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Decomposition, rating and filtering of tonality and other acoustic structures in noise

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ABSTRACT

For the subjective evaluation of noise and sounds often a note scale is used for the characterization of tonal components.
Here we present a method for an objective measure of the grade of tonality. For this a tool is developed which decomposes the sound online into tonal components, modulations, pulses and random noise.
From the random noise a set of equal loudness curves for the tonal components is derived and used to rate each tonal component according to its masked loudness. The results of this rating are compared with the results of the DIN 45681 rating for tonal components dependent on level and frequency.
A similar measure is introduced for the amount of pulses and modulation in the sound. The objective measures can be validated due to the ability to filter the components with independent filter sets for random noise, tonal components and modulations.

1 INTRODUCTION

Evaluation of sound quality today is still a mostly subjective task. There exists a number of psychoacoustic measures for the characterization of sound [1] but a general measure of the overall sound quality does not exist. This is because the human criteria for the sound depend on the context in which the sound is heard. Therefore we cant give the one number measure of sound quality for all sounds and all situations.

However, even the existing psychoacoustic measures like loudness, roughness, tonality and so on are not as widely used as one might think. There are reasons for this:

A) Many measures are available and its often not clear which one can and should be used to characterize the sound at hand.

B) The single value measures do not cover all effects and if the specific measures versus time and frequency are used the situation gets very quickly very complex.

C) It is difficult to relate the psychoacoustic measures to the physical quantities of the sound and to the properties of the machine producing that sound.

D) The relation between the subjective and objective rating often remains unclear and not shure.

In order to address these topics we need tools which are using our knowledge we have about the human hearing system but are showing the physical properties of the sound and giving the relation to the subjective rating made by humans in a specific application.

Here we introduce a new measure for the tonality of a sound together with a characterization of the temporal fine structure. This is integrated in a new tool to analyze the

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spectrum, tonality and other properties of the sound (like pulses and modulations). This includes a display of the physical sound properties and a set of filters to manipulate and verify those components acoustically if needed.

2 A MEASURE OF TONALITY

2.1 Existing Measures

In order to determine the perception of tonality it is necessary to separate the narrow band components from the rest of the sound. The rest or residual sound is filtered into frequency bands according to the human hearing system and the tonal components are rated against the energy of the residual sound of the same frequency band.

For the separation into frequency bands we use the ERB bands as in advanced hearing models [2] since they give a more realistic representation of the human hearing system than the often used Bark scale. For the separation we developed a nonlinear filter which is able to deliver the time signal of the tonal components as well as that of the residual noise. The algorithm works in real-time on todays PC´s which allows for online filtering and remixing of the sound.

In Germany DIN 45681 (Determination of tonal components of noise and determination of a tone adjustment for the assessment of noise immissions) suggests a measure of tonality as dL_tone = L_Tone - (L_Noise – a_v). With L_Noise as the level of the masking background and a_v a mesure for the masking. a_v is 6 dB for the most sensitive case. If the level of the tone is equal to the level of the noise in the same band minus 6 dB the overall energy in that band changes by just 1 dB and the tone is just audible. Therefore the measure in DIN 45681 determines the tone level relative to this detection level.

The difference levels are rated as KT level on a scale from 0 to 6 as shown in table 1.

Table 1: Tone difference level in dB in relation to KT rating

dL Tone [dB]	KT
<= 0	0
<= 2	1
<= 4	2
<= 6	3
<= 8	4
<= 10	5
> 10	6

2.2 Difference of KT rating and perception

The KT value should characterize how much a tonal component disturbs the listener while perceiving the noise. The problem with this measure is that the perception for different tone and noise situations will not fit very well to the rating given with the KT values. In order to see this we compute the loudness of tonal components matching the KT levels with two different noise levels. The noise used here is a pink noise with levels of 45 and 85 dB(A). These values roughly cover the range from an silent office situation to a loud production hall.

