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methods for automating prominent tone evaluation and for considering variations with time or other reference quantities

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Information Technology acoustic protocols include identifying prominent tones according to likely subjective importance. Most existing methods for calculating Tone-to-Noise Ratio (TNR) require a suspect tone to be selected by the analyst, who must also mark the width; both are potential sources of uncertainty and variability. One purpose of this paper is to present an automatic tone-detection and width-assessment methodology for more robust, less operator-intensive TNR calculation in accordance with ECMA-74. The paper will also present a process giving a complete spectral representation of the Prominence Ratio (a specific Prominence Ratio) by iterating the calculation at each frequency bin of the Fourier transform of the time-signal. The ECMA-74 tone-detection procedure for TNR is also applicable to the specific Prominence Ratio and is automatable, yielding tones-only prominence results without user intervention for any or all tones qualifying as prominent. The conventional average prominent tone evaluation over an operating interval can cause mis-assessment or no assessment of subjectively prominent tones which change frequency and/or level with time. We will therefore also discuss applying the described procedures as functions of time or other reference quantities, and suggest considering the subjective significance of time-domain effects such as modulation occurring from certain multiple prominent tone situations.

1 Introduction

The procedures currently standardized for evaluating and reporting prominent tones [1] provide a single assessment averaged over the defined operating interval or cycle of the equipment under test, an assumption valid only for steady-state conditions but potentially invalid for situations where tones may appear and disappear, go below and above reportable prominence, or change level and/or (particularly) frequency during the operating interval.

In addition, these procedures can require the test engineer or technician to determine if a tone is prominent by listening and/or comparing with a known audibly-produced or reproduced reference tone [1], a process potentially complicating when a tone varies with time.

2 Tone detection

2.1 Automatic tone-detection and tone-width assessment for Tone-to-Noise Ratio

Manual tone detection and, even more, manual extraction/definition of tone width may result in uncertain and unreliable TNR estimation. We therefore implemented an automatic procedure for both, consisting of the following steps:

Calculation of a “smoothed” spectrum based on the DFT spectrum. This smoothed spectrum is calculated by dB-domain averaging of the spectral lines of the original DFT spectrum in 1/24th octaves, followed by further smoothing using a 5th-order Gauss filter.

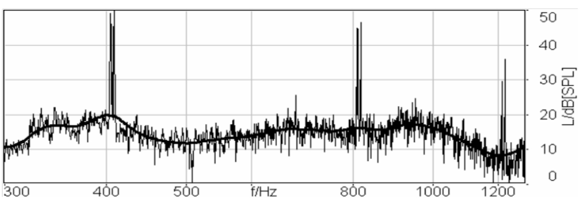

Fig. 1: DFT spectrum with several double tones and smoothed spectrum (bold line).

Searching for tone candidates: The spectral line must be greater than the smoothed spectral line plus 6 dB, greater than both of its neighbor lines and greater than an absolute dynamic limit (100 dB below maximum level). (The threshold of hearing lower limit [THLL] is currently proposed for standardization of prominent tone evaluation for the upcoming ECMA-74 10th Edition.)

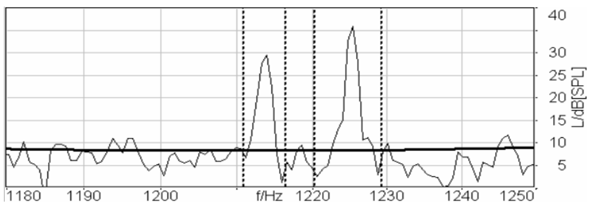

Fig. 2: DFT spectrum, smoothed spectrum (bold) and automatically-detected tone widths of a double tone (dotted).

Tracing the spectrum towards both lower and higher frequencies: Spectral lines are assigned to the tone as long as the spectrum is falling in level or remains above the smoothed spectrum. If a greater spectral line than the candidate line is observed, the candidate line will be replaced by that greater line.

Check of tone width: The tone will be discarded if the tone-width calculated from the number of lines assigned to the tone in the previous step is greater than half of the critical bandwidth calculated around the tone frequency.

