



A New Psychoacoustic Method for Reliable Measurement of Tonalities According to Perception

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ABSTRACT

It has become evident in consumer product sound quality, especially with quieter and quieter products, that tonality measurement methods currently in use exhibit various limitations and errors in registering tonalities as they are perceived. A primary expectation, for which the principal metrics were developed and their uses standardized (Tone-to-Noise Ratio, DIN 45681 Tonality, Prominence Ratio) is that tonality is caused by pure tones. Pure tones are indeed a cause, but so are other factors including elevated regions of narrowband noise (such as caused by resonances), impure tones, steep discontinuities in noise spectra without discrete tones, and conjunctions of pure or impure tones with the other mentioned phenomena. All circumstances affecting tonality perception should be evaluated, not just one subset. For these reasons a new fully psychoacoustic tonality assessment method has been developed and tested which separates tonal and non-tonal loudness via the running autocorrelation function in a hearing model implementing a large number of highly overlapped critical-bandwidth filters. The method sufficiently matches human perception that the listening test mandated in current tonality standards may be omitted. The paper will illustrate typical issues in practical tonality assessment and give comparisons of measurement methods in real-world product sound situations.

1 INTRODUCTION

A new fully psychoacoustic approach to the measurement of tonalities, *Tonality (Hearing Model)* [1] [2] [3], based on the Hearing Model of Sottek [4], has been developed due to concern about errors of existing metrics to quantify tonalities in product sounds according to perception (they may not be resolved, other times over-emphasized or presented with values not well correlated with perception). The new method automatically considers the threshold of hearing and

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the relationship of tonality perceptions to psychoacoustic loudness levels, and provides a high time resolution to measure transient and rapidly changing tonalities. It can also present the strength and the frequency of (maximum) tonality instant by instant vs. time, RPM or other reference quantity. The method will be published in the Information Technology acoustic standard ECMA-74, 15th Edition (June 2018).

The method *Tonality (Hearing Model)* offers several analyses:

1. ***Specific Tonality (Hearing Model)*** – average spectrum of psychoacoustic tonality
2. ***Specific Tonality (Hearing Model) vs. Time or RPM*** – spectrum of psychoacoustic tonality vs. time, RPM or other reference quantity
3. ***Tonality (Hearing Model) vs. Time or RPM*** – strength of the maximum psychoacoustic tonality at a given instant as a function of time, RPM or other reference quantity
4. ***Tonality (Hearing Model) Frequency vs. Time*** – frequency of (maximum) tonality (instant by instant) vs. time

The paper will present:

A review of existing methods

Tonality (Hearing Model)

Results with various tonality methods on real-world sounds

Capabilities of Tonality (Hearing Model)

Discussion: Relationships and Engineering Information

2 BRIEF BACKGROUND OF TONALITY MEASUREMENT: EXISTING METHODS

Tonality metrics currently in use are:

Tone-to-Noise Ratio (ECMA-74) [5]

Prominence Ratio (ECMA-74) [Ibid.]

DIN 45681 Tonality [6]

Tonality vs. time (Aures/Terhardt) [7]

The first three listed methods are hybrids, in that they use the critical bandwidth (a psychoacoustic factor) but operate with sound pressure, not psychoacoustic loudness. They do not consider the cavum conchæ resonance of the ear (an acoustic amplifier of approximately 12 dB at about 4 kHz affecting perceived loudness) and are not based on the calculation of psychoacoustic loudness. The fourth method (Aures/Terhardt) is psychoacoustic in concept but incompletely implemented.

The *Tone-to-Noise Ratio* and *DIN 45681 Tonality* can operate only on discrete tones. Although discrete tones can cause the perception of tonality, so can other factors: elevated regions of narrowband noise (such as caused by resonances), impure tones, steep discontinuities in noise spectra without discrete tones, and conjunctions of pure or impure tones with the other mentioned phenomena.

In the ECMA-74 standard to date, the *Tone-to-Noise Ratio* and *Prominence Ratio* are only to be applied to pure tones. Due to its mode of operation, the *Prominence Ratio* may be used with or without restriction to pure tones; it can often be more effective without the tones restriction.

The *Aures/Terhardt Tonality* method has a psychoacoustic basis but yields no spectral information, only the relationship of tonal to non-tonal loudness as a function of time. Due to the lack of spectral information and the high resolution in time, the results are often difficult to interpret. Thus, this method is seldom useful.

The *Tone-to-Noise Ratio*, *Prominence Ratio* and *DIN 45681 Tonality* all require very high resolution in frequency, which results in very low resolution in time. Brief, transient or short-term frequency-shifting tonalities are therefore either under-represented or not captured at all.

In many product sectors, quieter and quieter products are being developed and marketed. An increasingly evident flaw in the extant tonality methods is indicating and penalizing significant tonality magnitudes not actually associated with perception, from sound situations near or below the threshold of hearing.

3 TONALITY (HEARING MODEL)

The method *Tonality (Hearing Model)* employs only psychoacoustic loudness, and determines the loudness of tonal and non-tonal components of sounds by means of the running (updating) autocorrelation function. The method has been tested by jury evaluations with many participants and a wide variety of technical sounds having a wide variety of spectral shapes, event timings/variations and loudness levels.

