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Acoustics — Objective method for assessing the audibility of tones in noise — Engineering method

Acoustique — Méthode objective pour évaluer l'audibilité des tons dans le bruit — Méthode d'expertise

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Foreword

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The committee responsible for this document is ISO/TC 43, *Acoustics*, Subcommittee SC 1, *Noise*.

Acoustics — Objective method for assessing the audibility of tones in noise — Engineering method

1 Scope

This Publicly Available Specification describes a method for the objective determination of the audibility of tones in environmental noise.

This Publicly Available Specification is intended to augment the usual method for evaluation on the basis of aural impression, in particular, in cases in which there is no agreement on the degree of the audibility of tones. The method described can be used if the frequency of the tone being evaluated is equal to, or greater than, 50 Hz. In other cases, if the tone frequency is below 50 Hz, or if other types of noise (such as screeching) are to be captured, then this method cannot replace subjective evaluation.

The method presented herein can be used in continuous measurement stations that work automatically.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1996-1, *Acoustics — Description, measurement and assessment of environmental noise — Part 1: Basic quantities and assessment procedures*

IEC 61672-1, *Electroacoustics — Sound level meters — Part 1: Specifications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 1996-1 and the following apply.

3.1
tonality
presence of a tone in a noise, the level of which is below that of the remaining noise components in the *critical band* (3.5) about the *tone frequency* (3.2) by less than the value of the *masking index* (3.16), a_v

3.2
tone frequency
f_T
frequency of the *spectral line* (3.23) (or mid-band frequency of the narrow-band filter), to the level of which the tone contributes most strongly

3.3
tone level
L_T
energy summation of the *narrow-band level* (3.22) with the *tone frequency* (3.2), f_T, and the lateral lines about f_T, assignable to this tone

Note 1 to entry: If the *critical band* (3.5) for the frequency, f_T, under consideration contains a number of tones, then the tone level, L_T, is the energy sum of these tones. This level, L_T, is then assigned to the frequency of the participating tone that has the maximal value of *audibility* (3.4), ΔL.

Note 2 to entry: The method for the determination of the tone level, L_T, of a tone in a critical band is described in 5.3.3.

3.4
audibility
ΔL
difference between the *tone level* (3.3), L_T, and the *masking threshold* (3.15), L'_T

Note 1 to entry: The method for the determination of the *decisive audibility* (3.24), ΔL_j, of a *narrow-band spectrum* (3.12) is described in 5.3.8.

3.5
critical band
frequency band with a *bandwidth* (3.17), Δf_c, within which the auditory system integrates the sound intensity in the formation of loudness and within which it integrates the sound intensity in the formation of the *masking threshold* (3.15)

Note 1 to entry: This characteristic of a critical band (see also References [3] and [4]) holds only for a restricted sound level range. This dependence is neglected here.

3.6
mean narrow-band level of the critical band
L_S
energy mean value of all *narrow-band levels* (3.22) in a *critical band* (3.5) that (as a rule) does not exceed this mean value by more than 6 dB

Note 1 to entry: The method for the determination of the mean narrow-band level L_S of the masking noise is described in 5.3.2 and Annex D (iterative method).

3.7
critical band level
L_G
level of noise that is assigned to the *critical band* (3.5) that describes the masking characteristic of the noise for one or more tones of the noise in this critical band

Note 1 to entry: See *narrow-band level* (3.22) and Annex C for masking.

Note 2 to entry: For the definition formula for L_G, see Formula (12).

3.8
sampling frequency
f_S
number of samples taken per second

Note 1 to entry: The analogue data provided continuously are converted into samples through sampling at discrete time intervals for digital processing.

Note 2 to entry: To ensure the reproducibility of a digitized signal, the Shannon theorem requires that the sampling frequency, f_S, is at least 2 times the highest frequency of the signal components used for evaluation in the time signal [$f_S \geq 2\ f_N$, see also *aliasing* (3.9), *antialiasing filter* (3.10) and *useable frequency* (3.20)]. The algorithm of a Fast Fourier Transform analysis (the variant of a discrete Fourier Transform used typically and optimized for calculation) only permits *block lengths* (3.11), N, that correspond to a power of two. FFT analyzers thus need a sampling frequency that is at least 2,56 times the maximum frequency to be analysed.

3.9
aliasing
reflection in the *line spectrum* (3.12) of frequency components from the range above the *sampling frequency* (3.8) divided by two ($f_S/2$) in the range below $f_S/2$

Note 1 to entry: *Antialiasing filters* (3.10) are used to avoid errors through such reflections.

Note 2 to entry: Half the sampling frequency ($f_S/2$) is also known as the Nyquist frequency.

3.10
antialiasing filter
low-pass filter
ideal filter that allow frequencies below half the *sampling frequency* (3.8) to pass through completely (without influencing the signal), but completely block all higher frequencies

Note 1 to entry: To prevent *aliasing* (3.9), the noise under investigation shall be filtered using an antialiasing filter before analogue-to-digital conversion.

Note 2 to entry: Real aliasing filters have a final damping (generally 120 dB/octave) within the blocking range, i.e. signal components in this transition range are reflected (damped). For example, in the transformation of 2 048 (2 k) data points, 1 024 frequency lines are calculated and 800 lines shown. A component in the line number 1 248 is folded back into the line number 800. With a low-pass filter of 120 dB/octave the damping of these components is approximately 75 dB.

Note 3 to entry: The usual commercial FFT analyzers have an antialiasing filter, the limit frequency of which can be switched automatically with the selectable sampling frequency. The reflection of simulated *narrow-band levels* (3.22) is suppressed.

3.11
block length
N
block of sampling values that in discrete form represents a time-limited range of the time signal to be analysed

Note 1 to entry: In contrast to frequency analysis with analogue and digital filters, the noise with the Fast Fourier Transform is processed in data blocks. In general, these blocks embrace only a part of the noise recording. The block length, N, expresses the number of data points processed at the same time. Due to the nature of the Fast Fourier Transform, the value of N has the integer of power of 2. It has a value, for example, of $N = 2^{10} = 1\,024$ data points.

3.12
line spectrum
narrow-band spectrum
frequency spectrum
plot of the sound pressure level (*narrow-band level*) (3.22) as a function of the frequency in frequency bands of constant *bandwidth* (3.17) (*line spacing*, Δf) (3.13)

Note 1 to entry: A-weighting of the level is assumed in this Publicly Available Specification.

