

Application of a New Perceptually-Accurate Tonality Assessment Method

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ABSTRACT

For many years in vehicle and other product noise assessments, tonality measurement procedures such as the Tone-to-Noise Ratio, Prominence Ratio and DIN 45681 Tonality have been available to quantify the audibility of prominent tones. Especially through the recent past as product sound pressure levels have become lower, disagreements between perceptions and measurements have increased across a wide range of product categories including automotive, Information Technology and residential products. One factor is that tonality perceptions are caused by spectrally-elevated noise bands of various widths and slopes as well as by pure tones, and usually escape measure in extant tools. Near-superpositions of discrete tones and elevated narrow noise bands are increasingly found in low-level technical sounds. Existing pure-tone methodologies tend to misrecognize an elevated noise band as general masking lowering the audibility of a tone in the measured vicinity, whereas perceptually they add. To address such issues a new psychoacoustically-based tonality model is presented which evaluates the nonlinear and time-dependent loudness of both tonal and broadband components, separating them via the autocorrelation function (ACF) and giving their spectral relationships. Based on a hearing model of Sottek, the model has been validated by many listening tests. Its background and current state are presented, with particular attention to automotive situations such as perceptions inside electric and hybrid vehicles in stationary or low-speed operation, and IC sound design criteria balancing desired order tonalities and order-caused roughness.

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INTRODUCTION

There are four available tools for assessing audible tonality. The main three in their standardized implementations and use require reference to pure tones, according to which they calculate audibility above masking or above silence. The tools are:

1. **Tone-to-Noise Ratio (TNR):** ECMA-74 [1]; Information Technology main use)
2. **Prominence Ratio (PR):** ECMA-74 [1]; Information Technology main use)
3. **DIN 45681 tonality** (German standard, 2006) [2]
4. **Psychoacoustic tonality** ("Tonality": Terhardt et al.) [3]

Discussion of the Existing Methods

Tone-to-Noise Ratio (TNR)

According to ECMA-74 the user is asked to identify a suspect pure tone from the Discrete Fourier Transform (DFT) and from having listened. Then, the suspect pure tone is isolated using a very narrow, very steep band-pass filter. An additional critical bandwidth filter is centered on this suspect pure tone.

The next processing steps consist mainly of subtracting the pure tone from the signal in the critical bandwidth using a band-stop filter symmetrical to (inverse of) and at the frequency of the band-pass filter already mentioned, as well as the calculation of the difference between the power of the tone-only and the power of the critical band minus the tone. If the difference is a positive value (above 0 dB - here representing dB of audibility, not sound pressure level) it is reported as the Tone-to-Noise Ratio and the tone is assumed to be audible.

Prominence Ratio (PR)

As with Tone-to-Noise Ratio, the user is asked to identify a suspect pure tone from the Discrete Fourier Transform (DFT) and from having listened. Then a critical bandwidth filter is centered on this suspect pure tone and the next higher and next lower adjacent critical bandwidths are calculated.

In the next step, the averaged powers of the upper and lower adjacent critical bands are subtracted from the power of the central critical band (NOTE: tones are not isolated or removed; everything is done from unmodified critical-bandwidth powers).

If the difference is a positive value (above 0 dB - here again representing dB of audibility, not sound pressure level), it is reported as the Prominence Ratio and the tone is assumed to be audible.

If the tone determined in this manner exceeds a certain dB level of audibility according to a tolerance line, it must be reported as prominent (according to ECMA-74).

It should be noted that, although not so specified in ECMA-74, the method can be applied to a spectrum by performing the calculation at each frequency division of the Fourier transform which meets the criterion for formation of a flanking lower and upper critical band (for example tolerance curves in [Figure 2](#), [Figure 3](#), [Figure 4](#)), resulting in the Specific Prominence Ratio (SPR).