Due to its psychoacoustic accuracy, *Tonality (Hearing Model)* may for the first time in tonality measurement be relied upon for automatic, intervention-free determination of tonalities according to how they would be perceived, without the requirement for listening which is in the current standard descriptions [5 op. cit.] for use of *Tone-to-Noise Ratio* and *Prominence Ratio*. Due to the frequent unavailability of calibrated acoustic playback, the listening requirement can impose difficulty due to a necessity for direct audition.

Tonality (Hearing Model) automatically includes the threshold of hearing and the relationship of tonality perceptions to loudness levels. It operates at $\frac{1}{2}$ critical bandwidth spectral resolution but yields finer frequency-of-tonality detail. It provides both high time resolution and high frequency resolution. The inter-measurement time interval is approximately 5 ms at the highest signal frequencies and approximately 40 ms at the lowest frequencies, with four steps in time resolution between the 5 ms and 40 ms frequency-dependent time resolutions. Although calculations are made at $\frac{1}{2}$ critical bandwidth resolution, the (correctly-shaped) critical bandwidth filters are very numerous and highly overlapped across frequency. Thus the analysis *Tonality (Hearing Model) Frequency vs. Time* presents a resolution of approximately 3 Hz at the lowest signal frequencies and approximately 24 Hz at the highest signal frequencies. The *Specific Tonality (Hearing Model)*, an average measurement, and *Specific Tonality (Hearing Model) vs. time* or *RPM*, are displayed at the $\frac{1}{2}$ critical bandwidth resolution.

4 RESULTS WITH VARIOUS METHODS ON REAL-WORLD SOUNDS

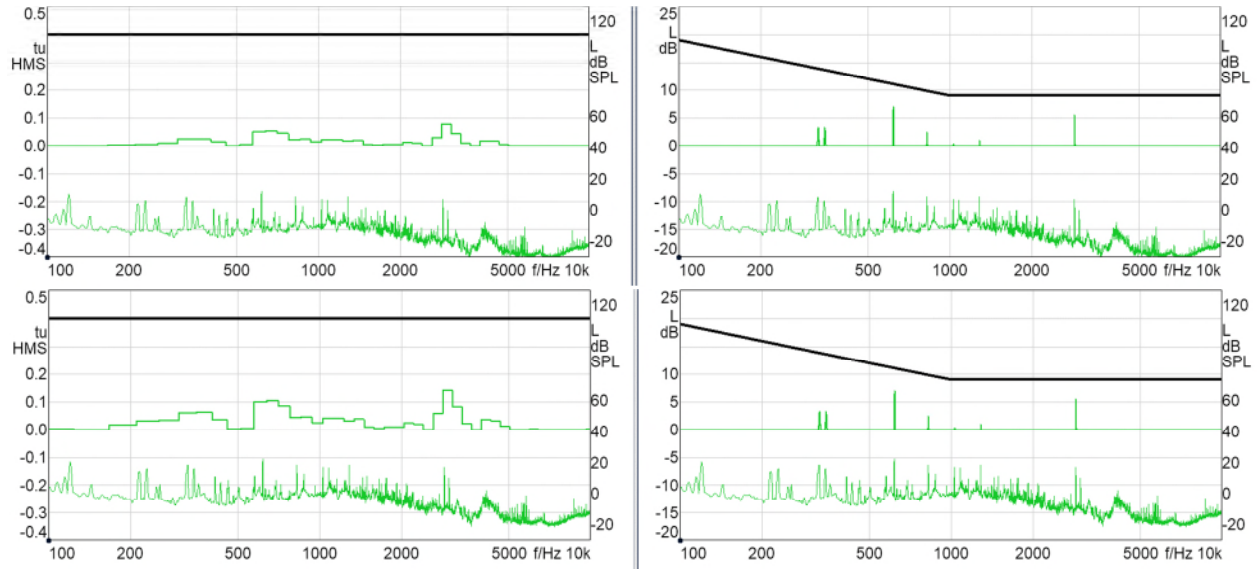


Fig. 1 -- An Information Technology product sound (steady): comparison of specific tonality by Tonality (Hearing Model) (left panels) and Prominence Ratio (tones-only, right panels). Upper: original sound pressure level. Lower: same recording, sound pressure raised 10 dB. Note: no change in the Prominence Ratio result, but change in the psychoacoustic tonality result matching the perception change. The black horizontal line in the left panels is the proposed tolerance for reportability of prominent tonality, at and above the value 0.4 tuHMS (Tonality Unit according to the Hearing Model of Sottek). The black line in the right panels is the tolerance for reporting tonality according to ECMA-74 for the Prominence Ratio.