The tonal component is placed at 1 kHz and the noise levels in the 1kHz band (900 to 1100 Hz) are 32.5 and 72.5 dB_SPL. The loudness without tones is 0.3 and 3.1 Sone respectively. For different tone levels meeting the available KT ratings the loudness in Sone in the 1kHz band is computed as well as the difference to the loudness without tone. The results for the 45 dB(A) noise are shown in table 2 and those for the 85 dB(A) in table 3.

Table 2: KT value, tone difference level, tone level, Sone value and Sone difference value in the 1kHz band for a 1kHz tone in pink noise with a level of 45 dB(A)

KT	dL Tone [dB]	L Tone [dB]	N[Sone]	dN[Sone]
1	1	27.5	0.33	0.022
2	3	29.5	0.34	0.034
3	5	31.5	0.36	0.051
4	7	33.5	0.38	0.076
5	9	35.5	0.41	0.11
6	11	37.5	0.45	0.14

Table 3: KT value, tone difference level, tone level, Sone value and Sone difference value in the 1kHz band for a 1kHz tone in pink noise with a level of 85 dB(A)

KT	dL Tone [dB]	L Tone [dB]	N[Sone]	dN[Sone]
1	1	67.5	3.3	0.18
2	3	69.5	3.4	0.28
3	5	71.5	3.5	0.42
4	7	73.5	3.7	0.63
5	9	75.5	4.0	0.88
6	11	77.5	4.3	1.20

The Sone difference levels show the masked loudness of the tones perceived by the listener. What we see in table 2 and 3 is that the loudness of the tones meeting the KT values at different noise levels can by very different. The tone in noise rated at a minimum KT = 1 at 85 dB(A) has a masked loudness of 0.18 Sone and will be therefore perceived louder than the maximum rated tone with KT = 6 at 45 dB(A) with a masked loudness of 0.14 Sone. This shows clearly that the KT value cannot reflect the perceived loudness of tones in noise at different levels.

In order to have a rating that matches the human loudness perception of masked tones we need a criterion which incorporates the loudness change in the frequency bands instead of using a certain dB difference.

2.3 Display with equal loudness curves

In order to find a better way to display and measure the masked loudness we can use the well known equal loudness curves. Those curves show the level of a tone versus frequency which produce a constant perceived loudness for a given background noise. in picture 1 we show the pink noise spectrum at 45 dB(A) together with equal loudness contours for the loudness differences from table 2 reflecting the KT ratings 1 to 6 at that noise level. The equal loudness curves show an increasing level at low and high frequencies due to the influence of the hearing threshold.

