

Objective Method for Assessing the Audibility of Tones in Noise Joint Nordic Method – Version 2

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1. Introduction

In the first part of this paper (Chapter 2) a simple procedure for assessing the audibility of tones in noise, based on a visual inspection of a narrow-band frequency spectrum is described. In Appendix B this is supplemented by a more elaborate and accurate procedure suitable for automation.

The aim of this objective method is to assess the prominence of tones in the same way as average listeners do subjectively.

The method is based on the psychoacoustic concept of critical bands (approximated Zwicker critical bands). These are frequency bands with bandwidths defined so that tones outside one critical band do not contribute significantly to the audibility of tones inside that critical band.

In accordance with the results from listening tests the audibility of tones with stationary or fluctuating level or of narrow bands of noise is calculated from a frequency spectrum averaged over “long” time (minutes). The audibility of tones with large variation in frequency is handled by looking at a number of frequency spectra, each representing part of the total measurement time.

2. Measurement and Analysis

The method has three steps:

- 1) Narrow-band frequency analysis (preferably FFT analysis)
- 2) Determination of the average sound pressure level of the tone(s) and of the masking noise within a critical band including the tone(s)
- 3) Calculation of the audibility of the tones, ΔL_{ta} , and the penalty, k

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2.1 Frequency Analysis

A narrow-band A-weighted spectrum is measured by linear averaging for at least one minute (designated “long-term averaging” in the text).

The effective analysis bandwidth shall be smaller than 5% of the bandwidth of the lowest critical band with tonal components.

Hanning weighting is recommended as window function. It is also recommended that the measuring set-up is calibrated so that the spectrum shows correct absolute levels in dB re 20 μ Pa.

Notes:

- The effective analysis bandwidth (or the effective noise bandwidth) of a filter is defined as the width of an ideal filter which would transmit the same power from a white noise source.
- With an effective analysis bandwidth of 5% of a critical band just audible tones will normally appear as local maxima of at least 8 dB above the surrounding masking noise in the averaged spectra.
- In rare cases of a tone complex with many closely spaced tone components a finer resolution may be needed to determine the level of the masking noise correctly.
- Preferably there shall be no “holes” in the sampling of the signal, so preferably 100%, but at least 75%, of the signal shall be represented in the measured spectrum.
- For wind turbines 1-minute averaging is recommended corresponding to the averaging time of L_{Aeq} and of wind speed.
- If the frequency of audible tones in the spectrum varies more than 10% of the frequency range of the critical band, it may be necessary to subdivide the long-term average into a number of shorter term averages, see Appendix B, Section B.1.4.

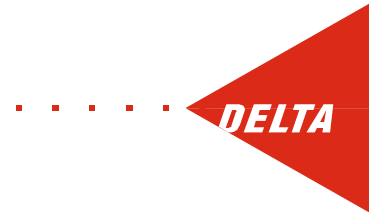
2.2 Determination of Sound Pressure Levels

2.2.1 Sound Pressure Level of Tones, L_{pt}

The tones may be identified from the frequency spectrum by visual inspection. An exact definition of a tone - and an automatic procedure for identifying tones - is given in Appendix B.

All local maxima with a 3 dB bandwidth smaller than 10% of the bandwidth of the actual critical band are regarded as “tones”. This definition includes narrow bands of noise and tones with frequency variation less than 10% of the critical bandwidth.

The sound pressure levels of the tones are determined from the narrow-band frequency spectrum.



The levels, L_{pti} , of all tones no. i in the same critical band shall be added on an energy basis to give the total tone level for that band, L_{pt} :

$$L_{pt} = 10 \log_{10} 10^{\frac{L_{pti}}{10}} \quad (1)$$

Notes:

- If the frequency of a tone varies more than 10% of the critical bandwidth in the averaging period, the tone will appear as a broader maximum in the spectrum. In such cases analyses shall be carried out as specified in Appendix B, Section B.1.4.
- For FFT-analysis, the tone levels read from the spectrum shall be corrected for the influence of the time window function (e.g. Hanning weighting). This is done by energy addition (minus the overlap of the noise bandwidths) of all lines belonging to the tone, see Appendix B, Section B.1.3.
- In cases where tones appear at low frequencies it is advisable to investigate if the tone level is above the hearing threshold (ISO 226, 1987). If the total tone level in a critical band is below the hearing threshold, this critical band shall be disregarded in the assessment of tonal audibility.

2.2.2 Bandwidth and Centre Frequency of Critical Bands

The widths of the critical bands are shown in Table 1:

Centre Frequency, f_c	50-500 Hz	Above 500 Hz
Bandwidth	100 Hz	20% of f_c

Table 1
Widths of critical bands.