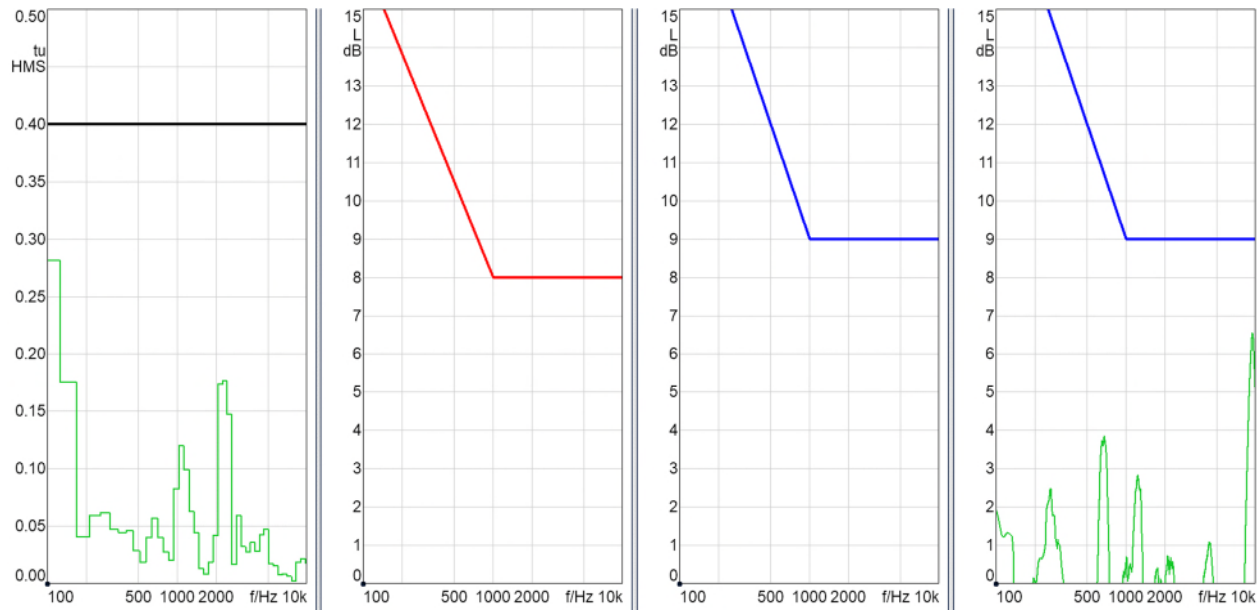


Fig. 2 -- For a printer printing a sequence of pages, the average spectrum of tonality (specific tonality) by, left to right: Tonality (Hearing Model), Tone-to-Noise Ratio, Prominence Ratio (tones only) and Prominence Ratio (not selecting for tones only). The tolerance lines for reportable tonal prominence are shown, color-coded by analysis type.

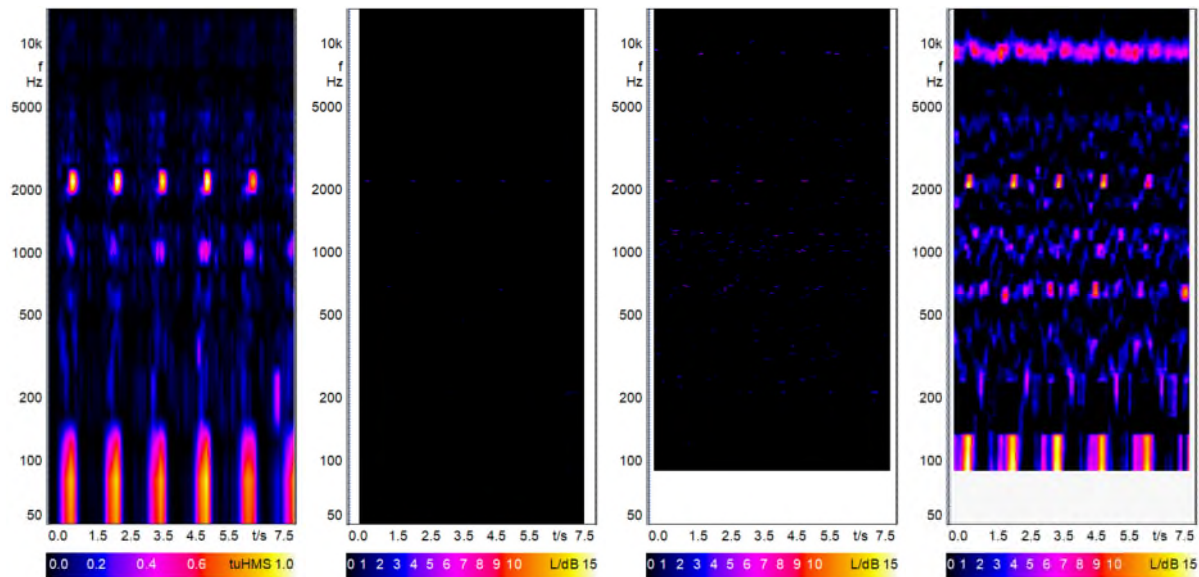


Fig. 3 -- For the same printer sound, here are the same measures versus time. Note that the maximum tonality magnitude during the brief events is much higher than that shown in the average specific tonality graph of Figure 2, due to the short duty cycle. Also note that the pure-tone methods greatly under-represent the tonalities. The Prominence Ratio displays a prominent tonality around 10 kHz which is inaudible at this loudness, hence does not appear in the psychoacoustic tonality result. This printer also has a significant audible transient tonality near 85 Hz (see Figures 2 and 4) not reported by the older methods.