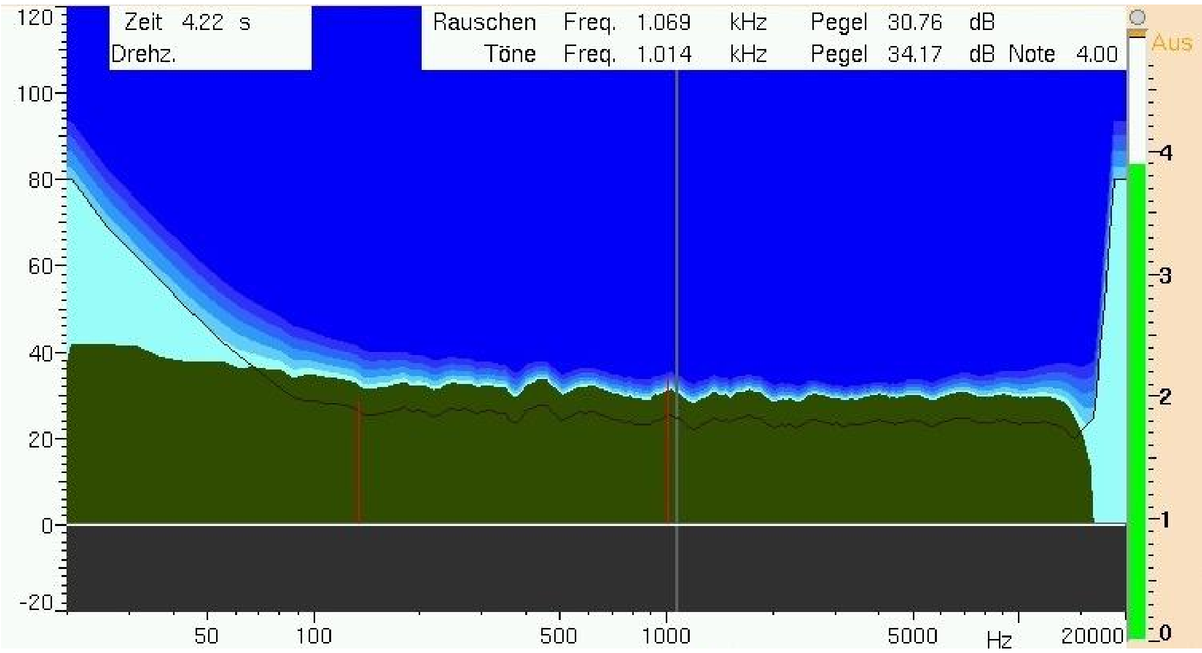

Figure 1: Sound pressure spectrum of pink noise at 45 dB(A) analyzed with ERB filters (green), Equal loudness contours according to the loudness difference levels from table 2 (different blue horizonts), tonal component (red) , masking threshold of the tone in noise (thin black curve) and small modulation components of the noise (yellow). On the right side a bar shows which of the equal loudness curves the tone matches. The grey cursor activates the read out for the next nearest tonal component and the noise level in the top of the figure.

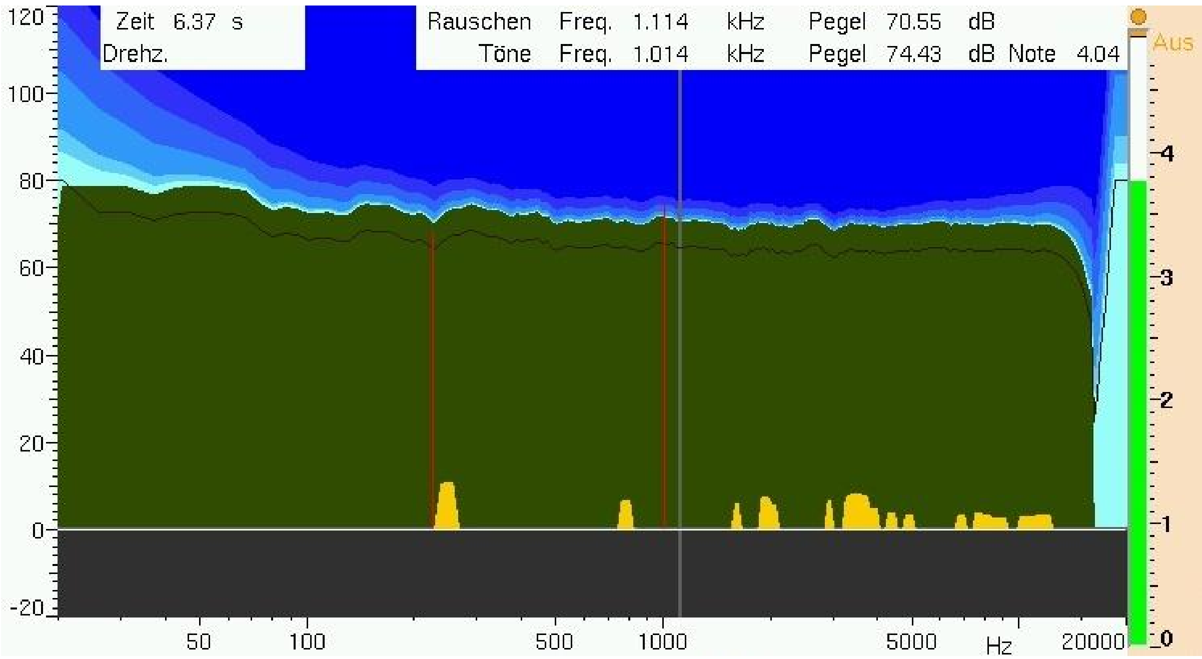

Figure 2: As figure 1 but with 85 dB(A) pink noise and with loudness difference values from table 3.