Check of audibility: The tone level must be greater than 4 dB below the noise level of the critical band centered on the tone. In order to calculate the noise level at this stage we use the smoothed spectrum because it does not incorporate the level of yet-undetected other tones. The noise level may be underestimated at this point, but this process is used only for tone detection, not for the TNR calculation.

From this procedure we obtain a list of tones consisting of tone frequencies and the discrete spectral lines assigned to them. Tone-to-Noise Ratio can now be calculated for each of these tones using the formulæ defined in ECMA-74 [1].

A precedent for fully-automatic tone detection, incorporating a similar methodology, exists (it also employs the same proximity criterion as ECMA-74 for tones within a critical band); the tonality standard DIN 45681 [2]. Fig. 3

shows a comparison of the automatic tone detection described in this paper for TNR and that of DIN 45681, for two quite different example sounds. Values returned by DIN 45681 are slightly higher than those from the automated TNR procedure discussed here because DIN 45681 assesses the difference between the tone level and the minimum level for the tone to become audible (the critical band noise lowered by a frequency-dependent masking level ranging from 2 to 6 dB), whereas the ECMA-74 procedure assesses the difference of the tone level and the surrounding critical band noise level.

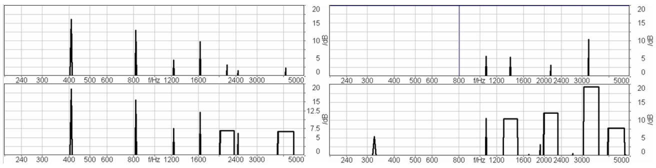

Fig. 3: Comparison of the TNR (upper) automated procedure and automatic DIN 45681 results (lower), for a fan noise (left) and a defective automobile tire (right).

When the tone-width exceeds 15% of the critical bandwidth, ECMA-74 recommends recalculating the DFT spectrum using a higher frequency resolution. We consider that the limitation to 15% is too narrow, because a tonal noise more complex than a pure tone may exceed this limit even if a higher-resolution DFT is applied. Others have also addressed this issue; Upton [3] recommended that a higher frequency resolution be standardized in ECMA-74 in order to circumvent the 15% problem. Because the ECMA-74 formula used to estimate the masking noise level compensates for the bandwidth of the extracted tone, the tone-width may be greater than 15% of the critical bandwidth without underestimating the masking noise level.

A pure tone wandering slightly about its average frequency could appear in a DFT measurement averaged over an operating interval as being wider than actual, invoking the 15% issue but leading to an uncertain solution, by worsening rather than improving the time resolution.

2.2 An iterative procedure for determining specific Prominence Ratio (complete spectrum)

The principal advantage of the Prominence Ratio concept [4] compared to the Tone-to-Noise Ratio concept is that it is not necessary to extract a detected tone from its surrounding critical band spectrum, because the Prominence Ratio estimates the masking noise level based on the level of the neighboring critical bands instead of the noise level of the critical band centered on the tone. Nonetheless, most applications are based on manually selecting a tone followed by calculating the Prominence Ratio.

The approach described here does not depend on detecting tones, either manually or automatically, so the results will be easily reproducible if the calculation is based on the same DFT spectrum and the standardized ECMA-74 formulæ are applied. The basic idea is to perform the Prominence Ratio calculation for all DFT lines of the spectrum and to plot this result as a “Prominence Ratio spectrum” or specific Prominence Ratio (SPR). Because tonal components (pure tones, more complex tones and narrow-band noise) exceed the surrounding spectrum, the Prominence Ratio spectrum should show its greatest values near (but not necessarily exactly at) the frequencies of tonal components.

The maximum value of the PR spectrum may be considered as an upper boundary or “worst case” Prominence Ratio overall value, because the manually-calculated PR at any depicted tone frequency cannot exceed it.

Of course, if still considered necessary, the PR value at any frequency may be easily read from the Prominence Ratio spectrum whose frequency axis is aligned with that of the DFT spectrum.

2.3 Applying the TNR automatic tone-detection process to the specific Prominence Ratio

The tone-detection algorithm described above for TNR may also be applied to the Prominence Ratio, resulting in a “single line(s)” SPR as opposed to the “continuous” Prominence Ratio spectrum described above.

