Application of Psychoacoustic Tonality for Product Sound Development

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Abstract

The perception of tonal sounds is one of the most important psychoacoustic sensations for product sound quality. In the past, a lot of work has been carried out to automatically quantify tonal sound events. The Psychoacoustic Tonality is a method for the quantification of tonal sounds, which is based on a hearing model that emulates the processing of human hearing. It is standardized in the ECMA-74 standard (since June 2018) [1].
In this paper, the results of the Psychoacoustic Tonality are validated by comparison with the results of listening tests for different signal types. The application of the Psychoacoustic Tonality according to the ECMA-74 standard is described. For several examples, it is shown how the Psychoacoustic Tonality can be used for NVH sound engineering and how the results can be interpreted.

Introduction

Technical and natural sounds frequently contain prominent tonal components. These sounds are often either produced by periodicity, for example by a rotating device, or by narrowband noises that can for example be generated by air flow.
Tonal components are perceived very prominently by a human listener and thus influence the individual perception and evaluation of a sound event. Tonal sounds significantly increase annoyance, if they are perceived as unwanted. Hence, the quantification of tonal sounds has been an important topic for a long time. The topic currently gains even more attention due to the increasing importance of electric vehicles. While these vehicles produce less overall noise, electric motors do produce a rather tonal sound.
Several attempts have been made in the past for the automatic quantification of tonalities. Methods like the Prominence Ratio (PR) [2] or the Tone-to-Noise Ratio (TNR) [3] have already been in use for some time, but they often lead to unsatisfactory results because they do not consider human perception. As a consequence, both methods produce implausible results in certain scenarios. For example, the same signals with different sound pressure levels lead to the same result when using these methods even though the perception of tonality has a level-dependence.
Research results show a strong correlation between tonality perception and the partial loudness of tonal sound components [4]-[6]. The Psychoacoustic Tonality, which has been published in the 15th edition of the ECMA-74 standard [1] is a method which uses this relationship. This method is based on a psychoacoustic hearing model that calculates the perceived tonal loudness as a basis for the tonality estimation. Thus, it takes into account several psychoacoustic effects that are not considered in PR and TNR. The applicability of the model was investigated for technical sounds and compared to established methods [7, 8].
The main goal of this paper is to give an overview of how this method can be applied to product sound development. This includes a closer look at the application according to ECMA-74 and some real world application examples. Additionally, the method is validated by comparing it to the results of listening tests.

Psychoacoustic Tonality

In the following, the processing steps of the Psychoacoustic Tonality as published in the ECMA-74 standard are roughly explained. Detailed information can be found in [1] or [9]. Figure 1 illustrates the basic steps of the Psychoacoustic Tonality calculation.