Note 2 to entry: Frequency analysis delivers a line spectrum, in which each line represents the output of a filter, the mid-frequency of which corresponds to the frequency of the *spectral line* (3.23).

3.13
line spacing
frequency resolution
distance between neighbouring *spectral lines* (3.23), where the line spacing in the FFT is given by

$$\Delta f = f_S / N$$

where

f_S is the *sampling frequency* (3.8);

N is the *block length* (3.11).

Note 1 to entry: In this Publicly Available Specification, the line spacing is 1,9 Hz ≤ Δf ≤ 4,0 Hz.

3.14
time window
time data set of the signal segment (*block length*) (3.11) that is multiplied by a weighting function (window function)

Note 1 to entry: In accordance with the definition of the Fourier integral, a prerequisite of the FFT analysis is that the time data set is periodic. If this is not the case (as with stochastic signals), cut-off effects at the edges of the time window will lead to distortion of the spectrum. These distortions are avoided through weighting functions such as the Hanning Function.

Note 2 to entry: For more information on window and weighting functions, see, for example, Reference [5] and Annex A.

3.15
masking threshold
L'_T
audibility (3.4) threshold for a specific sound in the presence of a masking sound (masker)

Note 1 to entry: See Annex C for more information on the audibility threshold and the masking noise.

3.16
masking index
a_V
difference between the *masking threshold* (3.15), L'_T, and the *critical band level* (3.7), L_G, of the masking noise

Note 1 to entry: For frequency-dependent masking index, a_V, masking and masking noise, see Annex C.

3.17
bandwidth
frequency bandwidth
frequency range of a number of neighbouring *spectral lines* (3.23)

Note 1 to entry: If the width of a frequency band is calculated for which its beginning or end does not correspond to the boundary between two spectral lines, then only the spectral lines that lie in their full width within the calculated frequency range are assigned to the frequency band.

3.18
distinctness
clarity
ratio of the conspicuousness of a tone based on a bandpass noise to the conspicuousness of a sinusoidal tone of the same *tone frequency* (3.2), f_T, and same *tone level* (3.3), L_T

3.19
edge steepness
ratio of the level difference between the maximum *narrow-band level* (3.22) of a tone, L_{Tmax}, and the narrow-band levels of the first line below/above the tone to the corresponding frequency difference

3.20
useable frequency
f_N
upper limit frequency of the signal components used for evaluation

3.21
investigation range
range within which tones are investigated in the *line spectrum* (3.12)

3.22
narrow-band level
averaged level within a *spectral line* (3.23)

3.23
spectral line
frequency band of *bandwidth* (3.17), Δf (*line spacing*) (3.13), in a *line spectrum* (3.12)

3.24
decisive audibility
ΔL_j
maximum *audibility* (3.4), ΔL, in the individual spectrum, j

4 Measurement procedure

4.1 General

The measurement procedure will depend on the aims. The requirements for the measurement and assessment procedure in terms of the choice of measurement point, measurement time and duration of measurement, extraneous noise, etc. shall be satisfied.

The variable for determination of audibility of prominent tones is the sound pressure $p(t)$. For frequency analysis, the A-weighted equivalent continuous sound pressure level, L_{Aeq}, as given in ISO 1996-1, is to be established for the respective spectral lines. If the spectrum is unweighted (linear), then it shall be corrected to A-weighting in accordance with IEC 61672-1.

4.2 Measurement instruments

Sound level meters that meet, or exceed, the requirements of Class 1 in IEC 61672-1 shall be used. These have a frequency weighting “A”/“LIN” or “A”/“Z” with a lower limit frequency equal to, or below, 20 Hz.

Additional instruments such as recording instruments (digital or magnetic tape) may also be used. The measured values derived through recording instruments shall lie within the tolerance range given in IEC 61672-1.

Analysis of frequency components in the measurement signals is performed using a frequency analyzer. The constant line spacing, Δf, shall lie in the range 1,9 Hz to 4 Hz (inclusive). The use of the Hanning window is mandatory in this Publicly Available Specification. For further processing, it shall be ensured that the digitalization of the sound pressure signal across the entire dynamic range used has a resolution of at least 0,1 dB.

Before it is processed further, the analogue measurement signal shall be passed through a steep low-pass filter (antialiasing filter) to avoid errors in frequency analysis. The sampling frequency (see 3.8) shall be at least two times the maximum usable frequency present (see 3.20). The Hanning window is to be used as time window to reduce lateral bands (see 3.14).

4.3 Merging the basic spectra

The spectra for the prominent tone assessment shall have an averaging time of approximately 3 s. Due to the line spacing of 1,9 Hz to 4 Hz (see 4.2) and the typical frequency range, f, of a few kHz, the basic spectra given by the frequency analyzer will have an averaging time below 1 s. To get the averaging time of approximately 3 s, a number of basic spectra shall be merged. This shall be done line by line with Formula (1):

$$L_i = 10\lg\left(\frac{1}{N}\sum_{j=1}^{N} 10^{0,1L_{i,j}/\text{dB}}\right)\text{dB} \tag{1}$$

where

$L_{i,j}$ is the level of the ith spectral line for the jth spectrum;

N is the number of merged spectra.

5 Evaluation

5.1 General information

The aim of evaluation is to establish the audibility, ΔL. The procedure is the same for stationary and non-stationary noises. For tones that can only just be perceived, a quaver (eighth note) is to be adopted as a base time that is adequate for hearing. However, comprehensive studies have shown that the lower limit for use of the procedure is reached at averaging times of approximately 3 s. Lower averaging times lead to unjustified values of audibility, ΔL (too high, but also too low). Signals that have a very high level dynamic and/or frequency dynamic that no longer correspond with a 3-second averaging can, therefore, not be evaluated using this Publicly Available Specification. The following conditions shall be satisfied for the measurements.

— The extended uncertainty, U, of the audibility, ΔL, with a coverage probability of 90 % in a bilateral confidence interval (see Clause 6) shall not exceed ±1,5 dB. This is generally the case with evaluation of at least 12 time-staggered narrow-band averaged spectra. If there are less than 12 averaged spectra then the uncertainty shall be taken into consideration as given in Clause 6.

— Where there are alternating operating states, all of the operating states shall be covered by the averaging spectra used (see Annex E).