The critical band shall be positioned with its centre frequency at the tone frequency. When a number of significant tones are present in the range of a critical band, the critical band shall be positioned so that the difference between the total tone level, L_{pt} , and the level of the masking noise, L_{pn} , (Section 2.2.3) is maximised.

Notes:

- In the frequency range of a critical band only tones with levels 10 dB or less below the level of the tone with the maximum level are regarded as significant for the definition of the centre frequency.
- The centre frequency of the critical bands, f_c , may vary continuously over the frequency range of interest. The lowest critical band is 0 Hz -100 Hz.

2.2.3 Sound Pressure Level of the Masking Noise within a Critical Band, L_{pn}

The total sound pressure level of the masking noise, L_{pn} , in a critical band is determined from the average noise level within that critical band, $L_{pn,avg}$.

The average noise level, $L_{pn,avg}$, may be found by visual averaging of the narrow-band frequency spectrum (in a range of approximately ± 0.5 to 1 critical band from the centre frequency, f_c) by disregarding all maxima in the spectrum resulting from tones and their possible side bands in that range.

A more precise definition – and a procedure for automatic calculation of the average noise level - is given in Appendix B, Section B.2.

L_{pn} is calculated from the average noise level within the critical band, $L_{pn,avg}$, as follows:

$$L_{pn} = L_{pn,avg} + 10 \log \frac{\text{Critical Bandwidth}}{\text{Effective Analysis Bandwidth}} \quad (2)$$

Note: With the recommended Hanning time window the effective analysis bandwidth is 1.5 times the frequency resolution. The frequency resolution is the distance between the lines in the spectrum.

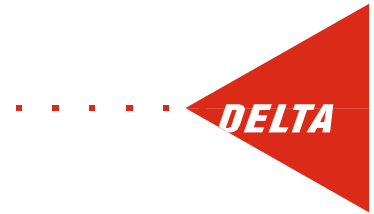
2.3 Calculation of the Tonal Audibility, ΔL_{ta} , and the Penalty, k

The tonal audibility, ΔL_{ta} , is expressed in dB above the masking threshold, MT. The penalty, k , is the value to be added to the value of L_{Aeq} for the noise source to give the tone-corrected rating level. From the difference between tone level and noise level in a critical band, $L_{pt} - L_{pn}$, both ΔL_{ta} and k may be determined by means of Figure 1.

The audibility of tones in a critical band can be calculated by means of Equation (3):

$$\Delta L_{ta} = L_{pt} - L_{pn} + 2 + \log \left(1 + \left(\frac{f_c}{502} \right)^{2.5} \right), \text{ dB re MT} \quad (3)$$

where L_{pt} is the total sound pressure level of the tones in the critical band,
 L_{pn} is the total sound pressure level of the masking noise in the critical band, and
 f_c is the centre frequency in Hz of the critical band.



The penalty, k , in dB is determined by Equation (4):

$$\begin{aligned}
 &\text{for } \Delta L_{ta} < 4 \text{ dB:} && k = 0 \text{ dB} \\
 &\text{for } 4 \text{ dB} \leq \Delta L_{ta} \leq 10 \text{ dB:} && k = \Delta L_{ta} - 4 \\
 &\text{for } \Delta L_{ta} > 10 \text{ dB:} && k = 6 \text{ dB}
 \end{aligned} \tag{4}$$

Note: k is not restricted to integer values.