5 CAPABILITIES OF TONALITY (HEARING MODEL)

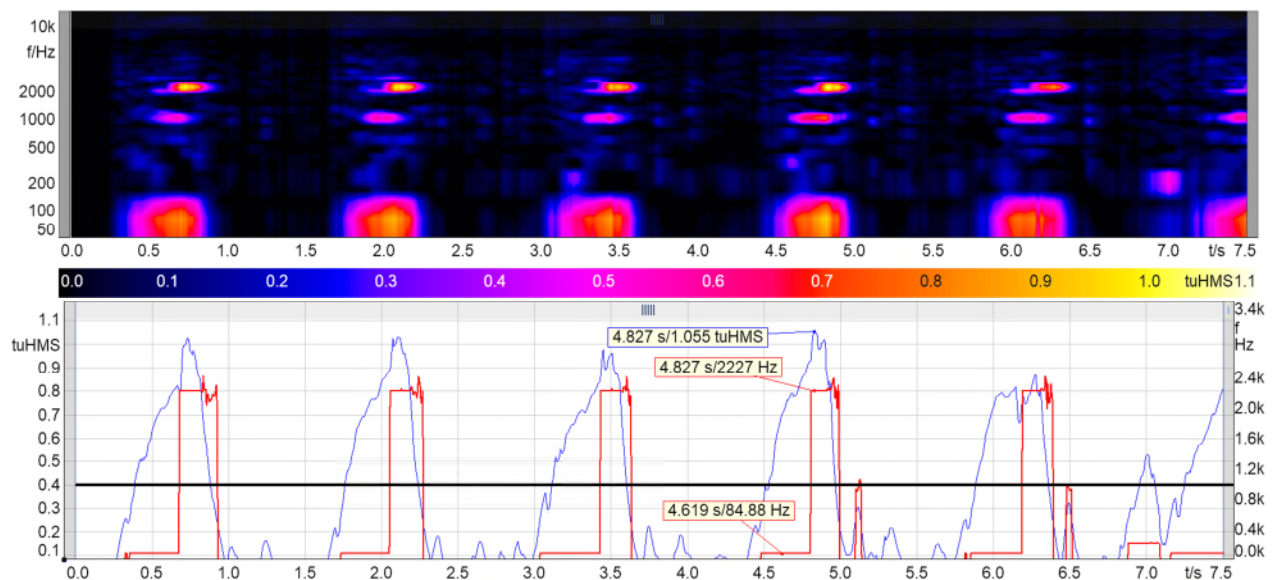


Fig. 4 -- (same sound as in Figs. 2 and 3) Unlike other tonality measures, Tonality (Hearing Model) can present the magnitude of maximum tonality vs. time (blue, lower panel) and frequency of maximum tonality vs. time (red). It is very informative to view these

relationships. Note: where the tonality frequency changes, the graphic transition is a vertical line.