3 Prominent tone evaluation versus time or other reference quantity

3.1 Behavior of human hearing

The human hearing appears to rank tonal or other transient or time-varying loudnesses more on the basis of peak or near-peak sensation magnitude rather than on averaged magnitude and is considerably more sensitive to “pattern” or shorter-term time and/or frequency variation, which draws attention and strengthens the sensation, than to steady or slowly-varying conditions [5]. A tone which is prominent even briefly in an operating sequence of a number of seconds, or recurs going below and above calculated prominence, is likely to elicit as strong or even stronger a subjective ranking as a steady tone of similar objective magnitude. Frequency variation can also strengthen a subjective impression of tone prominence.

3.2 Frequency resolution versus time resolution

Conventional prominent-tone evaluation assumes steady conditions and reports individual frequencies and single-value prominence levels. Tones varying in level or frequency challenge this procedure in several ways: they complicate manual tone-identification and listening-test tasks, and even in an automatic approach can be under- or mis-reported due, for example, to duty-cycle magnitude averaging on the one hand, and insufficient time resolution consequent from great frequency resolution on the other hand. The spectral resolution required by the “15% rule” of ECMA-74, for example, can be obtained at the expense of a time resolution requiring, depending on frequency, a stable tone for up to four seconds, preventing accurate level and frequency determination of varying tones of shorter time signatures which may be subjectively significant. Obtaining sufficient time resolution for representing subjective tonal impressions can push frequency resolution below mandated requirements.

3.3 Improving time resolution while retaining necessary frequency resolution

An alternative DFT-based spectral analysis tool might be applied in the role of the DFT spectrum to the calculation of tonal prominence, for example a window-deconvolution and frequency-resolution-multiplication procedure, the High-resolution Spectral Analysis (HSA) of Sottek [6] (Fig. 4).

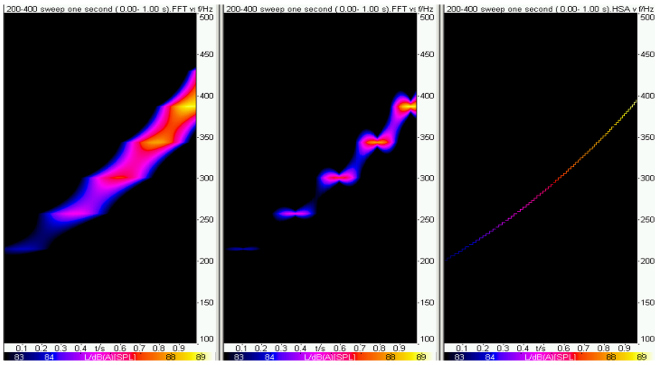

Fig. 4: High-resolution Spectral Analysis [6], A-weighted spectra vs. time: Hanning-windowed FFT vs. time (left), no window (middle), HSA: window deconvolved and frequency resolution multiplied 16X (right).

Fig. 4 represents an A-weighted FFT spectrum vs. time of a 200 to 400 Hz sweep tone of one-second duration, analyzed with a block size of 1024 points; the signal was sampled at 44.1 kHz as were all signals in this paper. At left the Hanning window was used, in the center no window, and at the right the High-resolution Spectral Analysis; in all cases Δt = 23.2 ms. In HSA analysis the user may accept the conventional Fourier unity product of time and frequency resolutions (in this case Δf = 43.07 Hz) or multiply the frequency resolution by 2x, 4x, etc. up to 16x as shown in the right graph, where Δf = 2.69 Hz. 512 spectral lines remain in positive frequency given by this block size, but may be spaced much closer in frequency. The HSA method permits not only meeting, but exceeding, the time-frequency resolution product of human hearing and can meet the ECMA-74-mandated frequency resolution for prominent tone evaluation while markedly improving the time resolution.

