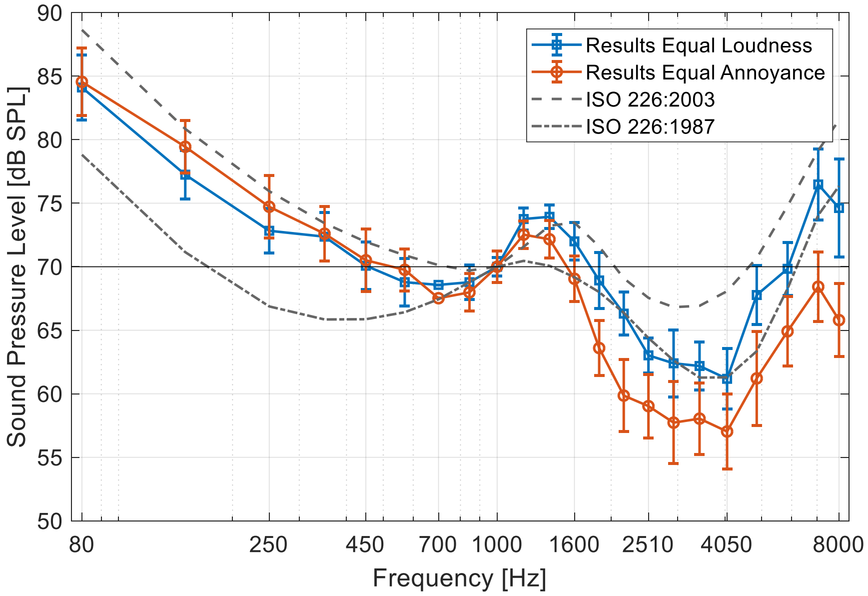

Fig. 5 – Results for equal loudness and equal annoyance adjustment experiment for 70 phon

Figure 5 shows the results of the 70 phon adjustment experiment. The results are similar to the results for 50 phon: For tones with a frequency less than 1 kHz, the equal loudness and equal annoyance curve are close together, both following the 70 phon equal loudness of ISO 226:2003 closely. For higher frequencies, the equal loudness rather follows the 70 phon contour of ISO 226:1987.

The sound pressure levels for equal annoyance decrease compared to equal loudness. For better interpretation, the difference between the average sound pressure levels of the equal loudness and equal annoyance curves of 50 phon and 70 phon is shown in Figure 6.

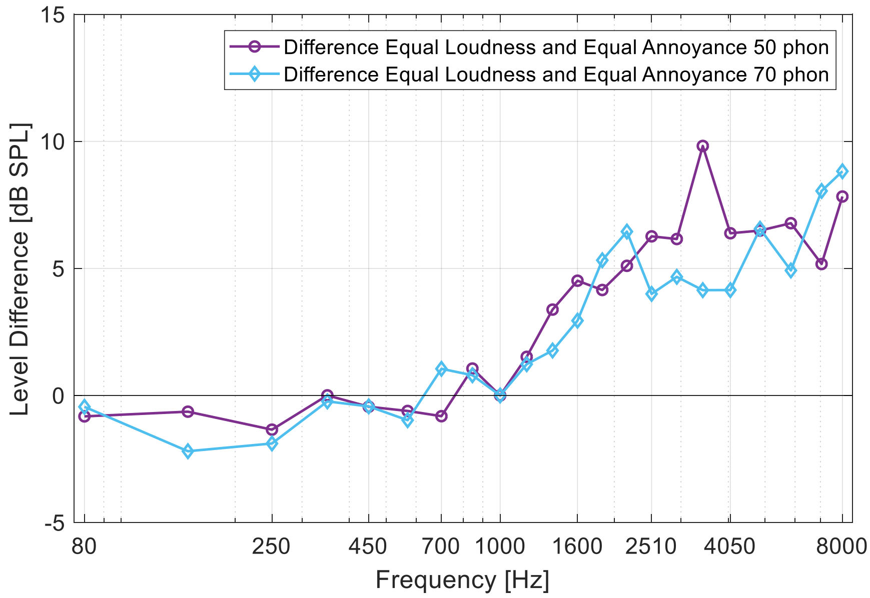

Fig. 6 – Difference between sound pressure *levels of equal loudness and equal annoyance (adjustment experiment)*

The difference is close to zero up to 1 kHz. Starting from this frequency, the difference increases. The increase is smaller compared to the results of the 2AFC experiment. It is interesting to notice that the increase is very similar for 50 phon and 70 phon. This indicates that there is no large dependency of the sound pressure level for the difference between equal loudness and equal annoyance for the investigated loudness levels.