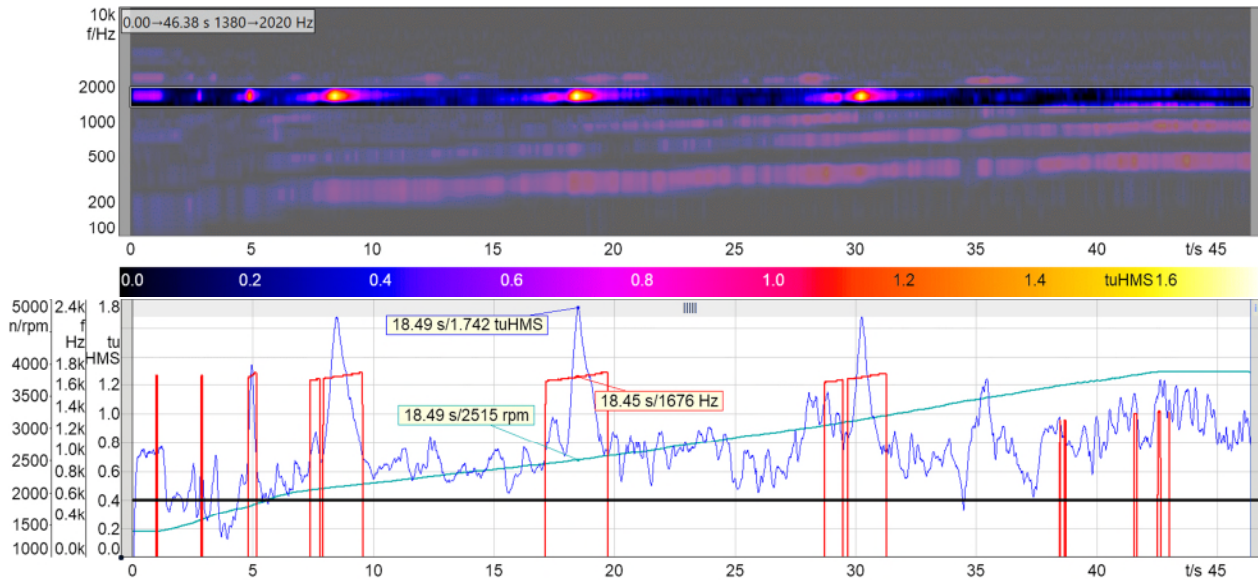


Fig. 5 -- Small cooling fan run-up with a very strong narrow resonance. The RPM history is also shown. All Tonality (Hearing Model) analyses have a setting for the displayed frequency range; this setting is after the calculation of full-band psychoacoustic tonality. In this figure, the frequency range for the tonality in the lower window is as highlighted on the specific tonality (Hearing Model) vs. time spectrogram (1380 to 2020 Hz). Clearly, fan rotational orders are exciting the strong fixed-frequency resonance. Restricting the presented frequency range assists in measuring particular tonalities. Also regarding the frequency readout, this analysis has an adjustable threshold, of default value 0.1 tuHMS. Because the tonalities of Fig. 5 are very strong, the threshold was set to 0.7 tuHMS.

6 USING TONALITY (HEARING MODEL) – PRACTICAL EXAMPLES

The Tonality (Hearing Model) can provide much more information than other methods. Ability to display the magnitude vs. time and the frequency vs. time of maximum tonality is not available in other tonality analyses. For multichannel data (especially binaural data) the readout of results of two or more channels superimposed (as in Figures 6 and 7), can reveal inter-channel (hence interaural) relationships significant in perceiving tonal events.

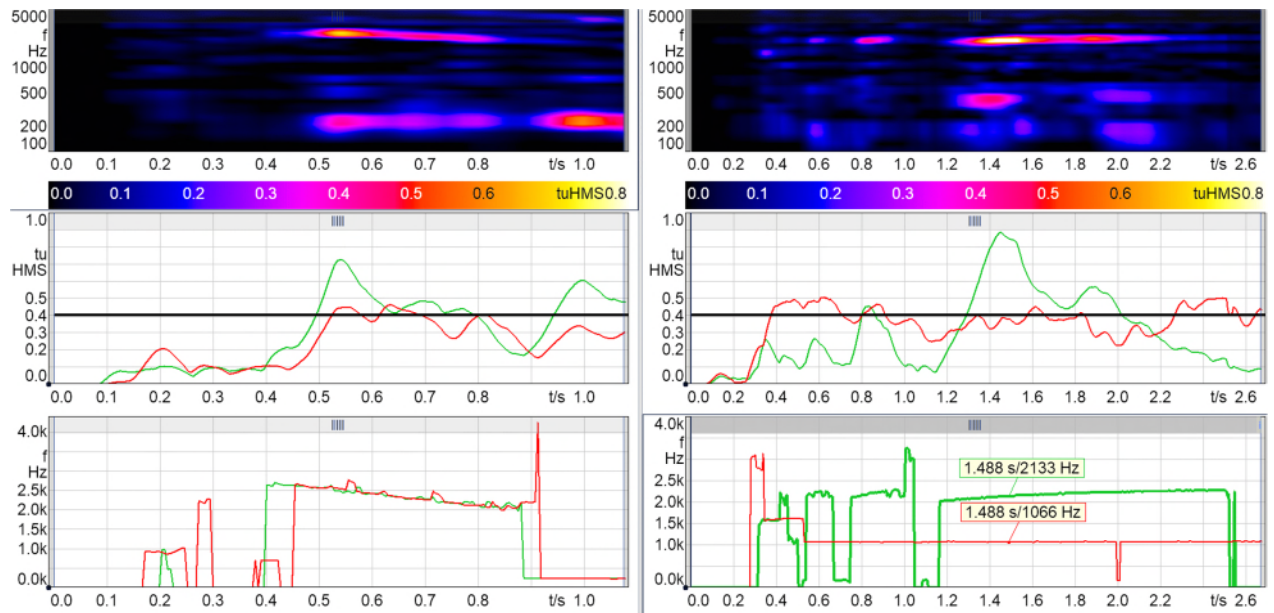


Fig. 6 -- (Both sets of results are from binaural recordings: left ear green, right ear red in the lower two panels each side.) Left panels: an internal combustion engine starter motor disengage/spin-down tonality, duration 0.4 second. Right panels: an Information Technology device run-up. Top-to-bottom: specific psychoacoustic tonality vs. time (left ear shown); Middle: psychoacoustic tonality (maximum) vs. time, both ears; Bottom: frequency of (maximum) psychoacoustic tonality vs. time, both ears.

In Figures 6 and 7 the left panels measure a short-duration tonality very difficult or impossible to measure using the previous methods. The (max.) tonality vs. time and frequency of (max.) tonality vs. time indicate reasonably-expected similarity of both quantities between the left and right ears of the binaural recording. (In both the left and right panels in Figure 6 the specific tonality (Hearing Model) vs. time spectrogram is of the left ear only.) The right panels (an Information Technology device run-up) reveal a very different situation: the source is extremely directive, so the magnitudes (briefly) and the frequencies (for a longer time) of maximum tonality vs. time differ strongly between the two ears. The hearer's attention is activated more strongly by this unusual interaural condition, and the sound is therefore evaluated more negatively than would be expected just by the tonality measurements of one or the other ear alone, or of data from a single microphone. Figure 7 shows, for the IT device run-up (upper right panel), the results for the right ear only – compare to Figure 6.