Tonal components in different critical bands are evaluated separately. To arrive at a decision on whether a tonal audibility has to be made, only the most pronounced tone is considered. If a number of tones are present within a critical band, then an energy summation of their tone levels, L_{Ti}, is carried out to yield a tone level, L_T (see 5.3.8).

A tonal audibility is performed for a tone only if its distinctness (see 3.18) is at least 70 %. This means a maximal bandwidth, Δf_R, dependent on the tone frequency [see Formula (9)] and necessitates edge steepness (see 3.19) of at least 24 dB/octave.

NOTE 1 For the distinctness of a tone, see 5.3.4.

NOTE 2 Harmonic multiples of a tone are evaluated, independently of that tone, similarly to all other components of the spectrum.

A sample program to determine audibility can be downloaded from http://standards.iso.org/iso/20065

5.2 Width Δf_c of the critical band

The width Δf_c of the critical band about the tone frequency f_T is given by Formula (2):

$$\Delta f_c = 25{,}0\,\text{Hz} + 75{,}0\left[1{,}0 + 1{,}4\left(\frac{f_T/\text{Hz}}{1\,000}\right)^2\right]^{0{,}69}\text{Hz} \tag{2}$$

Assuming a geometric position of the corner frequencies of the critical band (see Annex B), these corner frequencies, f_1 and f_2, are derived as follows:

$$f_T = \sqrt{f_1 \times f_2} \tag{3}$$

$$f_1 = \frac{-\Delta f_c}{2} + \frac{\sqrt{\left(\Delta f_c\right)^2 + 4 f_T{}^2}}{2} \tag{4}$$

$$f_2 = f_1 + \Delta f_c \tag{5}$$

5.3 Determination of prominent tones

5.3.1 General information

The audibility of a tone is determined using the tone level, L_T, and the critical band level, L_G, of the masking noise in the critical band about the tone frequency, f_T. The frequency of all maxima of the spectrum is considered as the tone frequency.

The use of the Hanning window is recommended in Annex A. With window functions (except for rectangular windows), the effective analysis bandwidth, Δf_e, is greater than the bandwidth, Δf, of an ideal filter (see 3.13), i.e. the individual bands are thus superimposed. In the summation process, the energy components are counted a number of times (see Annex A for more information).

In a frequency analyzer, this influence of summation (number of lines >1) is taken into consideration through a correction value; if the level addition is simulated by the analyzer program, then this correction value has to be considered in the computing program, both in the formation of the tone level [see Formula (8)] and in the calculation of the masking noise [see Formula (12)].

5.3.2 Determination of the mean narrow-band level L_S of the masking noise

The mean narrow-band level, L_S, [see Formula (6)] is derived in an iterative procedure from the lines of the critical band about the line under investigation. The procedure commences with the energy averaging of all lines of the critical band with the exception of the line under investigation itself. In the subsequent steps, the levels of the lines of the critical band under consideration are no longer taken into consideration in the averaging procedure if their level exceeds the energy mean value determined beforehand by more than 6 dB. The iterative procedure is discontinued, if in an iteration step, the new energy mean value is equal within a tolerance of ±0,005 dB to that of the previous iteration step or if the number of lines contributing to the mean narrow-band level to the right or left of the line under investigation falls below a value of 5. In this case, the energy mean value from the last iteration step, at which the number of energy averaged levels on both sides of the line under investigation in each case was still at least 5 is used to form the mean narrow-band level.

For determination of the mean narrow-band level, the entire critical band about the line under investigation is used. Consequently, the range under investigation (see 3.21) is limited relative to the useable frequency f_N such that the upper limit of the uppermost critical band being considered does not exceed the useable frequency f_N. A corresponding condition also applies in principle for the lower limit of the lowest critical band considered. Since the use of this Publicly Available Specification is restricted to tone frequencies greater than or equal to 50 Hz and the usual analyzers generate line spectra starting at 0 Hz, it is not generally necessary to take any special precautions.

The mean narrow-band level L_S is given by Formula (6):

$$L_S = \left[10\,\lg\left(\frac{1}{M} \sum_{i=1}^{M} 10^{0,1 L_i/\text{dB}} \right) + 10\,\lg\left(\frac{\Delta f}{\Delta f_e} \right) \right] \text{dB} \tag{6}$$

where

L_i is the narrow-band level of the ith spectral line, in decibels (dB);

M is the number of spectral lines to be averaged in the critical band;

Δf is the line spacing, in Hertz (Hz) (see 3.13);

Δf_e is the effective bandwidth in Hz; if a Hanning window is used then the effective bandwidth, Δf_e, is 1,5 times the frequency resolution (line spacing), Δf (see Annex A).

If the spectrum is unweighted (linear), then it shall be A-weighted in accordance within IEC 61672-1.

NOTE 1 If the iteration is discontinued, because the remaining number of spectral lines to be averaged on one or both sides falls below 5, then the audibility may be somewhat greater than the audibility calculated with this mean narrow-band level.

NOTE 2 The iteration procedure is described in Annex D.

NOTE 3 Using a digital calculation program, the equal condition in the iteration procedure is typically given by the resolution of the number format (high resolution should be used).

5.3.3 Determination of the tone level L_T of a tone in a critical band

The tone level L_T is determined from the individual levels of the spectral lines in the critical band about f_T that contain energy to be assigned to the tone. In principle, a tone may only be present if the level of the spectral line considered is at least 6 dB greater than the corresponding mean narrow-band level L_S.

In general, a number of spectral lines have to be taken into consideration, since, for instance, because of the Picket fence effect (see Annex A), or actual small frequency fluctuations during data capture, the tone energy is represented through the levels of a number of spectral lines.

Neighbouring spectral lines should be used for summation purposes if

— they differ from the narrow-band level at a frequency, f_T, by less than 10 dB, and

— they differ from the mean narrow-band level, L_S, of the masking noise within the critical band about the tone by more than 6 dB.

In case $K = 1$:

$$L_T = L_T \tag{7}$$

In case $K > 1$:

$$L_T = \left[10\,\lg\left(\sum_{i=1}^{K} 10^{0,1 L_i/\text{dB}} \right) + 10\,\lg\left(\frac{\Delta f}{\Delta f_e} \right) \right] \text{dB} \tag{8}$$

where

L_i is the narrow-band level of the ith spectral line of this critical band with tone energy, in decibels (dB);

K is the number of spectral lines with tone energy;

Δf is the line spacing, in Hertz (Hz) (see 3.13);

Δf_e is the effective bandwidth, in Hertz (Hz) (see 5.3.2).