4. COMPARISON TO TONALITY METRIC

In the following, it is analyzed how well the results of the listening experiment are modelled by the psychoacoustic tonality metric which was standardized in the 15^{th} edition of the ECMA-74 standard. It is also investigated, how the metric can be modified to describe tonal annoyance. For this investigation, only the results of the 2AFC experiments were considered as an example.

First, sinusoidal sounds with the sound pressure levels that were rated as equally loud, respectively equally annoying, were generated. For these sounds, the tonality according to ECMA-74 was calculated. For pure sinusoids, this method is supposed to result in equal tonality for sounds of equal tonal loudness. Thus, it can be expected that the generated sounds with the sound pressure levels of equal loudness result in rather similar tonality values. The tonality values calculated according to the 15^{th} edition of the ECMA-74 standard are shown in Figure 7 (green line, square markers).

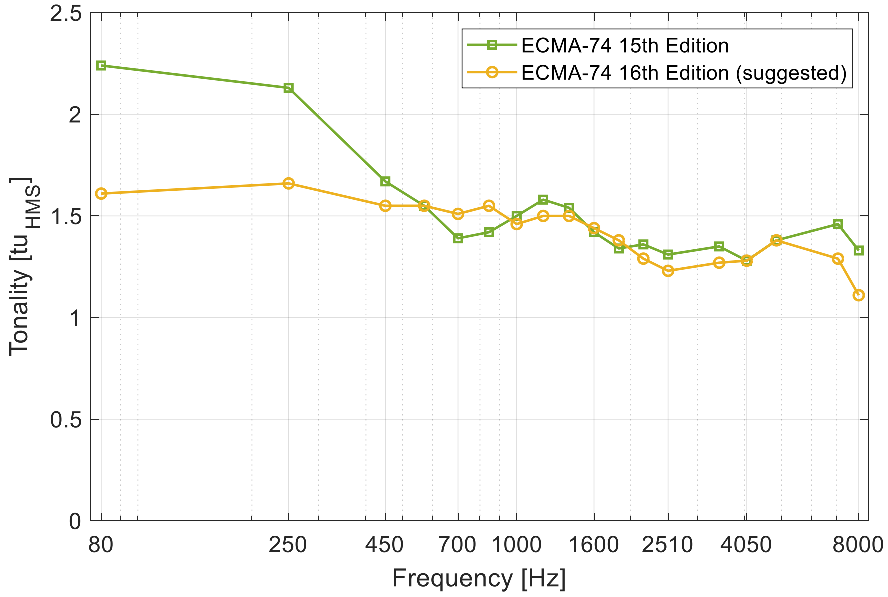

Fig. 7 – Results of the ECMA-74 psychoacoustic tonality for sounds with sound pressure level corresponding to equal loudness

For frequencies above 570 Hz, the results are indeed very similar. For lower frequencies, the tonality is clearly higher than expected. This is a known issue of the psychoacoustic tonality method. In this method, a filter was defined in order to model the equal loudness contours of ISO 226:1987 for frequencies below 1 kHz. Since these contours underestimate the sound pressure levels of equal loudness for low frequencies (see Figure 1), the loudness is overestimated in the process of tonality calculation. Since this is a known issue, work has been carried out to improve the ECMA-74 standard. A new filter was modeled, using the equal loudness contours of ISO 226:2003 as reference. This modification of the method is suggested for the 16^{th} edition of the ECMA-74 standard. The tonality values calculated with this method are also shown in Figure 7 (yellow line, circle markers). With this modification, the psychoacoustic tonality values are almost constant for all investigated frequencies. This result shows, that this method is capable of modeling the equal loudness and the equal tonality very well.