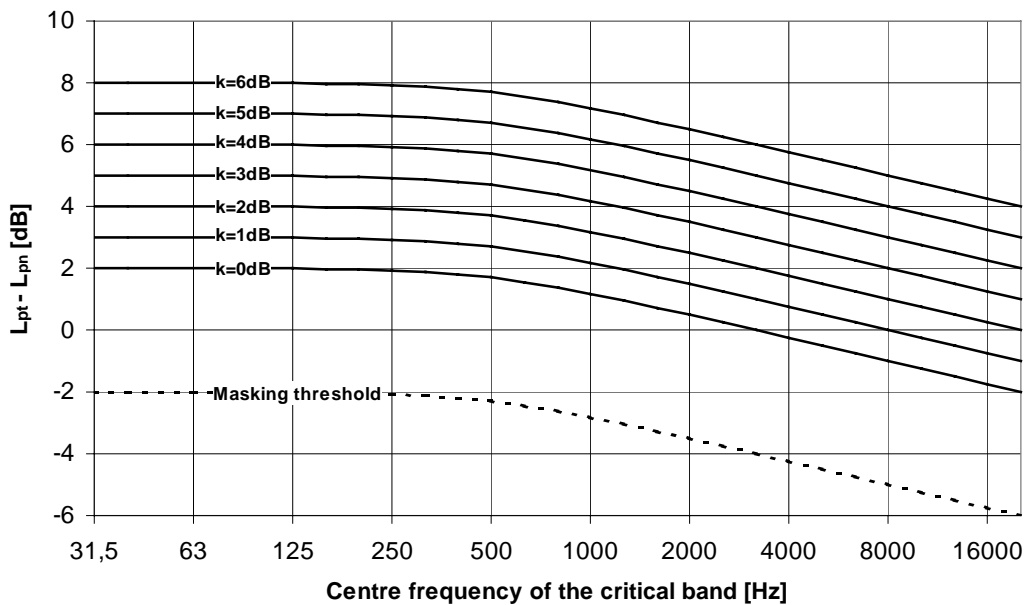


Figure 1
Masking threshold and curves for determining the penalty, k . L_{pt} is the total tonal level in the critical band, L_{pn} is the total masking noise level in the critical band, and the abscissa is the centre frequency of the critical band.

When several tones (or groups of tones) occur simultaneously in different critical bands, a separate assessment shall be made for each of these bands. The critical band containing the most dominant tone(s) (i.e. giving the highest value of ΔL_{ta}) is decisive for the value of ΔL_{ta} and the penalty, k .

3. Documentation

As documentation of the analysis the following information shall be given:

For the analysis:

- Number of averaged spectra and measuring time
- Time window (e.g. Hanning), time weighting (Lin) and frequency weighting (A)
- Effective analysis bandwidth
- One typical spectrum (at least)

For the calculations in the decisive critical band:

- A statement telling if the results were obtained by visual inspection or by automatic calculation
- The frequency limits of the critical band with the most prominent tones
- The frequencies and levels of the tones in that band (L_{pt} in dB re 20 uPa)
- The masking noise level in the critical band (L_{pn} in dB re 20 μ Pa)
- The audibility of the tones (ΔL_{ta} in dB above the masking threshold)
- The size of the penalty (k in dB)

It is recommended that the spectrum is shown together with an indication of the position of the critical band and of the average noise level in that band.

Tones in other critical bands that may cause a penalty should be mentioned by their frequencies.

Appendix A

Background

The method is based on the Zwicker critical bands. The psychoacoustic background of the method may be found in e.g. E. Zwicker & H. Fastl, "Psycho-acoustics, Fact and Models, Springer, 1999".

The method is a proposal for a revision of the Joint Nordic Method for assessing the audibility of tones in noise. The present Joint Nordic Method was accepted as a general Nordic method in 1984 and published by environmental protection authorities in each of the Nordic countries at that time. According to this method a penalty of 5 dB shall be added to the equivalent A-weighted sound pressure level when the noise contains clearly audible tone components, to determine the rating level of the noise. Stationary and non-stationary tones are treated differently. The audibility of non-stationary tones is assessed based on an analysis of several short-term spectra (time weighting F).

In Denmark the present method is used on a regular basis by approximately 30 laboratories for their administration of a +5 dB penalty for annoyance due to prominent (clearly audible) tones in environmental noise from industrial plants and other noise sources including wind turbines. The present objective method is recommended for all noise measurements for legal purposes and shall be used whenever there is doubt whether tones are "clearly audible" or not.

The following problems with the present method have been identified:

- Results from several Round Robin tests have shown that although the accuracy is in general satisfactory, the consistency of results from different laboratories is less for varying tones and noise than for stationary cases.
- The large variation in hearing threshold within the lowest critical bands has in some cases given unreasonable results.
- The 5 dB on/off penalty increases measuring uncertainty dramatically in borderline cases, and at the same time does not correspond to the subjective perception of tones with slightly different prominence.
- Tone and noise levels have not been defined in a precise manner suitable for automation of the objective assessment.

To overcome these problems the following major changes have been made in the Joint Nordic Method, Version 2:

1. The revised method is based on an A-weighted spectrum of the sound pressure level measured with a long averaging time (at least one minute).
2. Stationary and non-stationary conditions are in principle treated the same way.
3. A graduated 0-6 dB penalty replaces the 5 dB on/off penalty.
4. Precise definitions of tone and masking noise levels are included to facilitate automation.

Listening tests have shown good correlation ($R^2 = 0.91$) between subjective evaluations of the audibility of tones and objective evaluations according to this revised method - for stationary as well as non-stationary conditions.

The method has been tested in two experiments. Firstly, 10 persons assessed the tonal audibility in 17 different examples of noise. These examples were artificial head recordings made outdoors of stationary tones in the range 70-7000 Hz generated by a loudspeaker placed in a waterworks plant. The noise from the waterworks was a broadband stationary noise. Secondly, 13 persons assessed the tonal audibility of 14 other examples (mono recordings). These were both synthetic noise and recordings of real noise from industry and from wind turbines. In most of the examples the level of the tones, the noise, or both were varying. Figure 2 summarises the results of both experiments.