NOTE The individual levels of the spectral lines with tone energy [see Formula (8)] also contain energy components of the masking noise. These can generally be neglected.

5.3.4 Distinctness of a tone

The distinctness of a tone depends on the bandwidth of the tone and its edge steepness; if the corresponding criteria are not satisfied then the tone is not audible to individuals with normal hearing.

If a tone based on bandpass noise has a distinctness of 70 % relative to that of a sinusoidal tone then the maximum permitted bandwidth Δf_R as a function of the tone frequency f_T is approximated (see Figure 1 in Reference [8]) by

$$\Delta f_R = 26,0\left(1,0\,\text{Hz} + 0,001\,f_T\right) \tag{9}$$

The bandwidth of a tone with a frequency f_T is derived from the number of spectral lines K [see Formula (8)], multiplied by the line spacing, Δf.

First criterion: The bandwidth of the tone shall not exceed the maximum permitted bandwidth given by Formula (9).

Second criterion: The edge steepness shall be at least 24 dB/octave.

This yields the level differences between the maximum narrow-band level of the tone, L_{Tmax}, and the narrow-band levels of the first spectral line below the tone L_u/above the tone L_o as follows:

The lower level difference ΔL_u is given by Formula (10):

$$\Delta L_u = \frac{f_T}{2}\,\frac{L_{Tmax} - L_u}{f_T - f_u} \geq 24\,\text{dB} \tag{10}$$

where

f_u is the frequency of the first spectral line below the tone, in Hertz (Hz);

f_T is the frequency of the maximum narrow-band level, in Hertz (Hz).

The upper level difference ΔL_o is given by Formula (11):

$$\Delta L_o = f_T\,\frac{L_{Tmax} - L_o}{f_o - f_T} \geq 24\,\text{dB} \tag{11}$$

where

f_o is the frequency of the first spectral line above the tone, in Hertz (Hz);

f_T is the frequency of the maximum narrow-band level, in Hertz (Hz).

5.3.5 Determination of the critical band level, L_G, of the masking noise

The level L_G is given by Formula (12):

$$L_G = L_S + \left[10\lg\left(\frac{\Delta f_c}{\Delta f}\right)\right]\text{dB} \quad (12)$$

where

L_S is the mean narrow-band level, see 5.3.2;

Δf_c is the width of the critical band about the tone frequency, f_T, in Hertz (Hz) (see 5.2);

Δf is the line spacing (frequency resolution), in Hertz (Hz).

5.3.6 Masking index

The masking index, a_v, is given by Formula (13):

$$a_v = \left\{-2 - \lg\left[1 + \left(\frac{f/\text{Hz}}{502}\right)^{2,5}\right]\right\}\text{dB} \quad (13)$$

where

f is the frequency, in Hertz (Hz).

NOTE For information on the masking index, a_v, see Annex C.

5.3.7 Determination of the audibility, ΔL

The audibility ΔL between the tone level L_T (see 5.3.3) and the level of the masking threshold (see 3.15) is given by Formula (14):

$$\Delta L = \left(L_T - L_G - a_v\right) \quad (14)$$

where

L_T is the tone level, in decibels (dB) (see 5.3.3);

L_G is the masking noise, in decibels (dB) (see 5.3.5);

a_v is the masking index, in decibels (dB) (see 5.3.6).

NOTE Formula (14) holds correspondingly if all the parameters of that formula are given.

5.3.8 Determination of the decisive audibility, ΔL_j, of a narrow-band spectrum

To determine the audibility ΔL of a noise a number of narrow-band spectra (see Annex D), staggered in time, of the noise with the same line width and same number of lines are used. The measurement time for such a spectrum should be approximately 3 s. The decisive audibility ΔL_j of an individual spectrum is determined in the following four steps. For simplification purposes the run index j is not given.

Step 1

Each spectral line, i, is investigated in ascending sequence to establish whether it represents a potential tone. A narrow-band level is a potential tone if the following conditions are satisfied:

$$L_i > L_{i+1} \text{ and } L_i > L_{i-1} \quad (15)$$

and

$$L_i > L_{Si} + 6 \text{ dB} \quad (16)$$

NOTE 1 Mean narrow-band level, L_{Si}, see 5.3.2.

Step 2

The tone levels, L_{Tk}, (see 5.3.3) of all the potential tones (run index k across all potential tones) is determined. The masking noises, L_{Gk} (see 5.3.5), and the masking index, a_{vk} (see 5.3.6), are determined for the tone levels at which the condition of distinctness of a tone (see 5.3.4) is satisfied. These parameters are used to calculate the corresponding audibilities, ΔL_k [see 5.3.7, Formula (14)].

If $\Delta L_k > 0$, then a tone is present.

Step 3

Critical bands with the width Δf_{cm} are formed about each of these audible tones, L_{Tm} (run index m across all audible tones) of frequency f_{Tm}.

If a number of tones are present in a critical band, then their tone levels, $L_{Tm,n}$ (run index n across all tones in the critical band; H is the number) are summed in terms of energy.

$$L_{Tm} = \left[10 \lg \left(\sum_{n=1}^{H} 10^{0,1 L_{Tm,n}/\text{dB}} \right) \right] \text{dB} \quad (17)$$

where

H is the total number of all tones in the critical band;

$L_{Tm,n}$ is the tone level with the run index m across all audible tones and the run index n across all tones in the critical band, in decibels (dB).

It is possible for the energy of individual spectral lines to be assigned to a number of neighbouring tones at the same time. Upon addition of the tone levels of neighbouring tones, the energy of these individual spectral lines may not be summed more than once.

The tone frequency, f_{Tm}, is the frequency of the most pronounced tone, i.e. the tone with the greatest audibility, $\Delta L_{m,n}$.

The mean narrow-band level of the masking noise is that mean narrow-band level that was calculated in the iterative procedure in 5.3.2 [see Formula (6)] from the lines about the tone with this tone frequency.

The level of the masking noise is the critical band level, $L_{Gm,n}$, calculated with this mean narrow-band level in accordance with 5.3.5.

This tone level, L_{Tm}, is used to recalculate the decisive audibility, ΔL_k (see Step 2).

If exactly 2 tones with tone frequencies, f_{T1} and f_{T2}, appear in one critical band, then they are evaluated separately if both tone frequencies lie below 1 000 Hz and the frequency difference, f_D.

$$f_D = \left| f_{T1} - f_{T2} \right| \tag{18}$$

where

$f_{T1}, f_{T2} < 1\,000$ Hz.