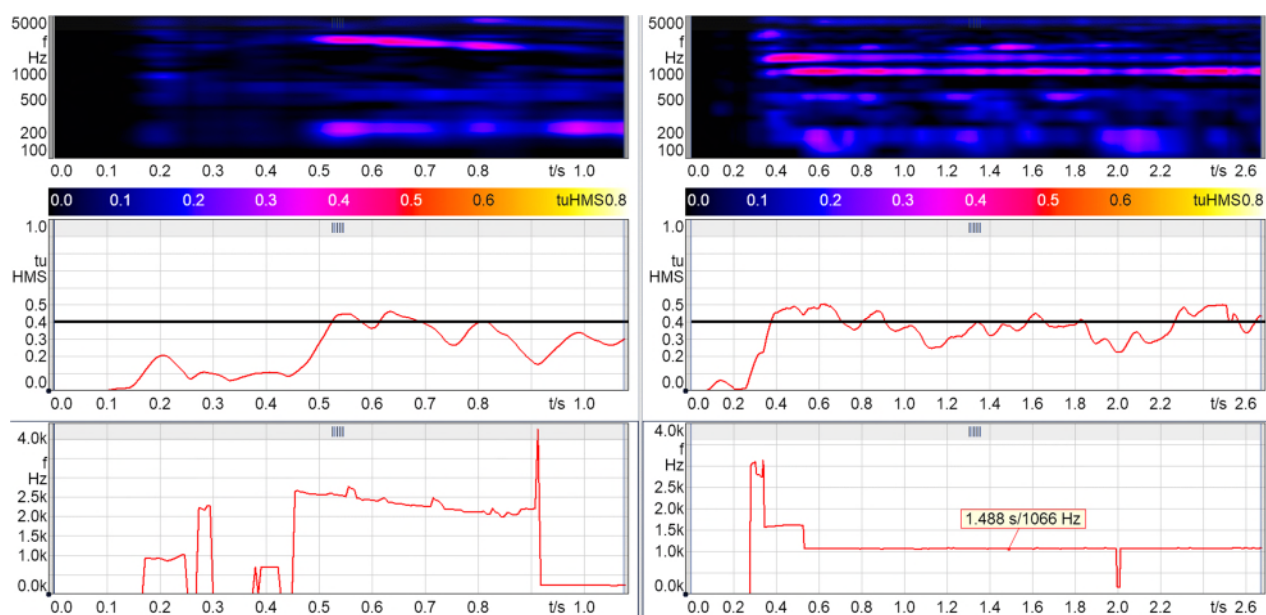


Fig. 7 -- For the IT device run-up (right panels), only the right ear results are now shown. Note the very different tonality history compared to the Figure 6 upper right panel. The dominant tonality in the specific tonality (Hearing Model) vs. time left ear data in the Figure 6 upper right panel is barely evident, and other tonalities not evident (therefore not perceived) in the left ear are strongly indicated and perceived in the right ear.