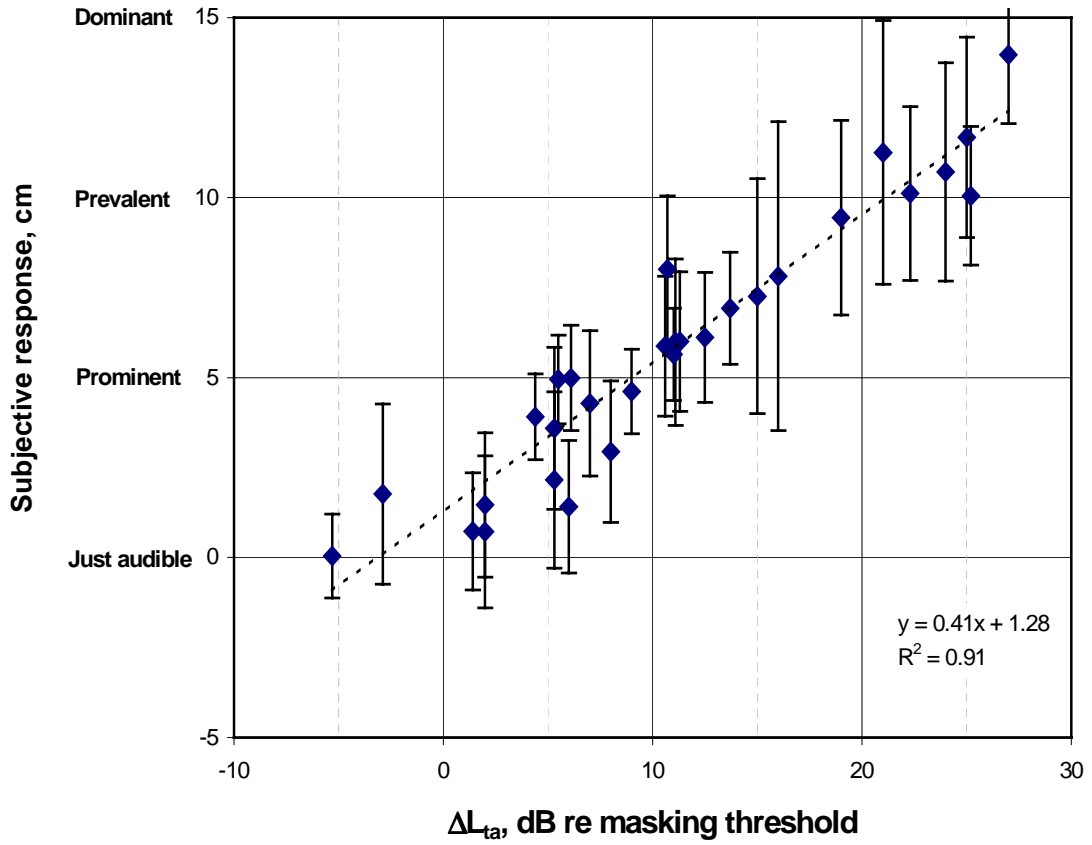


Figure 2

Subjective assessment of tones in noise. The points are the mean values ± 1 sample standard deviation of the subjective assessments of stationary and non-stationary noise examples. The abscissa is the tonal audibility ΔL_{ta} in dB above the masking threshold determined according to the Joint Nordic Method, Version 2.



B. Appendix B Definitions of Tone and Masking Noise Levels

In this appendix strict definitions are given to obtain unambiguous results. The definitions are especially given to facilitate the use of computers for measurement and interpretation of data from analysers.

The definitions are illustrated in Figure 3.