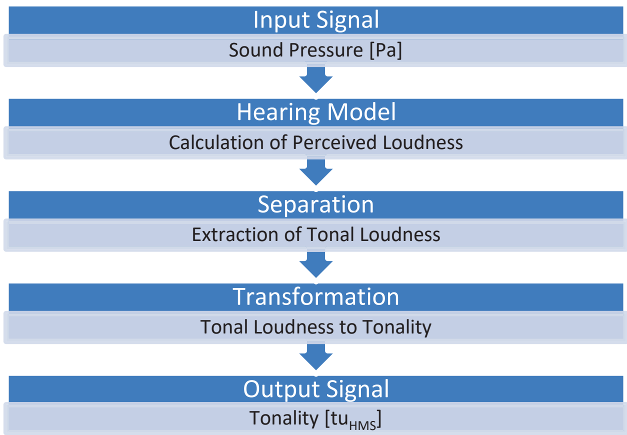

Figure 1. Processing steps of the Psychoacoustic Tonality algorithm

The Psychoacoustic Tonality algorithm processes sound pressure signals as input. This sound pressure signal is transformed into perceived specific loudness by the hearing model. The hearing model includes outer and middle ear filtering, an auditory filter bank modelling the critical bands of human hearing, consideration of the nonlinear relationship between sound pressure and perceived loudness, and consideration of the hearing threshold.
In the next step, the overall loudness which was estimated by the hearing model is separated into loudness produced by tonal components (tonal loudness) and loudness produced by non-tonal components. The tonal loudness is used as basis for the calculation of tonality. In this processing step, the frequency of the tonal components is additionally estimated.
Tonality is estimated from the tonal loudness by additionally considering the ratio of tonal and non-tonal loudness. The result is an estimation of the specific tonality over time. This result is used as basis to calculate the time-independent specific tonality $T'(z)$ (where z describes the critical band rate scale), a time-dependent tonality $T(l)$ (where l is the time index) and a single value T for the tonality.
The unit of the Psychoacoustic Tonality is tu_{HMS} (tonality unit according to the hearing model of Sottek) which is a linear measure of the perceived tonality. This unit is defined such that a reference signal (pure sinusoid with a frequency of 1000 Hz at 40 dB SPL) results in a tonality of 1 tu_{HMS}.

Validation of ECMA-74

The Psychoacoustic Tonality is evaluated by comparison with listening test results. As a reference, Prominence Ratio (PR) is also added to the comparison.

For the listening tests, mixtures of a sinusoidal tone of frequency 1000 Hz with different levels and pink noise with different levels were used. Thus, the effect of different signal-to-noise-ratios can be evaluated for different levels. Five different tests were performed. In all five tests, the level of the pink noise was varied from 40 dB SPL to 80 dB SPL with a step size of 5 dB SPL. The tests differed in the level of the sinusoidal tone, which was chosen from 55 dB SPL to 75 dB SPL with a step size of 5 dB SPL.

The tests were performed with 16 test subjects. The test subjects were asked to rate the tonality of each sound on a 13-point categorical scale (ranging from "0 - not tonal" to "12 - extremely tonal"). To compare the results of the listening tests with the results of the psychoacoustic model, a linear scaling factor was used for the results of the listening tests. Another scaling factor was used to map the results of the listening tests to the results of the PR. The scaling factors were derived by minimizing the root-mean-square error between the mean ratings of all participants and the calculated Psychoacoustic Tonality (or the PR, respectively) of all five experiments.

In Figure 2, the results for sinusoidal tones with a level of 65 dB and 75 dB are shown. The results illustrate one problem of the PR: it decreases linearly for decreasing SNR. The tonality perception however does not decrease linearly according to the experimental results. The results of the psychoacoustic hearing model fit much better to the perceived tonality.

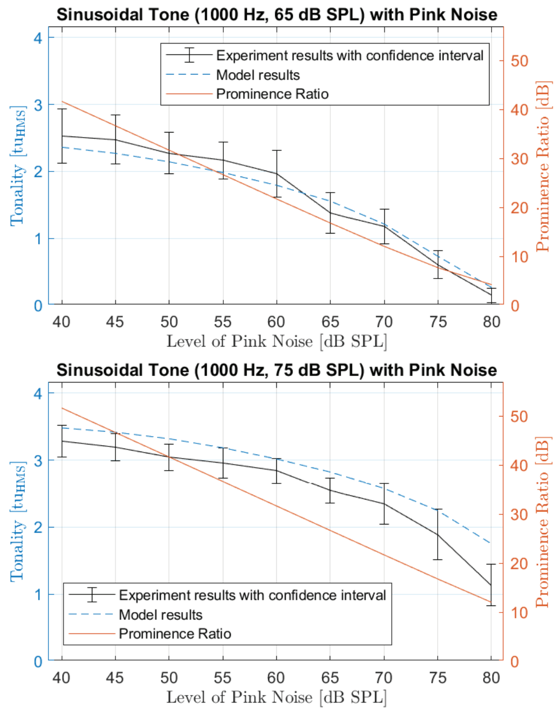

Figure 2. Psychoacoustic Tonality and Prominence Ratio compared to results of listening tests

In a second listening experiment, the frequency dependency was evaluated. The listening experiment was conducted to evaluate the loudness perception of tones of different frequencies. The two alternative forced choice (2AFC) method was used for this test. Twenty (Sixteen male and four female) participants took part in the listening test. An audiometry was conducted to confirm absence of hearing impairments. The age of the participants ranged between 23 and 40 years. Eight out of the 20 participants were students and 12 were experienced listeners.

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 test sounds had different frequencies between 80 Hz and 8000 Hz. In total, 17 different test sounds were used. The order of the test signals was chosen randomly from the 17 signals. The results are shown in Figure 3.