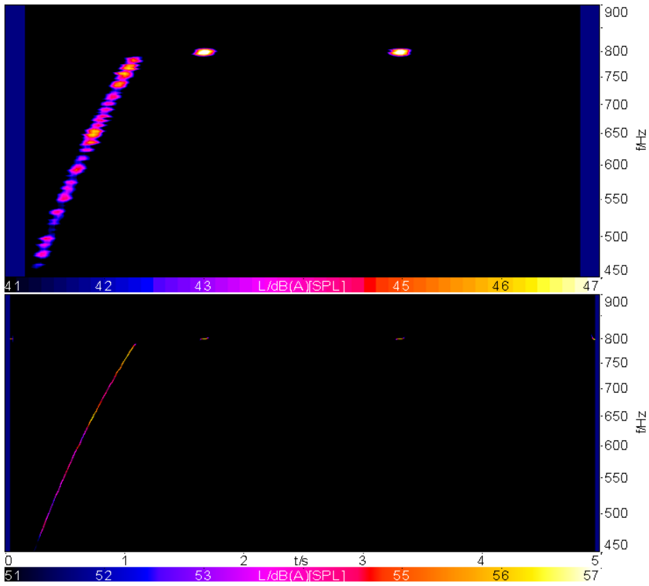

Fig. 5: A-weighted spectra vs. time of a situation with three time-varying subjectively prominent tones; a sweep 500-800 Hz at constant 57 dB[SPL] followed by two 800 Hz, 57 dB[SPL] tones of 70 ms duration each, all in continuous random pink noise of 60 dB[SPL]. Upper: FFT vs. time 16384 points, 96% overlap, Hanning window. Lower: HSA vs. time, 4096-point FFT, 99% overlap: Δf = 0.673 Hz, Δt = 92.9 ms. Note: the level scales differ by 10 dB. In the upper illustration the momentary tones occupy less than 1/5 the duration of a 16384-point Fourier block at this sampling rate and therefore are not represented at actual level, although they indicate higher than any point along the sweeping tone.

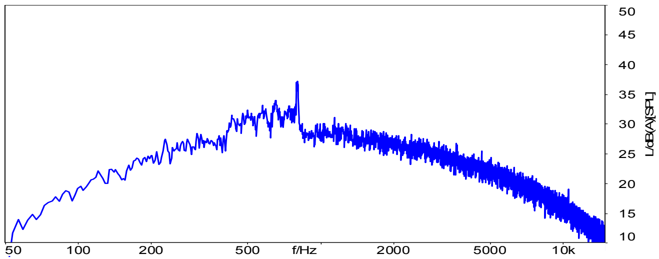

Fig. 6: A-weighted DFT spectrum (16384 points) of the same signal, averaged over the 5-second operating sequence. Prominence Ratio and Tone-to-Noise Ratio likewise averaged over this operating sequence produce null results; the principal single tone (800 Hz) resolved in this spectrum is not determined to be prominent by either method.

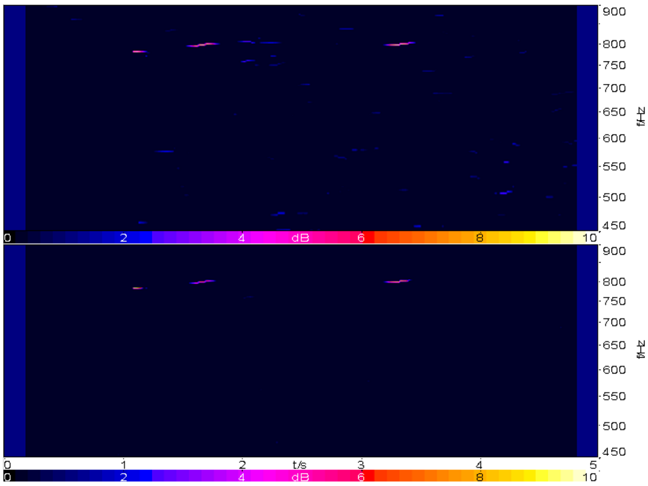

Fig. 7: The same signal. Upper: Prominence Ratio spectrum vs. time, DFT 16384 points, selecting tones automatically as described. Lower: Tone-to-Noise Ratio vs. time, 16384 points, using the same tone-selection procedure. Note that the prominently audible sweeping tone, except at its upper limit frequency, does not appear.