Figure 2 shows the similar curves for the 85 dB(A) noise and the loudness curves according to the KT ratings at that level. It can be seen that the distance of the loudness contours to the noise level in the region around 1kHz is very similar. This does not reflect the perception in which the loudness of a tone increases very quickly as soon as the tone stands out of noise with a high level. This is due to the fact that a tone will reach the same loudness as if would be presented without noise if it stands out enough of the noise. Therefore at low background levels a tone will only reach the same perception levels if it reaches nearly the same absolute amplitude as the tone in a high background level.

2.4 Loudness differences as a measure

Instead of using a dB difference we should use the loudness difference to measure the loudness of the tones in noise. A meaningful definition of loudness difference levels can be derived from the loudness of a tone in quiet. If we increase the loudness of that tone in equal loudness steps we can characterize those loudness steps by the equivalent dB level of the tone in quiet (in a frequency band with 0 dB SPL hearing threshold). This has the advantage that we do not need to use the loudness values to define the ratings. Table 4 shows possible loudness levels and the corresponding dB SPL levels.

Table 4: dB SPL level and loudness of a tone in quiet in a frequency band with 0 dB hearing threshold

dB SPL	N Sone
25	0.18
30	0.25
35	0.35
40	0.49
45	0.66

The tone levels shown in table 4 are in the range of 25 to 45 dB SPL in quiet. Those levels cover the range from a small to a very prominent tone. Please keep in mind that this experiment can only be done in a isolated chamber. However the dB SPL steps are 5 dB and the adjacent Sone values have a factor of about 1.4. The exact values and step sizes are not significant here. The scaling may vary a little bit depending on the application but the point here is that the loudness levels are characterized by a tone level in quiet and its corresponding loudness.

If we use this tone levels in quiet and compute the equal loudness curves for the pink noise with the two different levels we get the curves in figure 3.

Here we see that the equal loudness curves have a very different shape for the two noise levels, due to the different amount of masking through the pink noise and because of the influence of the hearing threshold. For instance a tone with a level matching the lower red curve presented in 45 dB(A) noise will be perceived with the same loudness as a tone matching the upper red curve presented in 85 dB(A) noise. And both are equal to a tone at 45 dB SPL in quiet (if the hearing threshold is 0 dB SPL in that band).