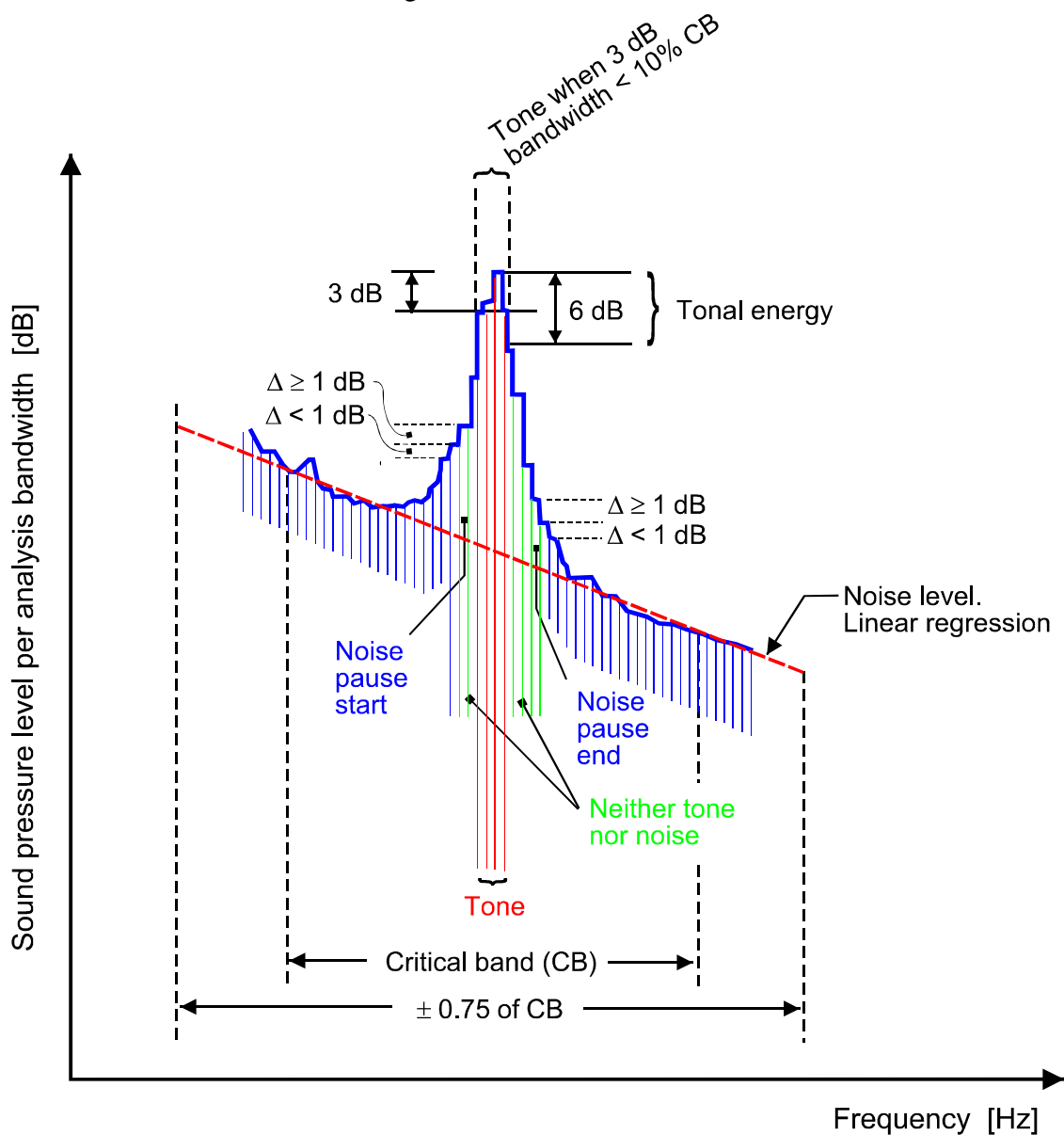


Figure 3
Definitions of tones, noise, and noise pause (neither tone nor noise).

General note:

The technician performing the analysis has the final responsibility for the correctness of the results. It is therefore important that software implementations make it possible to visually inspect the results. At least a spectrum is needed with the lines defined as tones indicated together with the corresponding critical bands and regression lines, see Section B.2.2. Furthermore, separate colouring of spectrum lines characterised as noise, noise pause, and tones would be helpful.

The method given in Chapter 2 has been used for several years in the practical work in a number of laboratories in Denmark. In general analyses are made without problems, but in a few cases it has been necessary to change the tone seek criterion (see Section B.1.2) and the range for the linear regression (see Section B.4.2) to get reasonable results. The above-mentioned tools are necessary in such cases.

B.1 Tones

B.1.1 Definition of a Tone

Tones are defined as maxima in the spectrum with a 3 dB bandwidth less than 10% of the width of the surrounding critical band (see Section 2.2.2). This definition includes tones as well as narrow bands of noise.

Tones with frequencies varying more than 10% of the bandwidth of the critical band are also defined as tones, but they require special analyses as described in Section B.1.4.

For manual or semiautomatic calculation of tone audibility, the tones may be pointed out manually.

B.1.2 Tone Seek Procedure

For automatic calculation based on spectra measured with Hanning time window, the following tone-see procedure may be used to identify tones.

B.1.2.1 Determination of Noise Pauses

Noise pauses are local maxima with a probability of a tone. The noise pauses are identified by Procedures 1 and 2.

Procedure 1a - forward search

The noise pauses are identified by investigating the lines in the spectrum from low towards higher frequencies.