Formula (18) exceeds the following value (see Annex B):

$$f_D = 21 \times 10^{1,2\left[\left|\lg\left(\frac{f_T/\text{Hz}}{212}\right)\right|\right]^{1,8}} \text{ Hz} \tag{19}$$

where

$50 \text{ Hz} < f_T < 1\,000$ Hz;

f_T is the frequency of the more pronounced tone (the tone with the greater audibility, ΔL_k).

NOTE 2 If precisely 2 tones are present in a critical band below 1 000 Hz, then the human ear can distinguish differences less than half the critical bandwidth (see Reference [6] and Annex B).

Step 4

The audibility with the maximum value, ΔL_k, is the decisive audibility, ΔL_j, of the individual spectrum.

5.3.9 Determination of the mean audibility ΔL of a number of spectra

As given in 5.3.8, the decisive audibility ΔL_j is calculated for each narrow-band averaged spectrum (run index j, J is the number). These J audibilities, ΔL_j, are averaged in energy terms to yield a ΔL:

$$\Delta L = 10 \lg\left(\frac{1}{J}\sum_{j=1}^{J} 10^{0,1\Delta L_j/\text{dB}}\right) \text{dB} \tag{20}$$

where

ΔL_j is the decisive audibility, in decibels (dB);

j is the run index;

J is the number of spectra.

The tone frequencies are the frequencies of the tones to which the audibilities are assigned. To ensure a sufficient distance from the positive audibilities, ΔL_j, for all spectra in which no tone is found, the following value is used for ΔL_j:

$$\Delta L_j = -10 \text{ dB} \tag{21}$$

No tone frequencies are stated for this ΔL_j.

NOTE The audibilities, ΔL_j (and not the tone levels, L_{Tj}), are averaged in energy terms since the tones in the individual spectra have different tone frequencies, and thus, different masking index, a_v [see Formula (13)] and masking noises [see Formula (12)] have to be calculated.

6 Calculation of the uncertainty of the audibility ΔL

The mean audibility, ΔL, between the tone level and the level of the masking threshold of a noise is calculated using Formula (20) from the decisive audibilities, ΔL_j, of the individual narrow-band spectra (see 5.3.8 and 5.3.9):

$$\Delta L = 10\ \lg\left(\frac{1}{J}\sum_{j=1}^{J} 10^{0{,}1\Delta L_j/\mathrm{dB}}\right)\mathrm{dB}$$

ΔL_j is calculated through the use of Formula (14) and Formula (12):

$$\Delta L_j = L_{\mathrm{T},j} - L_{\mathrm{S},j} - 10\lg\left(\frac{\Delta f_{\mathrm{c}\,j}}{\Delta f}\right)\mathrm{dB} - a_{\mathrm{v},j}$$

with the expressions of

Formula (8):

$$L_{\mathrm{T}} = \left[10\ \lg\left(\sum_{i=1}^{K} 10^{0{,}1L_i/\mathrm{dB}}\right) + 10\ \lg\left(\frac{\Delta f}{\Delta f_e}\right)\right]\mathrm{dB}$$

Formula (6):

$$L_{\mathrm{S}} = \left[10\lg\left(\frac{1}{M}\sum_{i=1}^{M} 10^{0{,}1L_i/\mathrm{dB}}\right) + 10\lg\left(\frac{\Delta f}{\Delta f_{\mathrm{e}}}\right)\right]\mathrm{dB}$$

Formula (13):

$$a_{\mathrm{v}} = \left\{-2 - \lg\left[1 + \left(\frac{f/\mathrm{Hz}}{502}\right)^{2{,}5}\right]\right\}\mathrm{dB}$$

NOTE All frequencies are expressed in Hertz.

A normal distribution within the level zone is to be assumed for the term $10\lg\left(\frac{\Delta f_{\mathrm{c}\,j}}{\Delta f}\right)$.

No uncertainty is assumed for the masking index, a_{v}.

The $L_{\mathrm{T},j}$ values are derived through summation and the $L_{\mathrm{S},j}$ values through averaging of intensities. It is therefore necessary to assume a normal distribution of these values within the intensity range. To simplify the procedure, however, a normal distribution within the sound level range is assumed for all summands. Since, for the consideration of uncertainty, it is of interest to know the probability of determining a tonal audibility that is too low, and for the upper limit of the confidence interval the consideration in the level zone yields greater uncertainties than a corresponding consideration in the intensity zone, the agreement can be regarded as a safe estimation.

A number of sound sources act on the emission point and may be regarded as incoherent. Their emitted output levels are uncorrelated in their statistical behaviour. The uncertainty consideration of L_{T} and L_{S} is based only on the uncertainty of the level of the spectral lines involved. The question as to which spectral lines contribute to $L_{\mathrm{T}}/L_{\mathrm{S}}$ is neglected in the consideration of uncertainty herein.

These assumptions are used to determine the uncertainty of the audibility, ΔL_j, using the Gaussian uncertainty propagation principle:

$$\sigma_{\Delta L_j}{}^2 = \sum_{i=1}^{K}\left(\frac{\delta \Delta L_j}{\delta L_{\mathrm{T}_{j,i}}}\sigma_{L_{\mathrm{T}_{j,i}}}\right)^2 + \sum_{i=1}^{M}\left(\frac{\delta \Delta L_j}{\delta L_{\mathrm{S}_{j,i}}}\sigma_{L_{\mathrm{S}_{j,i}}}\right)^2 + \left(\frac{\delta \Delta L_j}{\delta \Delta f_{\mathrm{c}_j}}\sigma_{\Delta f_{\mathrm{c}_j}}\right)^2 \quad (22)$$

The three expressions above are determined in Formula (23) to Formula (25):

First expression:

$$\frac{\delta \Delta L_j}{\delta L_{\mathrm{T}_{j,i}}}\sigma_{L_{\mathrm{T}_{j,i}}} = \frac{10^{0,1 L_{\mathrm{T}_{j,i}}/\mathrm{dB}}}{\sum_{i=1}^{K} 10^{0,1 L_{\mathrm{T}_{j,i}}/\mathrm{dB}}}\sigma_{L_{\mathrm{T}_{j,i}}}$$

$$\sum_{i=1}^{K}\left(\frac{\delta \Delta L_j}{\delta L_{\mathrm{T}_{j,i}}}\sigma_{L_{\mathrm{T}_{j,i}}}\right)^2 = \frac{\sum_{i=1}^{K}\left(10^{\frac{0,1 L_{\mathrm{T}_{j,i}}}{\mathrm{dB}}}\sigma_{L_{\mathrm{T}_{j,i}}}\right)^2}{\left(\sum_{i=1}^{K} 10^{\frac{0,1 L_{\mathrm{T}_{j,i}}}{\mathrm{dB}}}\right)^2} \quad (23)$$

where K is the number of all tone-containing narrow-band levels that result in the tone level, L_{T}, in accordance with 5.3.3 and 5.3.8.