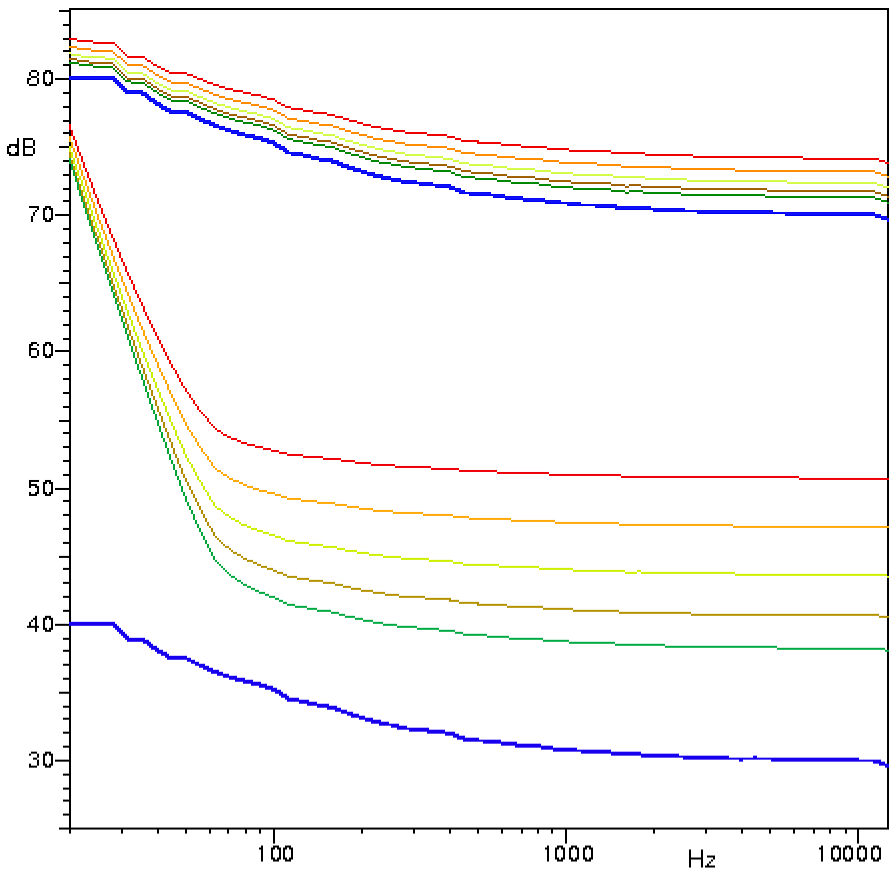

Figure 3: dB SPL levels in ERB bands for pink noise at 45 and 85 dB(A) (thick blue curves) together with the equal loudness level curves at both levels shown for the Sone differences from table 4. The curves with colors green, brown, yellow, orange and red are equivalent to the loudness of tones in quiet with the dB SPL values of 25, 30, 35, 40 and 45 dB.

2.5 Rating with equivalent tone in quiet levels

Now we can use these "tone in quiet" levels to rate the tonal components in noise by the following procedure:

1. Separation of tones and other sound components (residual noise) with a nonlinear filter method
2. Calculation of the Sound Pressure Levels of the residual noise in ERB bands
3. Determination of the equal loudness contours for given "tone in quiet" levels as a reference
4. Rating of the level of each tonal component according to the equal loudness contour it matches. Levels between two contours may get an interpolated rating

With this procedure we get a score for each tonal component and we derive the overall score from the maximum score of all tonal components found. In figure 1 and 2 we can see a bar display on the right side of the figure showing the score which was in those figures adjusted to different levels in quiet in order to match the KT rating at the different levels. With the levels from table 4 we now get the figures 4 and 5 instead.