To evaluate the Psychoacoustic Tonality method, the sounds, which were (on average) rated as having equal tonal loudness, were analyzed with the Psychoacoustic Tonality. For pure sinusoids, tonality is equal to tonal loudness according to this method. Thus, a rather constant tonality should be estimated for those sounds. The results of the version first presented in the ECMA-74 15th Edition and the version according to ECMA-74 17th Edition are shown in Figure 4. The results show that the tonality is overestimated for lower frequencies for ECMA-74 15th Edition. The changes in the 17th Edition aimed for this problem [10]. Thus, the results for the 17th Edition are improved. The calculated tonality is rather constant for the sounds of perceived equal tonal loudness.

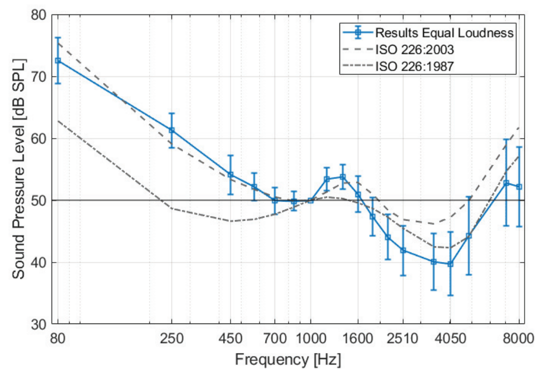

Figure 3. Results of equal tonal loudness listening test

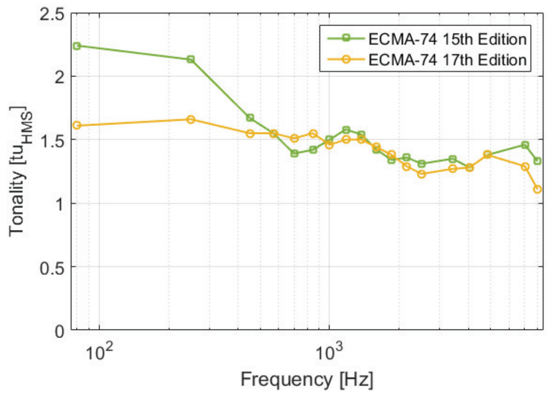

Figure 4. Tonality for sounds of equal tonal loudness calculated with the Psychoacoustic Tonality according to ECMA-74 15th Edition and 17th Edition

Application According to ECMA-74

The ECMA-74 standard defines two different application scenarios: stationary and non-stationary sounds.

For stationary sounds, the specific tonality $T'(z)$ is calculated by averaging over time. This result contains tonality values for 53 overlapping critical bands centered at the critical band rate scale $z = 0.5, 1.0, 1{,}5, \ldots, 26.5$ in the range of human hearing up to 20 kHz. The ECMA-74 standard defines a reportability threshold of 0.4 tu_{HMS}. If this threshold is exceeded for any critical band around z, the tonal component is identified as prominent. For each critical band centered at z exceeding the threshold, the following information shall be recorded according to ECMA-74:

- if a frequency range was defined, the frequency range for searching prominent tonalities,
- the frequency, in hertz, of the tonality in the corresponding critical band,
- details of the method used to evaluate the tonality (Psychoacoustic Tonality calculation method), together with a reference to the ECMA-74 standard,
- the Psychoacoustic Tonality value $T'(z)$.

Figure 5 shows an example. The figure shows the specific tonality of an electric motor. The red line indicates the reportability threshold of 0.4 tu_{HMS} which is exceeded by four peaks which are displayed in the legend with the corresponding tonalities and frequencies that have to be reported.

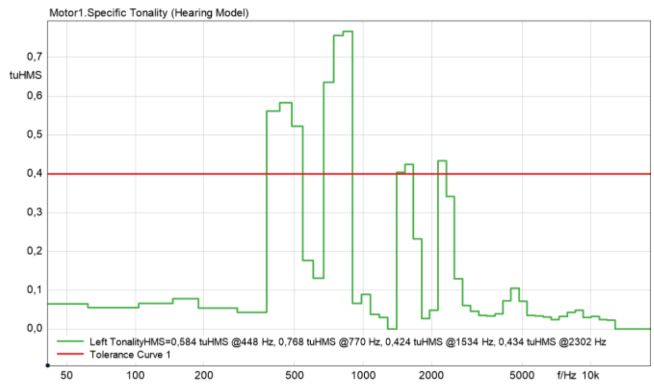

Figure 5. Psychoacoustic Tonality of an electric motor with peaks exceeding the reportability threshold of 0.4 tu_{HMS}