If, in accordance with 5.3.8 Step 3, a number (N) of tone levels are summated then the sum of all tone-containing narrow-band levels in the affected critical band is to be used for K.

Second expression:

$$\frac{\delta \Delta L_j}{\delta L_{\mathrm{S}_{j,i}}}\sigma_{L_{\mathrm{S}_{j,i}}} = \frac{10^{0,1 L_{\mathrm{S}_{j,i}}/\mathrm{dB}}}{\sum_{i=1}^{M} 10^{0,1 L_{\mathrm{S}_{j,i}}/\mathrm{dB}}}\sigma_{L_{\mathrm{S}_{j,i}}}$$

$$\sum_{i=1}^{M}\left(\frac{\delta \Delta L_j}{\delta L_{\mathrm{S}_{j,i}}}\sigma_{L_{\mathrm{S}_{j,i}}}\right)^2 = \frac{\sum_{i=1}^{M}\left(10^{0,1 L_{\mathrm{S}_{j,i}}/\mathrm{dB}}\sigma_{L_{\mathrm{S}_{j,i}}}\right)^2}{\left(\sum_{i=1}^{M} 10^{0,1 L_{\mathrm{S}_{j,i}}/\mathrm{dB}}\right)^2} \quad (24)$$

M is the number of narrow-band levels that contribute to the formation of the mean narrow-band level in the critical band in question.

Third expression:

$$\frac{\delta \Delta L_j}{\delta \Delta f_{\mathrm{c}_j}}\sigma_{\Delta f_{\mathrm{c}_j}} = \frac{4{,}34\,\mathrm{dB}}{\Delta f_{\mathrm{c}_j}}\sigma_{\Delta f_{\mathrm{c}_j}} \quad (25)$$

The uncertainty of the critical bandwidth Δf_{c} maximally corresponds to the line spacing Δf. No uncertainty is assumed for this line spacing. It follows from this that

$$\sigma_{\Delta f_{c_j}} = \Delta f$$

$$\frac{\delta \Delta L_j}{\delta \Delta f_{c_j}} \sigma_{\Delta f_{c_j}} = 4{,}34 \frac{\Delta f}{\Delta f_{c_j}} \text{dB} \tag{26}$$

A uniform value of $\sigma_{L,j} = 3\,\text{dB}$ is assumed for the uncertainty of all narrow-band levels. Formula (23) to Formula (25) can be used to calculate the uncertainty, $\sigma_{\Delta L_j}$, of the audibility. ΔL_j:

$$\sigma_{\Delta L_j} = \sqrt{\left(\frac{\sum_{i=1}^{K} \left(10^{0,1 L_{\mathrm{T}_{j,i}}/\mathrm{dB}} \right)^2}{\left(\sum_{i=1}^{K} 10^{0,1 L_{\mathrm{T}_{j,i}}/\mathrm{dB}} \right)^2} + \frac{\sum_{i=1}^{M} \left(10^{0,1 L_{\mathrm{S}_{j,i}}/\mathrm{dB}} \right)^2}{\left(\sum_{i=1}^{M} 10^{0,1 L_{\mathrm{S}_{j,i}}/\mathrm{dB}} \right)^2} \right) \sigma_{L_j}{}^2 + \left(4{,}34 \frac{\Delta f}{\Delta f_{c_j}} \text{dB} \right)^2} \tag{27}$$

The uncertainty of the mean audibility, ΔL, is given by Formula (28):

$$\frac{\delta \Delta L}{\delta \Delta L_n} \sigma_{\Delta L_n} = \frac{10^{0,1 \Delta L_n/\mathrm{dB}}}{\sum_{j=1}^{I} 10^{0,1 \Delta L_j/\mathrm{dB}}} \sigma_{\Delta L_n}$$

$$\sigma_{\Delta L} = \frac{\mp \sqrt{\left(\sum_{j=1}^{I} 10^{0,1 \Delta L_j/\mathrm{dB}} \right)^2}}{\sum_{j=1}^{I} 10^{0,1 \Delta L_j/\mathrm{dB}}} \tag{28}$$

For $\sigma_{\Delta L_j}$ see Formula (27).

I is the number of narrow-band spectra.

The extended uncertainty is:

$$U_\mathrm{o}, U_\mathrm{u} = k \sigma_{\Delta L} \tag{29}$$

The coverage factor, k, for a 90 % coverage probability in a bilateral confidence interval has a value of 1,645.

The experience also shows that with fluctuating noise, one achieves an extended uncertainty, U, of the audibility, ΔL, of about ±1,5 dB with 12 averages.

NOTE To ensure the above-mentioned uncertainty, it is necessary to have a minimum number of spectra with an averaging time of approximately 3 s. The number of spectra necessary to achieve the above-mentioned uncertainty will depend on the variability of the noises. Investigations have shown that even with strongly fluctuating noises (e.g. wind turbines), the number of spectra necessary does not generally exceed 12.

7 Recommendations on the presentation of results

7.1 Measurement

a) Date and place of measurement.

7.2 Acoustic environment

a) Description of the measurement environment with the position of the source and the measurement point, a sketch of the surrounding area, including a physical description of the measurement environment.

b) Air temperature in degrees Celsius, air pressure in Pascal and relative air humidity.

c) Mean wind speed and direction.

d) Any special information, e.g. dominant sources, fluctuating sources.

7.3 Instruments for measurement, recording and evaluation

a) The manufacturer.

b) Designation/model.

c) Serial number.