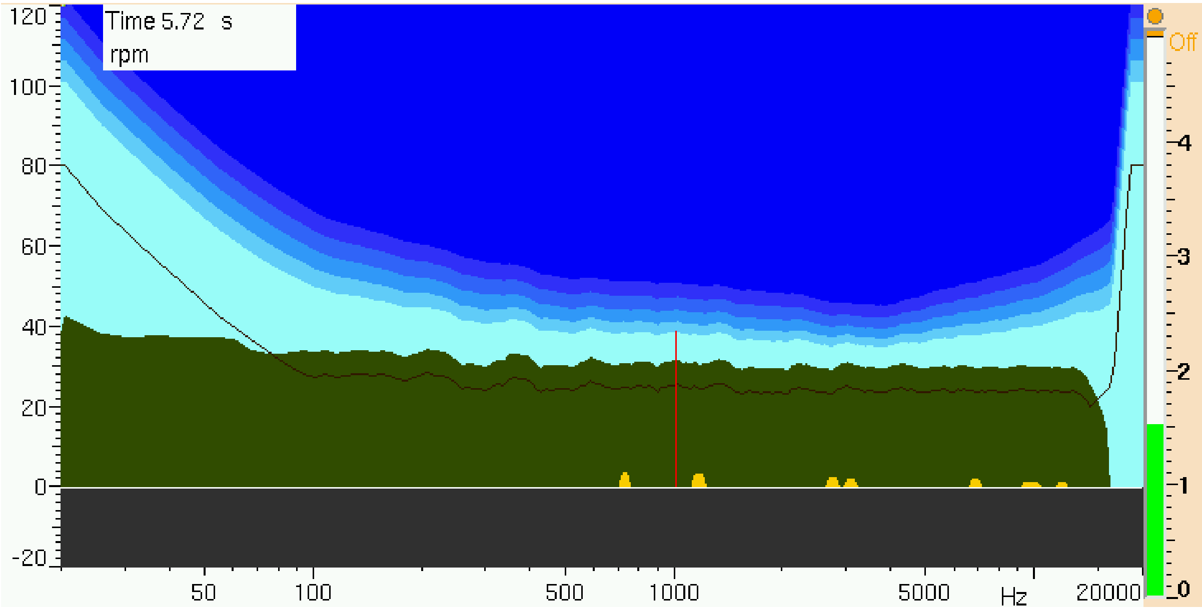

Figure 4: Sound pressure spectrum of pink noise at 45 dB(A) as in figure 1 but with loudness difference levels for the equal loudness contours from table 4.

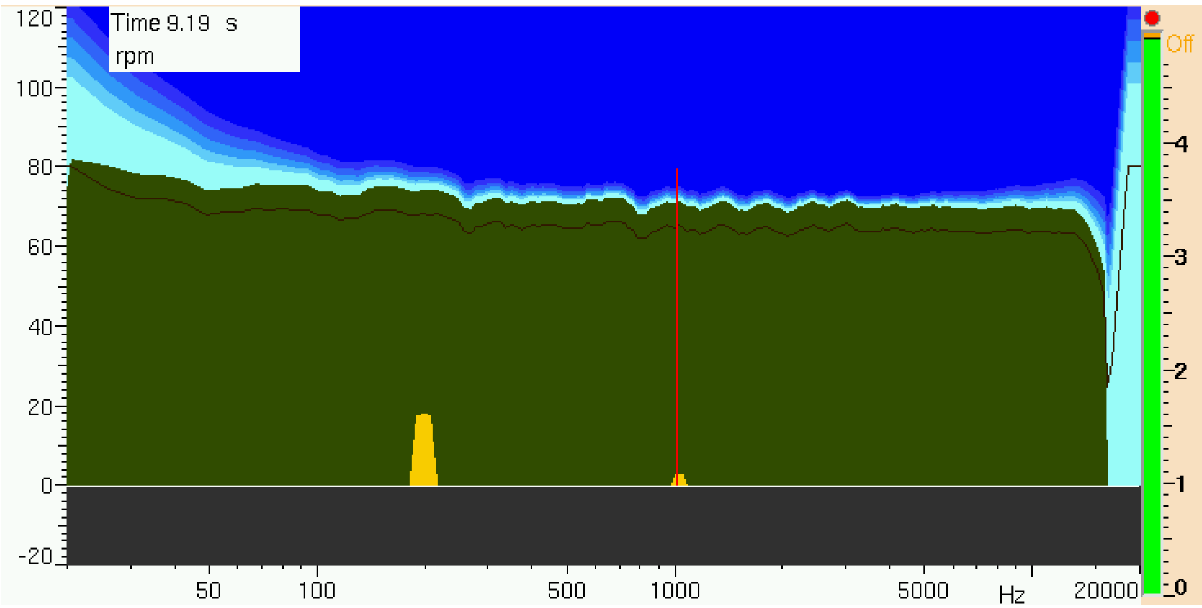

Figure 5: Sound pressure spectrum of pink noise at 85 dB(A) as in figure 2 but with loudness difference levels from table 4.

Now we see that the scores for the tone levels at KT ratings of 4 are very different for the two noise levels. While the tone with a constant dB difference to the noise gets a very low score around 1.5 at 45 dB(A) it gets a very high score (much above 5) at 85 dB(A). The score matches the audible impression much better here than the KT rating.

3 CHARACTERIZATION OF THE RESIDUAL NOISE

3.1 Display of modulation degree

While the tonality of the sound can be characterized now with a score defined by a tone level in quiet the residual noise need to be characterized as well. The spectral content can be seen easily in the display of the ERB band levels. What is missing is the temporal fine structure in each band. This temporal structure or amplitude modulation in each band is detected by the human hearing system up to 100 Hz if the bandwidth of the ERB band allows this [3].