DIN 45681 Tonality

The German standard DIN 45681 is similar to TNR by use of complementary tone-isolating band-pass filters and tone-eliminating band-stop filters to determine critical band level minus tone or tones level.

The method is applied for the complete spectrum of signal frequencies, whereas the calculation of TNR or PR is conventionally performed “one tone at a time”. (NOTE: PR and TNR may be calculated as complete spectra but typically they are not).

DIN 45681 determines pure tones at discrete frequencies (i.e., like TNR and PR used according to ECMA-74. DIN 45681 is not able to assess tonality of narrow bands of noise where tones are not present).

The standard employs an automatic tone detector and displays any/all discrete tones in a spectrum which meet the tone-audibility criterion (including a critical-bandwidth-dependent factor of tone audibility at tone levels from 2 to 6 dB below the density level of the critical-bandwidth-minus-tone when tone is incoherent with the rest of the energy in the critical bandwidth) - therefore tone audibility shown by DIN 45681 is usually higher than from TNR or PR.

The method will show a square or “flat-topped” representation, called a “tone group”, if a region of discrete-tone frequencies falling within one critical bandwidth would be heard as tonal - i.e., if there is more than one discrete tone contributing to tonality in a particular critical bandwidth.

Instead of a tolerance line for “reportable prominence” as in TNR and PR, DIN 45681 assigns a penalty of from 1 to 6 dB which is to be added to the overall sound pressure level.

Tonality Method According to Terhardt et al.

The oldest of the current tonality methods, the model according to Terhardt et al. [3], is also the one most directly based on psychoacoustics. It provides a magnitude difference vs. time or vs. reference quantity, between the loudness of tonally-audible effects

and of broadband non-tonal effects. The magnitude difference is registered between any psychoacoustic tonal conditions (both from pure tones and from narrow noise bands) relative to surrounding broader bandwidths. The method's principal disadvantage is lack of spectral information: the frequencies and relative audibilities of individual tonal effects are not revealed, nor is information available about whether the tonal or the non-tonal loudnesses are varying or a combination of both. It is therefore often necessary to make other, spectral, measurements along with this tonality calculation, to derive enough information.

Remarks

Although ECMA-74 [1] states that a tone centered in a critical bandwidth of noise becomes audible as tonal at a threshold level between 2 and 6 dB below the density level of the critical bandwidth minus the tone, and therefore chooses 4 dB below critical bandwidth density level as the zero-tonality threshold, tonality audibility is assumed anywhere above 0 dB TNR or PR. A tolerance (and tolerance line) for prominence is given, at and above which ECMA-74 requires reporting a tone as prominent.

The DIN 45681 tonality method determines, on a tone-by-tone basis depending on tone frequency and the according centered critical bandwidth density level, the threshold of pure-tone tonal audibility in noise within the range of 2 to 6 dB below critical bandwidth density level rather than assuming, as does ECMA-74, a constant value of 4 dB below.

TYPICAL RESULTS AND CONCERNS WITH EXTANT TOOLS

The precondition in standard usage of PR and TNR according to ECMA-74 (and in any use of DIN 45681), that tonality occurs only from pure tones, fails to consider known tonality perception from narrow elevated noise bands not containing any discrete tones. Band-induced “toneless” tonalities are widely found in automotive applications and Information Technology product noise situations: for example weak but tonal resonances in car HVAC system ductwork, resonances in IC or electric powertrain/mount interactions and transfer paths, and hard disk drive top plate structural resonances excited by atmospheric turbulence inside the case from the rotating disks. [Figure 1](#) gives an example of an automotive HVAC blower run-up in vehicle interior. Blower blade-pass prominent pure-tone tonality is seen and heard from about 1000 to 1400 rpm over a frequency range of about 150 Hz to 240 Hz. The other principal tonalities, always present but growing in loudness, are due to elevated noise bands at 223, 485 and 1654 Hz.