7.4 Acoustic data

a) Line spacing (see 3.13).

b) Range investigated (see 3.21).

c) For noise spectra for which a decisive audibility, $\Delta L_j > 0$, was calculated, the tone frequencies, $f_{\mathrm{T}j,k}$, of all tones and the corresponding audibilities, $\Delta L_{j,k}$ (see 5.3.8).

d) For the averaged noise spectrum

1) the mean audibility, ΔL (see 5.3.9), and

2) if less than 12 spectra have been averaged, the extended uncertainty (see Clause 6).

e) A diagrammatic representation of the narrow-band levels across the frequency of the 3-second averaged spectrum with the greatest ΔL.

Annex A
(informative)

Window effect and Picket fence effect

In the Fast Fourier Transform (FFT), the noise is determined in data blocks of block length N of the time window. N corresponds to the number of sampling values, e.g. $2^{10} = 1\,024$.[5]

In accordance with the definition of the Fourier integral, a pre-requirement of the FFT analysis is that the time data set is periodic. An unchanged further processing of the data points, as with the use of the rectangular time window, will only lead to correct results with transient signals and signals that fit exactly in the time window with a whole number of full periods. With stochastic noises, it can lead to severe distortions of the spectrum as the signal is cut off at the edges of the time window. To counter this "smearing" of the frequency lines (leakage effect), the signal is multiplied by a weighting function that sets the amplitude values to zero at the limits of the time window and thus overcomes discontinuities in the signal course within the window. The weighting functions, w(t), are as follows:

— for the rectangular window: $w(t) = 1$ for $0 \le t < T$ and $w(t) = 0$ for all other values of t;

— for the Hanning window: $w(t) = 1 - \cos(2\pi t/T)$ for $0 \le t < T$ and $w(t) = 0$ for all other values of t.

NOTE T corresponds to the width of the time window.

The use of the Hanning window is mandatory in this annex. Depending on the window function chosen (weighting function), the bands of the individual filters are superimposed to varying degrees corresponding to the edge steepness; the resultant so-called "effective bandwidth", Δf_e, with the Hanning window is 1,5 times the frequency resolution, Δf. This means that each frequency band always has energy components of the neighbouring bands (where present). Power components are therefore counted more than once in the summation process. Because of the leakage effect (see above) for determination of the level with the Hanning window, it is necessary to add at least three lines. These influences are taken into consideration through a correction value in the summation process (number of lines > 1) in the frequency analyzer. With the Hanning window, this value is 10 lg (1/1,5) dB = −1,76 dB. If the level addition is simulated in a program, then this correction value has to be taken into consideration in the computing program — both in the derivation of the tone level and in the calculation of the masking noise.

If a noise is analysed with discrete filters, then it is as if viewed through a lattice fence, hence the expression "picket fence effect". The analysis of individual tones provokes different amplitude and frequency errors (see Figure A.1), depending on the correspondence of the analysis frequency of the FFT spectrum with the frequency of the individual tone. With the Hanning window, this amplitude error, ΔL, lies between 0 dB (if both frequencies correspond exactly) and 1,42 dB, if the analysis frequency falls exactly between two lines. As the two following examples show, this error is corrected through summation over a number of lines and subsequent Hanning correction of the errors.

Exception: If all lateral bands are discarded because of the low difference to the mean and only a tone containing narrow-band level of frequency, f_T, forms the tone level, L_T, then no Hanning correction is carried out.

EXAMPLE 1 The analysis frequency corresponds to the tone frequency.

As shown in Figure A.1 a), left, the difference Δ between the maximum level and the lateral level is 6 dB, and the difference ΔL between the (measured) original level of the tone frequency and the analyzer value is 0 dB; the following values result.

Level of the tone frequency (original and analyzer value):	80 dB
The level of the two lateral lines in the analyzer (80 dB – 6 dB):	74 dB
Level sum without correction:	81,77 dB
Hanning correction, 10 lg (1/1,5):	–1,76 dB

The result of the level sum with correction corresponds to the level of the tone frequency.

EXAMPLE 2 The tone frequency lies exactly mid-way between two analysis frequencies.

As shown in Figure A.1 b), middle, the maximum level is divided into two lateral levels with a difference $\Delta = 0$ dB. The difference ΔL between the (measured) original level of the tone frequency and the analyzer value is 1,42 dB. The following values result.

Original level of the tone frequency distributed over four lateral lines:	80 dB
Of which the two highest (80 dB – 1,42 dB):	78,58
Level sum of the two lateral lines without correction:	81,59 dB
Hanning correction, 10 lg (1/1,5):	–1,76 dB

The result of the level sum with correction corresponds approximately to the level of the tone frequency.

Figure A.1 is derived from Reference [5] and a brief explanation is given below.

Figure A.1 a) shows three different cases (from left to right):

— the analysis frequency corresponds to the tone frequency;

— the tone frequency (indicated by the dashed line) lies midway between two analysis frequencies;

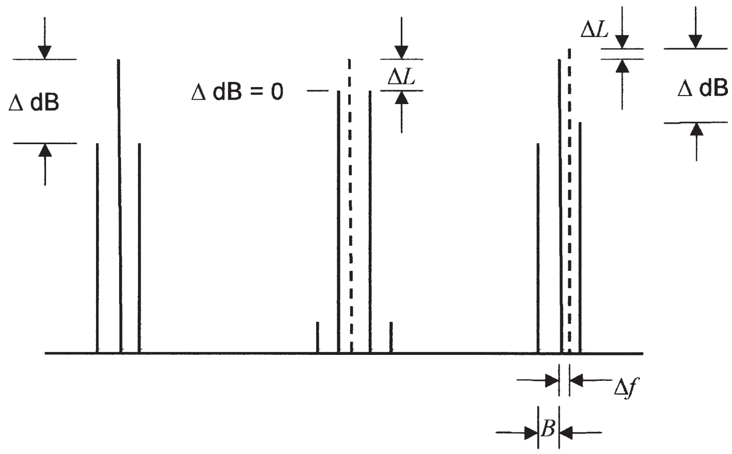
— the tone frequency (indicated by the dashed line) lies displaced towards the analysis frequency.