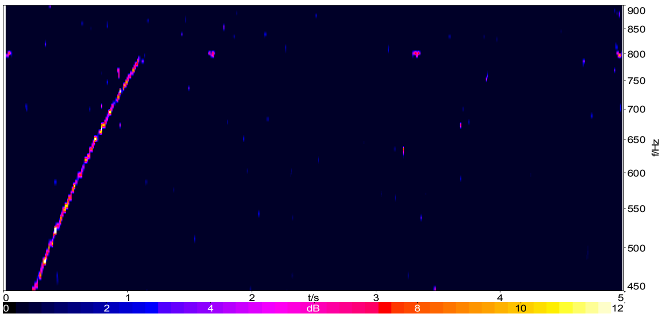

Fig. 8: The same signal, Tone-to-Noise Ratio vs. time calculated by HSA (4X frequency resolution multiplication): block size 8192 points; Δt = 185.8 ms, Δf = 1.346 Hz.

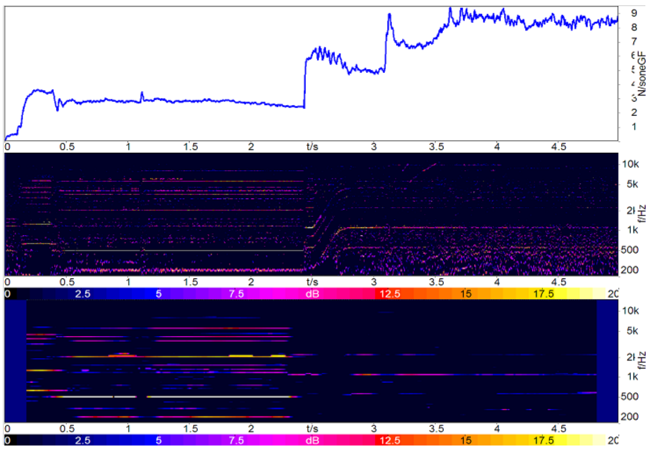

Fig. 9: Printer including rapid frequency sweep. Upper, loudness vs. time (DIN 45631/A1) [7]); Tone-to-Noise Ratio vs. time: middle, by HSA (4X frequency resolution multiplication), block size 4096 points, Δt = 92.9 ms, Δf = 2.69 Hz; lower, calculated conventionally (16384 Hanning, Δt = 371.5 ms, Δf = 2.69 Hz).

In the printer TNR calculation example of Fig. 9, the greatest subjective tonal prominence occurs at about 1 kHz very briefly, immediately after the start of the rapid frequency sweep (time location approximately 2.4 seconds); the entire short sweep is also perceived as tonally prominent. Obtaining the same frequency resolution by DFT and HSA provides similar results for tones of steady frequency and slow to moderate level change, but different results during more rapid level and/or frequency changes, due to the different time resolutions.

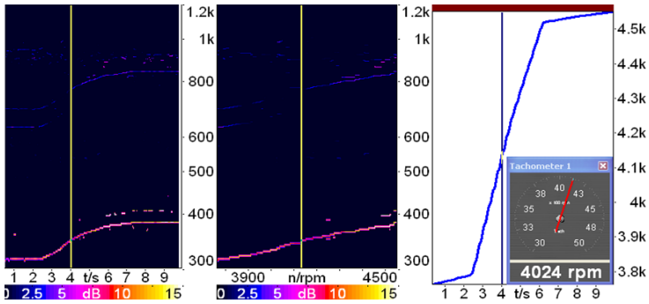

Fig. 10: Computer cooling fan, Prominence Ratio spectrum by conventional DFT method (16384 points, Hanning): left, vs. time, center, vs. RPM; right, the FPM vs. time. It may be useful to determine prominent-tone spectra and magnitudes versus other references than time, for example RPM, air pressure, flow rate, stepping rate, temperature, voltage, etc.

3.4 Normalizing RPM-varying frequency to constant frequency

For rotating devices of varying RPM where a tachometer or stepping rate is available as a synchronizing reference, the time-signal may be resampled into the angle domain and the prominence spectrum calculated vs. time or RPM either as an *order* prominence spectrum or as the prominence history of a set of tones normalized to fixed frequency, simplifying the reporting of tonal prominence. The spectral relationship of the tones and their surrounding noise is maintained, and the results of averaged TNR or Prominence Ratio calculation, especially for tones originally above 1 kHz, would have greater validity than in the original situation because the tones are less likely to be "lost." A potential complication involves differences in critical bandwidths and their positions versus the original tone frequency (although in the middle frequency range this may not be an issue especially when frequency change is not large, due to near-uniform critical bandwidths in this region – please see Fig. 12). Another consideration is adjusting the prominence tolerance according to original tone frequency when/where that falls below 1 kHz. An example of this approach is given in Fig. 11. If no tachometer is available but a rotationally-related tone is recognizable throughout an operating interval, a tachometer may be synthesized, perhaps automatically, permitting this method to be applied. The author hopes to elicit discussion and suggestions regarding these and other points.