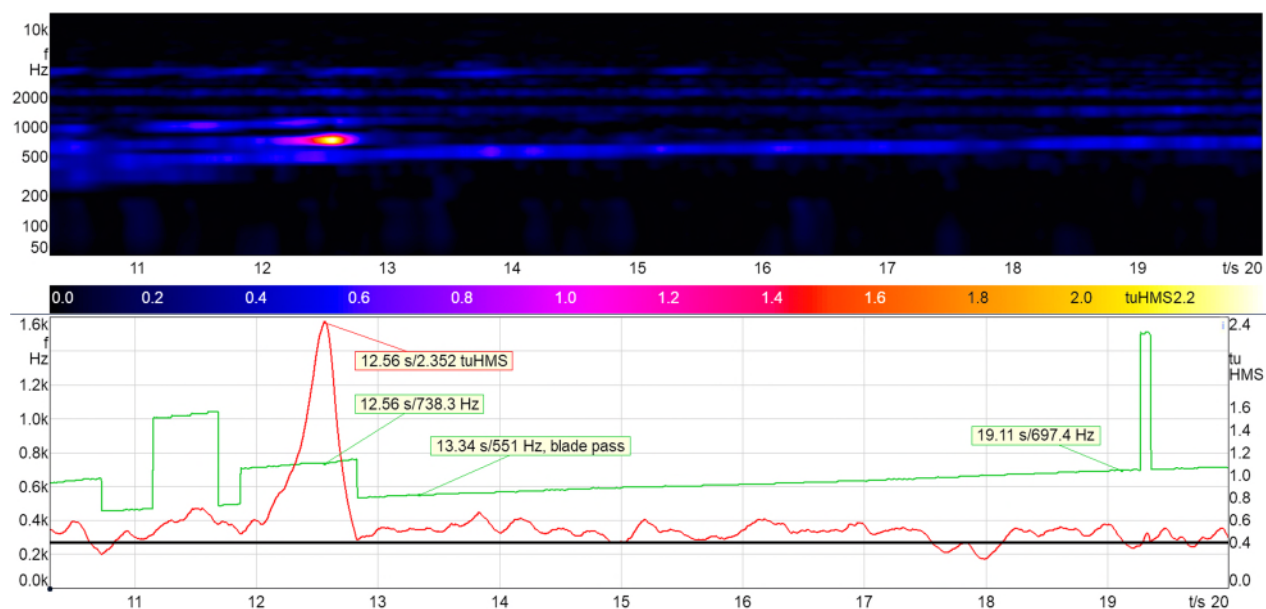


Fig. 8 – Hair dryer run-up (rising voltage): Upper: Specific Tonality (Hearing Model) vs. time. Lower: frequency (green, left scale) and magnitude (red, right scale) of Tonality (Hearing Model) vs. time. From 13 to 19 seconds, the principal tonality is from the blade pass, while at 12.56 seconds another rotational order excites a strong resonance.

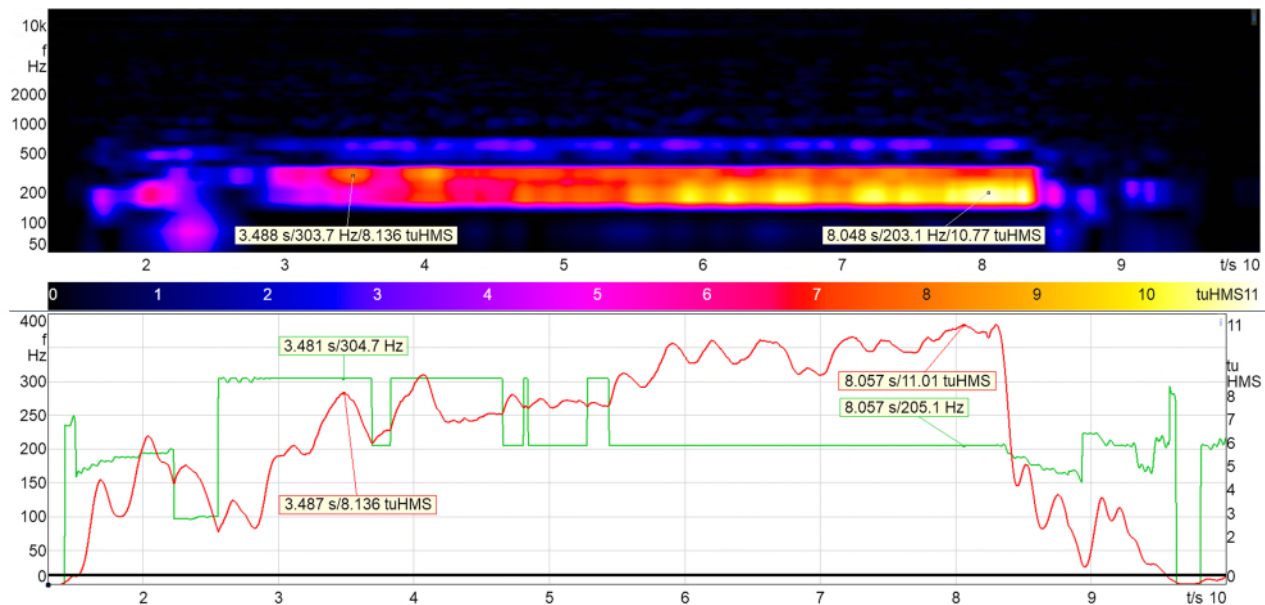


Fig. 9 – Electric lawn mower started, run up to speed and stopped (same analyses as in Fig. 8).

Because the suggested tolerance for reportable prominent tonality in *Tonality (Hearing Model)* is a constant, 0.4 tuHMS (the horizontal black line in Figures 6, 7, 8 and elsewhere), it can be applied against a time or RPM abscissa, as well as against a frequency abscissa.

7 DISCUSSION: RELATIONSHIPS AND ENGINEERING INFORMATION

As shown in Figs. 4 through 9, the *Tonality (Hearing Model)* analysis which provides great detail in frequency is *Frequency of Tonality (Hearing Model) vs. time*. The analyses *Specific Tonality (Hearing Model)* (an average measurement) and *Specific Tonality (Hearing Model) vs. time (or vs. RPM)* display $\frac{1}{2}$ -critical-bandwidth frequency resolution in $\frac{1}{2}$ -critical-bandwidth steps, and therefore do not directly reveal the precise center frequency of a tonality (whether due to a pure tone or other relationship). Whereas by employing very numerous highly overlapped critical bandwidth filters, the analysis *Frequency of Tonality (Hearing Model) vs. time*, not available as an average measurement, provides approximately 3 Hz resolution at lower signal frequencies and 24 Hz at the highest signal frequencies with four steps between those resolutions. Therefore, even for a steady-state signal, it is recommended additionally to use *Frequency of Tonality (Hearing Model) vs. time* to determine fine frequency-of-tonality detail.