The start of a noise pause is defined as the line, s , where the following conditions are met:

$$L_s - L_{s-1} \geq X \text{ dB} \quad \text{AND} \quad L_{s-1} - L_{s-2} < X \text{ dB} \quad (5)$$

where L_s is the level of line no. s and L_{s-1} is the level of line no. $s-1$, etc. X is the tone-seek criterion and is normally chosen as 1 dB.

Note: For normal and smooth spectra a tone-seek criterion of $X = 1$ dB works without problems. For irregular spectra (e.g. spectra with short averaging time as mentioned in Sections 2.2.2 and B.1.4) values of up to 3 or 4 dB may give better results. It is recommended that this parameter is user-defined in software implementations of the method.

The end of a noise pause is defined as the line, e , where the following conditions are met:

$$L_e - L_{e+1} \geq X \text{ dB} \quad \text{AND} \quad L_{e+1} - L_{e+2} < X \text{ dB} \quad (6)$$

A preliminary noise pause interval is defined as all the lines s to e including both.

The search for the next noise pause starts at line no. $e+1$.

Procedure 1b – backward search

A noise pause can only contain one noise pause start and one noise pause end. A procedure similar to Procedure 1a shall be performed by investigating the lines in the spectrum from high towards lower frequencies.

Final noise pause intervals

Lines defined as preliminary noise pause in both Procedures 1a and 1b are included in the final noise pause intervals. The remaining lines are preliminarily classified as noise.

Procedure 2 – reclassification of high level noise lines

A group of n lines, no. $j-1$ to no. $j-n$ with levels L_{j-1} to L_{j-n} , shall be formed. n shall satisfy (7).

$$(n-1) \times \text{frequency resolution} < 10 \% \text{ of CBW} < n \times \text{frequency resolution} \quad (7)$$

CBW is the width of the critical band with its centre frequency at line no. j or of the lowest critical band 0 Hz – 100 Hz.

Step 2a

First, the group of n lines shall be positioned at the lowest frequencies. The highest level L_{\max} of the lines in the group classified by Procedure 1 as noise shall be determined.

If this first group does not contain any line classified by Procedure 1 as noise, then the group shall be moved in steps of one line until the group contains one line classified as noise.

Step 2b

When line no. j has been preliminarily classified as noise by Procedure 1, and when $L_j - L_{\max} \geq 2 \times X$, then its classification shall finally be changed to noise pause. When $L_j - L_{\max} < 2 \times X$, no change is made.

Step 2c

When line no. j (before or after performing Step 2b) is a noise pause, then for this reclassification procedure it shall be assigned the level L_{\max} .

Note: The tone level and the masking noise level shall be calculated using the original levels, no matter if other preliminary values have been assigned in this reclassification procedure.

Step 2d

The group shall be moved one line towards higher frequencies. If needed, the number n of lines in the group shall be adjusted to satisfy (7). The whole procedure shall be repeated from Step 2b.

Note: In an attempt to clarify Procedure 2, a pseudo program code is given in Appendix D.

B.1.2.2 Identification of a Tone within a Noise Pause

The tones are to be found within noise pauses. A tone may exist when the level of any line in the noise pause is 6 dB or more above the levels of lines no. $s-1$ and $e+1$.

The bandwidth of the detected peak in the spectrum is defined as the 3 dB bandwidth relative to the maximum line in the noise pause.

When this 3 dB bandwidth is larger than 10% of the critical bandwidth, the lines are regarded as neither tones nor narrow-band noise. No penalty is given for this phenomenon, unless it is caused by a tone with varying frequency, see Section B.1.4.

When the 3 dB bandwidth is smaller than 10% of the critical bandwidth, all lines with levels within 6 dB of the maximum level are classified as tones. The tone frequency is defined as the frequency of the line with the maximum level in the noise pause.

Note: If a pure tone is assumed, then the exact tone frequency may be determined from the frequency of the maximum line by correcting for the picket fence effect for the applied window function. This is not a part of the method.

B.1.3 The Level of the Detected Tones

The tone level, L_{pt} , is the energy sum of all lines, L_t , with levels within 6 dB of the above-mentioned maximum level and corrected for the influence of the applied window function (e.g. Hanning weighting) according to Equation (8):

$$L_{pt} = 10 \log \left(10^{\frac{L_t}{10}} + 10 \log \frac{\text{Frequency resolution}}{\text{Effective Analysis Bandwidth}} \right) \quad (8)$$

Notes:

- The levels of the lines classified in this way as tones shall not be corrected for the influence of the noise (i.e. no correction shall be made for the masking “background noise”).
- For the Hanning window function the effective analysis bandwidth is 1.5 times the frequency resolution.