For non-stationary sounds, the time dependent tonality $T(l)$ is calculated by taking the maximum over all critical bands. Additionally, a single value T is calculated by averaging $T(l)$ over time (using only values $T(l) > 0.02$ tu_{HMS}). If the single value T exceeds a value of 0.4 tu_{HMS}, the non-stationary sound is considered to contain prominent tonalities. In this case, the following information shall be recorded according to ECMA-74:

- if a frequency range was defined, the frequency range for searching prominent tonalities,
- the time-dependent frequency, in hertz, of the time-dependent tonality,
- details of the method used to evaluate the tonality (Psychoacoustic Tonality calculation method), together with a reference to the ECMA-74 standard,
- the time-dependent Psychoacoustic Tonality value $T(l)$,
- the time-independent single value T.

Application Examples

In this section, three application examples are described. The first example is a printer with two repeating tonal components: One high frequency component around 2000 Hz and one low-frequency component around 80 Hz. In the upper part of Figure 6, the A-weighted FFT of this signal is shown. The high-frequency component (green circle) can barely be seen. The low-frequency component (blue circle) can be detected more easily. However, it is not possible to estimate which of the two components is perceived as more tonal.

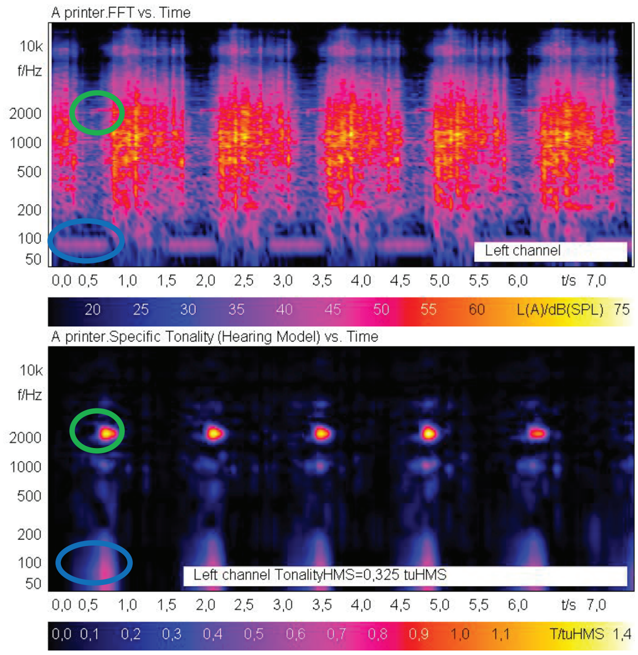

Figure 6. Printer analysis. Top: FFT (A-weighted) vs. Time, Bottom: Specific Tonality vs. Time

In the lower part of Figure 6, the Psychoacoustic Tonality of the signal is shown. The tonal components are extracted very well. It can also easily be seen that the high-frequency component produces a higher tonality than the low-frequency one.

Figure 7 shows another application example. Two electric motors are compared, where motor B produces a more annoying sound than motor A. The FFT (upper part) does not show a significant difference between the two motors. The average levels are also very similar at around 55 dB(A) SPL.

The tonality analysis (lower part) shows that there is in fact a difference between the two motors: motor B has a significantly higher tonality than motor A. This explains the higher annoyance of motor B since tonal sounds are usually perceived as more annoying than non-tonal sounds.