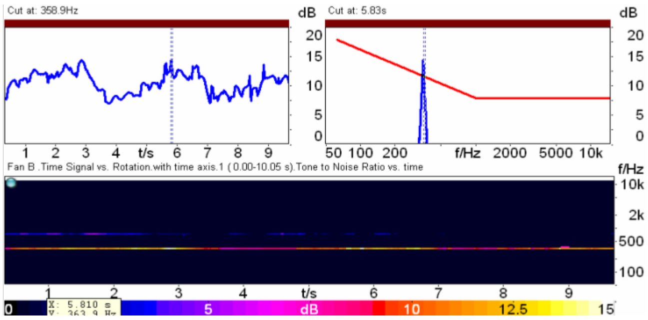

Fig. 11: The computer fan Tone-to-Noise Ratio spectrum vs. time, from time-data resampled synchronized to the tachometer. The resampled signal may carry either an angle or time abscissa (the latter giving a constant and selectable effective rotation rate, as here where 4000 RPM was chosen, for constant frequency of this 5th-order blade-pass and other rotationally-generated tones). Upper left: prominence in dB vs. time of the blade-pass tone. Upper right: instantaneous prominence spectrum. (The cursor, visible onscreen, does not appear in the image capture.)

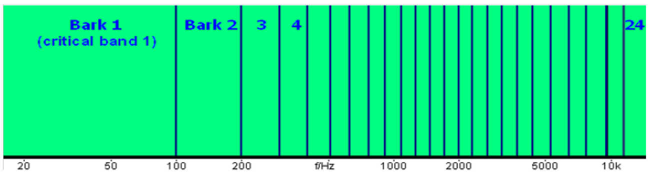

Fig. 12: Critical bandwidths displayed contiguously on a log frequency scale. Between about 500 Hz and 5 kHz, they vary only slightly.

4 Reporting results

Clearly there are challenges in how to report prominence of a tone whose frequency, and/or prominence magnitude, changes during the defined operating cycle. One possibility might be, for a tone anywhere evaluated as prominent, to report the percentage of the time that the tone was prominent according to the prominence tolerance [1], the minimum and maximum prominence magnitudes and, if the tone dropped below prominence and recurred, the fact that it recurred, number of times it appeared as prominent and a single typical prominent duration. For changing frequency, the maximum frequency span or deviation during prominence could be reported.

5 Other psychoacoustic factors in subjectively-suitable assessment of some prominent-tone situations

Although outside the main scope of this paper, other subjectively significant effects often occur involving repetitive slow to rapid level changes (modulation) for some situations involving tones within a critical bandwidth. Modulation analysis, and the psychoacoustic analyses Roughness and Fluctuation Strength, can be valuable adjuncts to prominence findings.

6 Summary

We have addressed two concerns facing practitioners of prominent-tone assessment in Information Technology equipment: on the one hand the requirement for operator involvement in both the determination of whether a tone is prominent (including a listening test) and the tone-selection process leading to prominence calculation, and on the other hand variation of tones versus time in level and/or frequency, particularly the latter, which can compromise the conventional tone assessment methodology. We have therefore presented an automation procedure for tone selection and prominence determination, and suggested a strategy for improving time resolution while retaining mandated frequency resolution. For situations where a tachometer is present and frequency-varying tones arise from rotational speed change, we have described a resampling procedure to “straighten out” tones, lessening their likelihood of being “lost” to measurement and thereby, for cases where tone levels are fairly constant, allowing the conventional averaged-over-the-interval tone-assessment procedure to function.

Acknowledgments

The author wishes to thank two of his colleagues: Georg Caspary for considerable assistance, including development and implementation of the TNR and SPR methods discussed; and Dr.-Ing. Roland Sottek for suggesting applying the High-resolution Spectral Analysis (HSA) to the calculation of time-varying TNR.

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