B.1.4 Tones with Frequency Varying more than 10% of the Critical Bandwidth

Tones with varying frequency appear as broad maxima in the long-term average spectrum. The width of these maxima depends on the range of the frequency variation of the tone. When the frequency of a tone varies more than 10% of the width of the critical band during the averaging period, the 10% bandwidth criterion (see Section B1.1) shall be overruled, and all lines within the broad maximum of the tone shall be classified as tones

If the level of each of the spectral lines originating from the tone is more than 6 dB above the surrounding noise, the total tone level can be found by energy summation of these lines according to Equation (8). Alternatively, the long-term averaging can be subdivided into a number of periods with shorter averaging time, and the tone level may be found as the energy average of the tone levels found from each of these short-term spectra.

A result of the analysis of a tone with varying frequency is illustrated in Appendix C, Example 4.

Notes.

- Software implementations of the method shall allow for overruling the 10% criterion and preferably provide the possibility of manual selection of the frequency range to be defined as tone.
- For wind turbines in general an averaging period of one minute is recommended. If one minute is too long for variable speed wind turbines, it is recommended to subdivide the averaging period into 10-second periods.

B.2 Masking Noise

B.2.1 Definition of Masking Noise

In a spectrum all lines which are not characterised as noise pauses (see Section B.1.2) are defined as masking noise.

B.2.2 Masking Noise Level

The masking noise level of the spectral lines within a critical band is defined by making a first order linear regression through all lines defined as noise. The range of the regression should usually be chosen as ± 0.75 critical bandwidth around the centre frequency of the critical band.

Note: For irregular spectra (e.g. the short-term spectra mentioned in Section B.1.4) or for spectra with broad tonal maxima, the range of the linear regression may be extended to ± 1 or 2 critical bands. This may bring the regression line in better correlation with the general shape of the noise floor. It is recommended for the range of the regression analysis to be user-defined in software implementation.

To each spectral line within the actual critical band a noise level, L_n , shall be assigned as predicted by the regression line. The total masking noise level, L_{pn} , in the critical band is determined as the sum on an energy basis of the assigned levels, L_n , for all lines in the critical band with correction for the applied window function.

$$L_{pn} = 10 \log \left(10^{\frac{L_n}{10}} + 10 \log \frac{\text{Frequency resolution}}{\text{Effective Analysis Bandwidth}} \right) \quad (9)$$

Note: For the Hanning window function the effective analysis bandwidth is 1.5 times the frequency resolution.



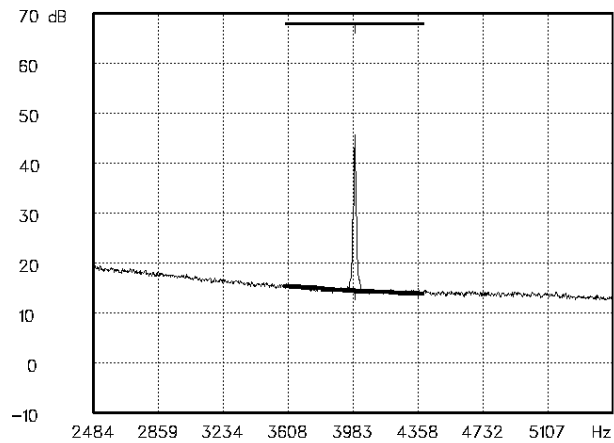
Appendix C Examples

The examples in this appendix have been analysed with an automatic procedure as follows:

- Number of spectra: 350, measuring time: 2 minutes
- Hanning weighting, linear averaging
- Effective analysis bandwidth: 4.39 Hz

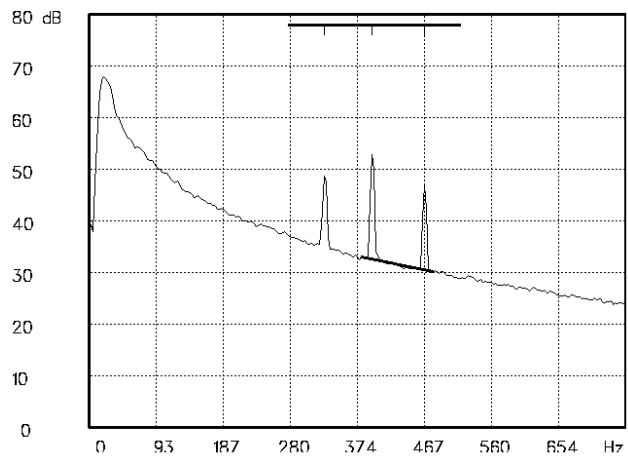
Example 1

Critical band: 3.6 kHz - 4.4 kHz
 Tones: 4 kHz, 46.7 dB
 Tonal level, L_{pt} : 46.7 dB
 3 dB bandwidth of tone: 0.5% of 800 Hz
 L_{pn} in critical band: 37.3 dB
 Tonal audibility: ΔL_{ta} : 13.7 dB re MT
 Penalty, k: 6 dB