Narrow noise band duct resonance tonalities are registered in SPR much as perceived, also the blade-pass pure tone near the beginning. TNR displays only the blade-pass pure tone contribution. The FFT reveals both the blade-pass pure tones and the tonally-perceived elevated noise bands.

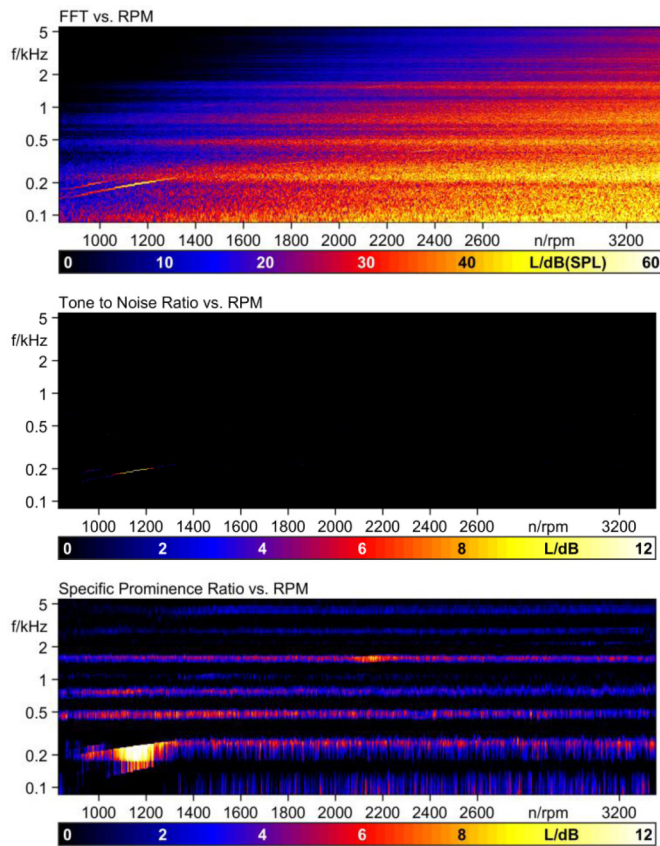


Figure 1. Full-spectrum measurements of an automotive HVAC system blower run-up vs. blower RPM: top to bottom, FFT vs. RPM; Tone-to-Noise Ratio (TNR) vs. RPM; Specific Prominence Ratio (SPR) vs. RPM (not restricted to pure tones).

TNR and DIN 45681 have no provision for determining spectral slope within their single pure-tone-containing assessed critical bandwidth or nearby, so they mis-evaluate a tonally-perceivable locally-raised noise bandwidth as general masking noise reducing the tonality of the contained tone. Perceptually, these band and tone tonalities add.

Figure 2, Figure 3, Figure 4 give an example: the signals are synthetic emulating a small hard disk drive (very low sound pressure level, yet tonalities are a concern) with discrete tones from the rotating mechanism, and with two additional differently pronounced “structural resonances” of the top plate at about 1100 Hz and at 3500 Hz. Figure 2 shows from top to bottom 1. the spectrum (FFT size 65536, sampling rate 44.1 kHz), an averaged spectrum (1/24th octave smoothed FFT: the “background noise”, useful to show general shapes while not resolving pure tones), and a 1-critical-bandwidth peak-hold spectrum as “critical bandwidth ruler”; 2. the Tone-to-Noise Ratio results along with the ECMA-74 TNR tolerance line; 3. the Prominence Ratio calculated as a full spectrum (SPR), both with and without recognition only of pure tones along with the ECMA-74 PR tolerance line. Note that the ECMA-74 tolerance lines for TNR and PR are identical in shape and in the 1 kHz inflection point, but not in dB level of prominence.