In order to cover all the different effects in one display the degree of modulation in each band can be computed. This is also a physical measure and can be shown as a proportional curve to the sound spectrum. That is if the modulation degree in one band is for instance 0.5 we show an additional curve with half of the dB level.

The modulation display is shown in figure 6 for a noise in the range of 1500 to 8000 Hz which is 100% modulated in the range of 3000 to 6000 Hz.

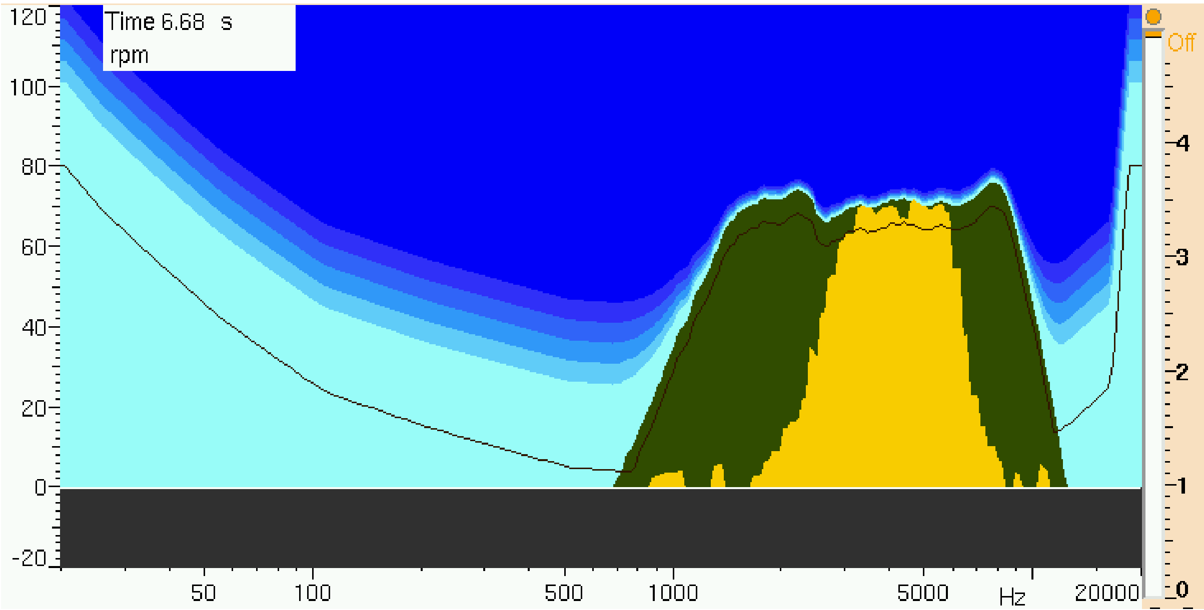

Figure 6: Noise in the range of 1500 to 8000 Hz which is 100% modulated in the range of 3000 to 6000 Hz. The noise level is shown by the green area and the modulation degree is shown by the yellow area. The height of the yellow area relative to the green shows the degree of modulation.

With the display of the modulation degree all fast temporal properties of the sound are covered. This are all properties which show variations in the range from 10ms to 200ms. All slower variations called fluctuations and can be seen as changing noise level in the spectral display. All faster variation like pulses are also detected as modulations since they are handled very similar to the processing in the human hearing system.

3.2 Filtering of noise components

In order to verify the properties of the sound or to design a certain sound it is helpful to filter the the sound components and check acoustically if the effects are as expected.

Since the tonal components are separated from the residual noise and available as time signals they can be filtered independently. For this purpose a different filter set for noise and tonal components exist. Due to the separation the tonal components can be filtered even with filter forms not very specific to certain frequencies. This is a big advantage for tonal components with changing frequency if the frequency of the components is not available separately as in turbo chargers or similar. Some examples for the possible filter forms are shown in figure 7.