The tonality values were also calculated with both methods (ECMA-74 15^{th} edition and ECMA-74 suggested 16^{th} edition) for the signals generated with sound pressure levels according to the equal annoyance. The results are shown in Figure 8.

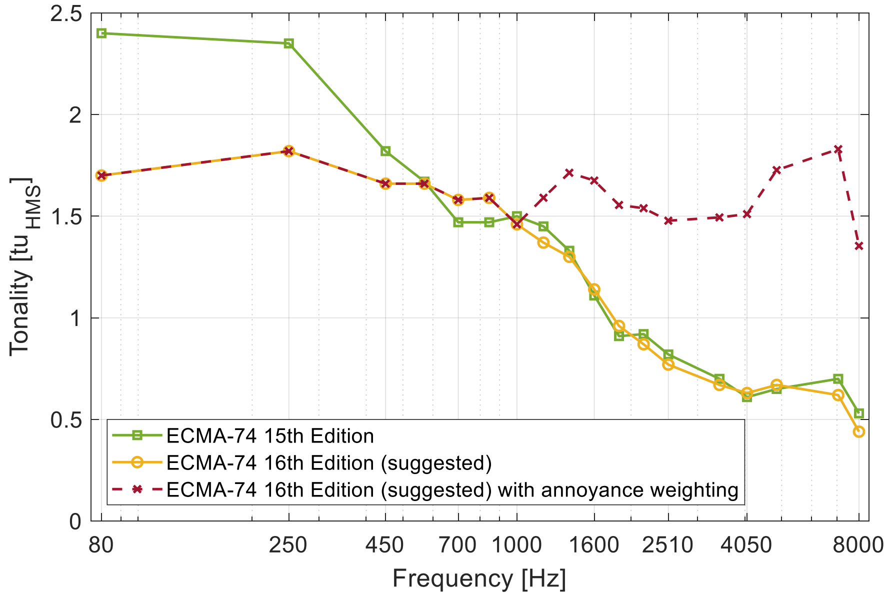

Fig. 8 – Results of the ECMA-74 psychoacoustic tonality for sounds with sound pressure level corresponding to equal annoyance

The tonality values for higher frequencies are much lower than for the sounds of equal loudness. This was to be expected because the sound pressure levels for equal annoyance are much lower in this frequency range than the sound pressure levels for equal loudness. For frequencies below 1 kHz, however, the tonality values are almost constant for the sounds with sound pressure levels corresponding to equal annoyance. The results show that the tonality metric could be used to model tonal annoyance for frequencies below 1 kHz. For higher frequencies, tonality is not sufficient to describe tonal annoyance. However, the tonality metric could be used as a basis for a metric describing tonal annoyance by using a weighting function for higher frequencies. A simple logarithmical weighting function was defined as

$$w(f) \quad = \quad \begin{cases} 1, & f < 1\,\text{kHz} \\ 2.3 \cdot \log_{10}(f) - 5.9, & f \geq 1\,\text{kHz}' \end{cases} \qquad (1)$$

and applied to the results of the tonality calculation. The result is also shown in Figure 8 (dashed line). With this rather simple weighting function, the results already lead to a reasonable metric for the tonal annoyance for the given sound pressure levels for frequencies up to 8 kHz.

5. CONCLUSIONS & OUTLOOK

In this paper, the results of listening experiments evaluating the perception of equal loudness and equal annoyance of tonal sounds was presented. The experiments were conducted using the 2AFC method and a method of adjustment using a slider. The results show that the perception of annoyance of tonal sounds is closely related to the perception of loudness for frequencies below 1 kHz. For higher frequencies, annoyance increases, leading to lower sound pressure levels for the equal annoyance contours as compared to the equal loudness contours.

It was also evaluated, how well the results can be modeled by the ECMA-74 psychoacoustic tonality. The results show that this metric provides good results regarding the perception of equal loudness with a modification for low frequencies as suggested for the 16th edition of the ECMA-74 standard. The metric can also be modified by a simple weighting function for frequencies above 1 kHz to model the perception of equal tonal annoyance for the tested sound pressure levels.

This study can only be interpreted as a first step in basic research of tonal annoyance. In a next step, the study needs to be extended to equal-loudness contours of more phon values and the corresponding equal-annoyance contours.

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