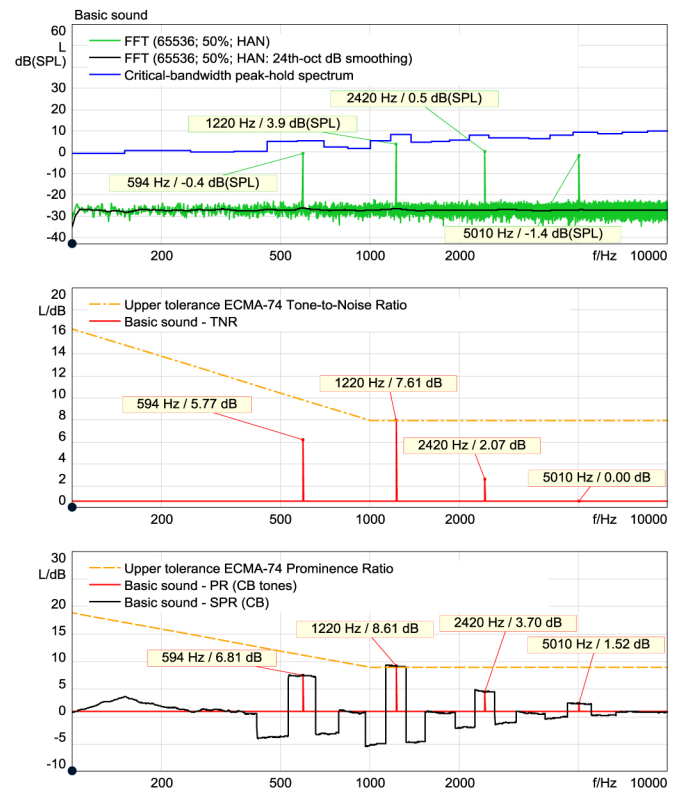


Figure 2. Different spectral representations (FFT and smoothed FFT, upper picture), Tone-to-Noise Ratio (TNR) results (middle picture, scale gives dB of tonal audibility) and PR values tones-only (per ECMA-74) using critical bands (CB), complete SPR not constrained only to pure tones results (bottom picture) of a synthetic small hard disk drive noise of very low sound pressure.

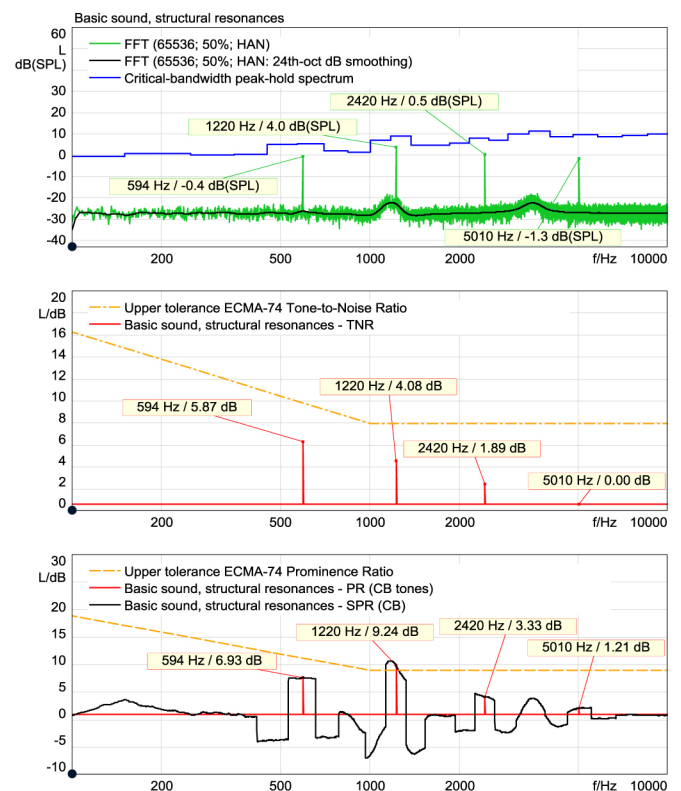


Figure 3. Same representation of Figure 2 for the basic sound with moderate structural resonances at about 1100 Hz and at 3500 Hz.