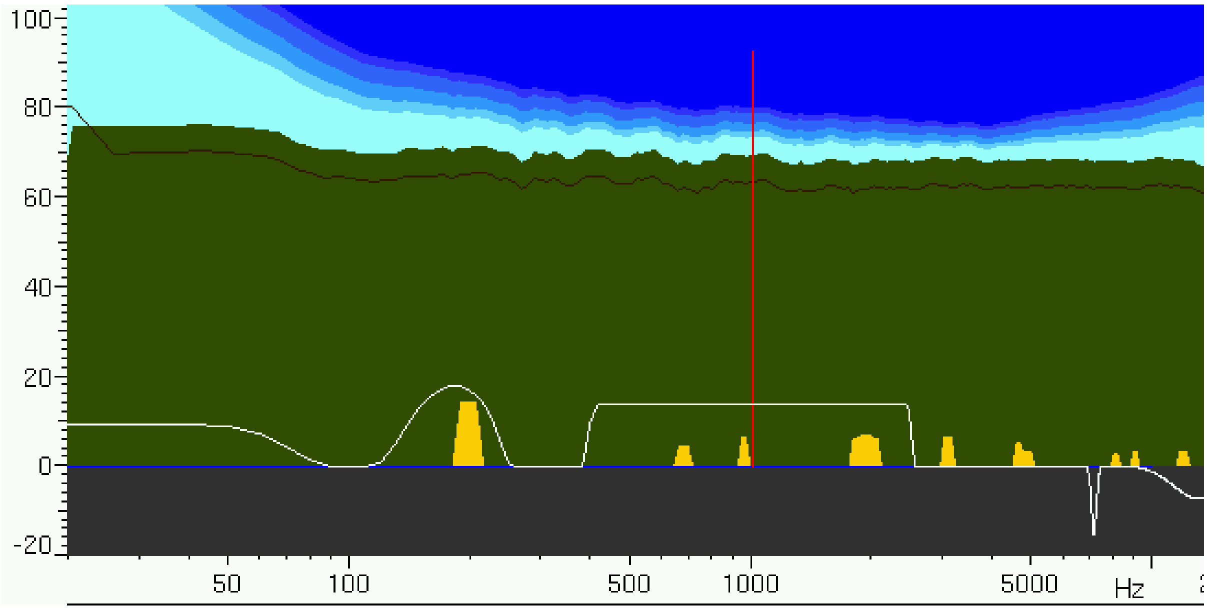

Figure 7: possible filter forms to be freely applied on noise, tones and even modulation: frequency step, smooth band filter, sharp band filter, narrow filter

In order to check the display of modulation degree it is helpful to change the modulation in a frequency band. This is also realized as a nonlinear filter which can reduce the degree of modulation up to the point where no temporal significant structure is available anymore. The spectral shape and energy remains constant but the temporal cues are filtered out of the sound with a 3rd set of filters.

4 CONCLUSIONS

Tonality can be measured with a new measure using the masked loudness of tonal components. The scores for tonality can be defined by a comparison with the level of tones in quiet instead of using loudness quantities.

The noise without tones may be characterized by the modulation degree in each frequency band. With those measures – spectrum level, tonal components and modulation degree --- the sound is completely covered. This can be verified acoustically with filters operating separately on the sound components.

All this is possible due to the use of nonlinear filter techniques in order to decompose sound elements and to filter modulations. The complete analysis and filter capabilities are easily available now in a tool which allows for real time processing.

5 REFERENCES

[1] E.Zwicker and H.Fastl, *Psychoacoustics facts and models* (Springer Verlag, Berlin Heidelberg, 1990).

[2] T. Dau, D. Pueschel, and B. Kollmeier, “A quantitative model of the ``effective'' signal processing in the auditory system. I. Model structure,” Journal of the Acoustical Society of America, **99**, 3623 (1996).

[3] A. Kohlrausch, R. Fassel and T. Dau, “The influence of carrier level and frequency on modulation and beat-detection thresholds for sinusoidal carriers,” Journal of the Acoustical Society of America, **108**, 723 (2000).