Example 2

Critical band: 380 Hz – 480 Hz
 Tones: 395 Hz, 53.1 dB
 468 Hz, 47.0 dB
 Tonal level, L_{pt} : 54.1 dB
 3 dB bandwidth of tone: 3.1% of 100 Hz
 L_{pn} in critical band: 45.2 dB
 Tonal audibility: ΔL_{ta} : 11.1 dB re MT
 Penalty, k: 6 dB



Notice: The two tones with the highest frequencies give the highest ΔL_{ta} .



Example 3

Critical band: 258 Hz – 358 Hz

- Tones: 278 Hz, 33,3 dB
- 299 Hz, 38,4 dB
- 319 Hz, 54,3 dB
- 334 Hz, 37,1 dB

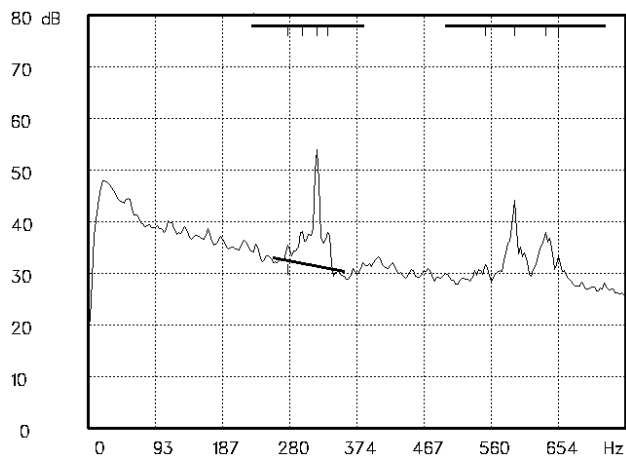
Tonal level, L_{pt} : 54.6 dB

3 dB bandwidth of tone: 3.4% of 100 Hz

L_{pn} in critical band: 45.5 dB

Tonal audibility: ΔL_{ta} : 10.6 dB re MT

Penalty, k: 6.0 dB



Example 4

Critical band: 680 Hz - 830 Hz

Tone is varying between 680-758 Hz

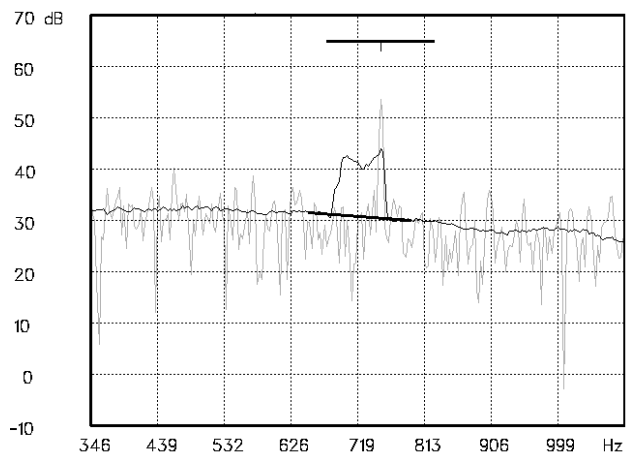
Tonal level, L_{pt} : 53.6 dB

L_{pn} in critical band: 45.5 dB

Tonal audibility: ΔL_{ta} : 10.7 dB re MT

Penalty, k: 6 dB

Notice: The graph shows both an averaged spectrum and an instantaneous spectrum. According to Sections 2.2.1 and B1.4 the tonal level may either be found by energy summation of the lines in the broad maximum in the averaged spectrum or by averaging the tone levels from a number of spectra measured with short averaging time, giving the same total averaging time.



Appendix D

Pseudo Program Code Illustrating Procedure 2 – Reclassification of High Level Noise Lines

X = tone seek criterion

n = number of lines in group from (7)

B[j]: TRUE = noise, FALSE = noisepause

```
FOR j=2 TO n DO
BEGIN
  IF B[j] = FALSE THEN
  BEGIN
    L[j] = max(L[1] TO L[j-1])
  END
END

FOR j= n+1 TO last line DO
BEGIN
  IF B[j] = TRUE AND L[j] - max(L[j-1] to L[j-n]) >= 2 * X THEN
  BEGIN
    B[j] = FALSE
  END
  IF B[j] = FALSE THEN
  BEGIN
    Lj= max(L[j-1] to L[j-n])
  END
END
```