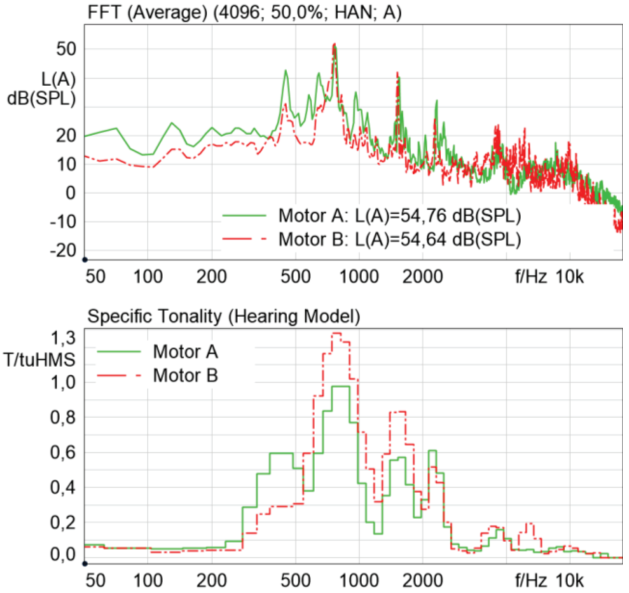

Figure 7. Electric motor analysis. Top: FFT (A-weighted), Bottom: Specific Tonality

Figure 8 shows the analysis of a car engine starter. This is a non-stationary sound containing a tonal component with decreasing frequency. The upper part of the figure shows the specific tonality vs. time. The color map of the plot was set such that all tonality values smaller than 0.4 tu_{HMS} are shown in black. Thus, the plot directly shows all regions were the reportability threshold of 0.4 tu_{HMS} as defined in ECMA-74 is exceeded. This is only possible because the threshold is constant for all frequencies. For the other tonality measures TNR and PR, ECMA-74 defines thresholds that are frequency-dependent. Thus, it is not possible to visualize all regions were the threshold is exceeded in such an easy way as shown in the upper part of Figure 8 for the Psychoacoustic Tonality. The figure shows that the signal contains two tonal components with prominent tonality: The main tonal component ranges from a time range between 0.5 s to 0.8 s at a frequency of around 2 kHz. The second component has a lower tonality and is located at a time of around 1 s and a frequency of around 200 Hz. In the plot, it is also shown that the single value of the signal is 0.541 tu_{HMS}. Thus, the sound is considered to contain prominent tonalities according to ECMA-74, since the single value exceeds the threshold.

In the middle part of Figure 8, the Tonality vs. Time is plotted, where it can also be seen at which times the threshold of 0.4 tu_{HMS} is exceeded. This plot shows the time-dependent Psychoacoustic Tonality value $T(l)$ that needs to be reported for non-stationary sounds according to ECMA-74.

In the lower part of Figure 8, the Tonality Frequency vs. Time is shown, which needs to be reported for non-stationary sounds according to ECMA-74: a very helpful analysis to investigate the exact frequency characteristics of the tonal components. In the plot, only frequencies at times when the time-dependent tonality exceeds the threshold are considered. This analysis shows that the main tonal component starts at a frequency of 2602 Hz at a time of 0.464 s and then decreases to a frequency of 2039 Hz at a time of 0.843 s. The second tonal component starts at a time of 0.96 s and has a frequency of 228 Hz.

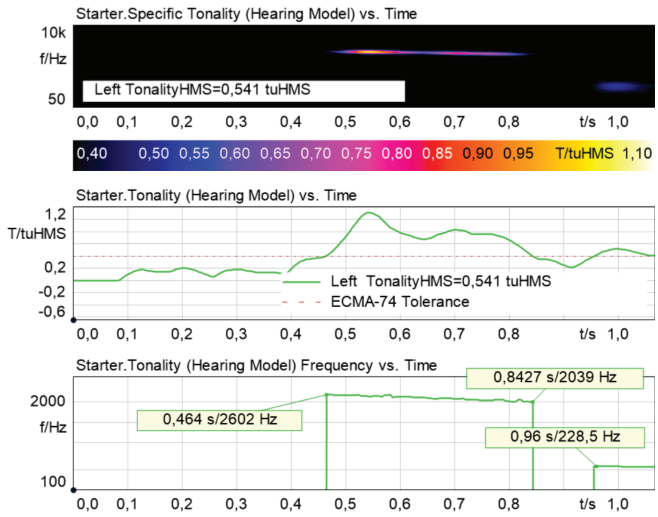

Figure 8. Analysis of a car engine starter. Top: Specific Tonality vs. Time, Middle: Tonality vs. Time, Bottom: Tonality Frequency vs. time

Conclusion and Outlook

This paper has taken a closer look at the ECMA-74 Psychoacoustic Tonality method. The algorithm was briefly explained, and the method was validated by comparison with the results of listening tests. It was described how the method should be applied according to the ECMA-74 standard. Finally, three real world application examples were shown to illustrate how the method can be applied for product sound development.

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