Although *Tonality (Hearing Model)* results are entirely sufficient concerning perceived tonalities, evaluation of other analyses along with the psychoacoustic tonality results can provide engineering information regarding causes of tonalities and relationships to spectral shapes. For this purpose it can be worthwhile to display an *FFT average* analysis along with a *Specific Tonality (Hearing Model)* (average) analysis (in the same graphic window or disposed vertically with identical frequency axes – see Figure 1 for an example), or for a time-varying situation, an *FFT vs. time* side-by-side with a *Specific Tonality (Hearing Model) vs. time* analysis, with identical (vertical) signal frequency axes.

Product sounds often exhibit other perceptually-important characteristics besides tonality, so the idea of making more than one analysis can again be useful. In a similar way to evaluating the *FFT vs. time* side-by-side with *Specific Tonality (Hearing Model) vs. time* as mentioned above, it can be valuable to display side-by-side the analyses *FFT vs. time*, *Specific Tonality (Hearing Model) vs. time* and *Specific Roughness vs. time*, as in Fig. 10 regarding the sound of a small compressor which exhibits tonality in one frequency range and roughness (fast modulation) in another frequency range, both effecting the perception.

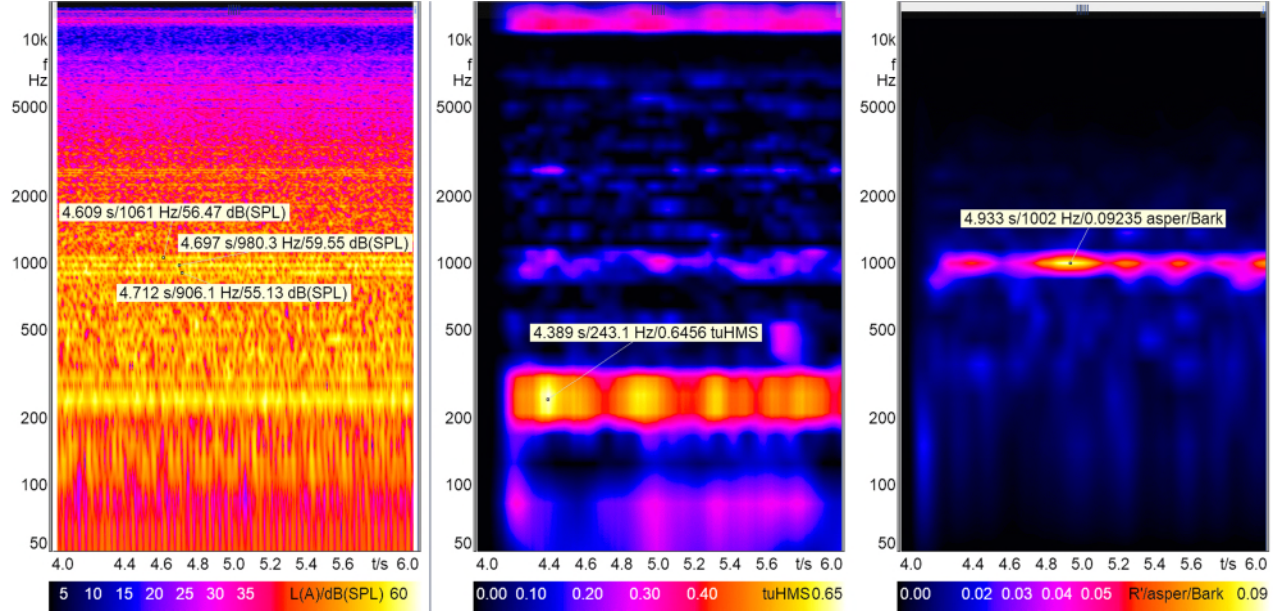


Fig. 10 – Small compressor with both tonality and roughness: use of multiple analyses. Left to right: *FFT vs. time* (A-weighted), *Specific Tonality (Hearing Model) vs. time*, *Specific Roughness vs. time*. The *FFT vs. time* reveals the cause of the roughness centered at about 1000 Hz: beating of three tones (frequencies labeled, highest to lowest, spaced about 78 Hz). Also note the rapid changes of tonality (fine vertical stripes seen in the region of high tonality in the center analysis).

8 CONCLUSIONS

The new psychoacoustic tool, *Tonality (Hearing Model)*, can measure essentially all perceivable tonalities in a reliable, perceptually-valid way with high resolution in both time and frequency, and can provide more information than other methods.

9 ACKNOWLEDGMENTS

The author would like to thank his colleagues, Prof. Dr. Roland Sottek and Dr. Julian Becker, the developers of *Tonality (Hearing Model)*, not only for their work bringing this process into existence but also for many fruitful conversations. The interest and encouragement of

Information Technology and automotive colleagues and contacts over a number of years is much appreciated and has been a material impetus in arriving at this capability. The topic of tonality measurement and its historically variable agreement with perception has been the most frequent issue brought to the attention of this author in assisting those working in product sound quality.

10 REFERENCES

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