The designation B is identical to the line spacing, Δf (see 3.13), of this Publicly Available Specification. In Figure A.1 a), Δf represents the difference between the tone frequency and the analysis frequency:

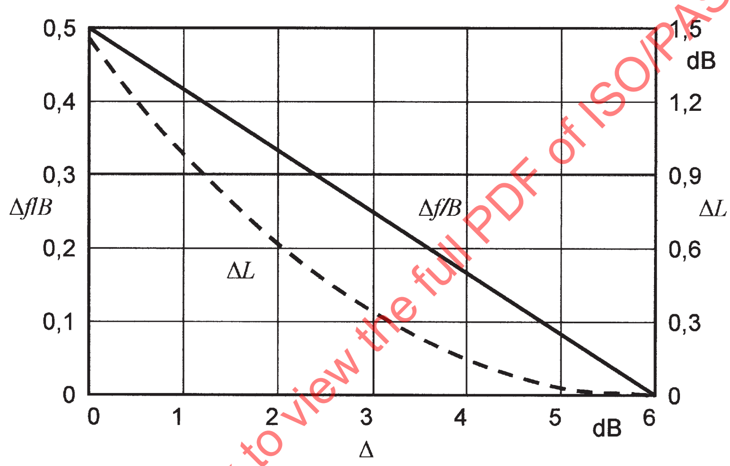
a) in the first case: $\Delta f = 0$;

b) in the second case: $\Delta f = 0,5 \times B$;

c) in the third case: $0 < \Delta f < 0,5 \times B$.



a)



b)

Key

B line spacing, in Hertz (Hz)

Δ difference, in decibels (dB)

Δ*L* difference between the real narrow-band level with the tone frequency, f_T, and the level of the direct lateral band with the greater of the two levels, in decibels (dB)

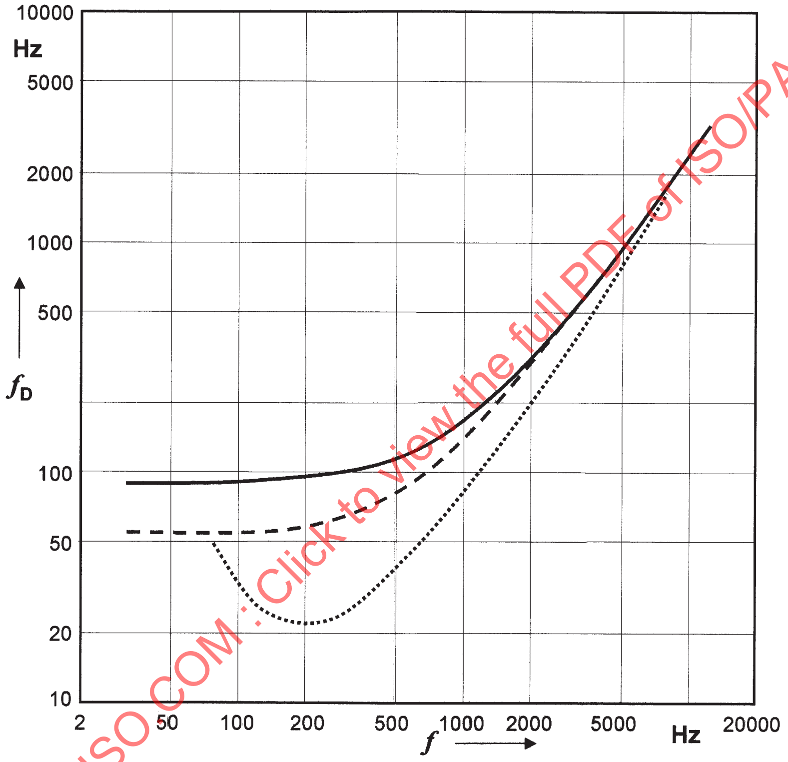
Δ*f* difference between the tone frequency and the analysis frequency, in Hertz (Hz)

Figure A.1 — Frequency correction and level correction for the Picket fence effect using the Hanning window

Annex B
(informative)

Resolving power of the human ear at frequencies below 1 000 Hz and geometric position of the critical bands — corner frequencies

At a frequency below 1 000 Hz, if there are several tones in a critical band, the human ear is able to distinguish between differences in the tone frequencies that are lower than the half width of the critical band. If the critical band has two or more tones, then the ear can detect differences as shown by the points or dashed lines in Figure B.1.



Key

— critical bandwidth as a function of frequency[4]

··· noise that comprises two tones

--- noise that comprises more than two tones in the critical band under consideration

f frequency, in Hertz (Hz)

f_D frequency difference, in Hertz (Hz)

Figure B.1 — Frequency differences between the tones of complex noises that the human ear can still resolve[6]

Two tones of tone frequencies, f_{T1} and f_{T2}, are evaluated separately if both tone frequencies lie below 1 000 Hz and the frequency difference, f_D:

$$f_D = \left| f_{T1} - f_{T2} \right| \qquad (B.1)$$

where

$f_{T1}, f_{T2} < 1\,000$ Hz.

Formula (B.1) exceeds the following value:

$$f_D = 21 \times 10^{1,2\left[\left|\lg\left(\frac{f_T/\text{Hz}}{212}\right)\right|\right]^{1,8}} \text{Hz} \qquad (B.2)$$

where

50 Hz < f_T < 1 000 Hz;

f_T is the frequency of the more pronounced tone, in Hertz (Hz).

In this Publicly Available Specification, the critical band is modelled as an ideal rectangular filter with a mid-frequency, f_T (tone frequency), the lower corner frequency, f_1, and the upper corner frequency, f_2, with these two corner frequencies having a geometric position to the tone frequency [see References [1],[2]; all frequencies in Hertz (Hz)].

$$f_T = \sqrt{f_1 f_2} \qquad (B.3)$$

$$f_2 - f_1 = \Delta f_c \qquad (B.4)$$

With the quadratic supplement, it follows from Formula (B.3) and Formula (B.4):

$$f_1 = -\frac{\Delta f_c}{2} + \frac{\sqrt{\left(\Delta f_c\right)^2 + 4 f_T^2}}{2} \qquad (B.5)$$

$$f_2 = f_1 + \Delta f_c \qquad (B.6)$$

Annex C
(informative)

Masking, masking threshold, masking index

Masking is the raising of the audibility threshold for a sound as a result of the influence of another sound.[3]

The masking threshold, L'_T, is that sound pressure level of a sinusoidal test tone that is required for it to be just perceivable in the presence of a masking noise (critical band level, L_G). The masking threshold is determined in repeated tests in which a group of subjects with normal hearing can just perceive the tone in 50 % of the cases.

The masking index, $a_v = L'_T - L_G$, is the difference between the level of the test tone, L'_T, and the critical band level, L_G. At low frequencies, the masking index has a value of approximately −2 dB. Above a transition range between 0,2 kHz and 1 kHz, it falls at a constant logarithmic rate to −6 dB at 20 kHz.

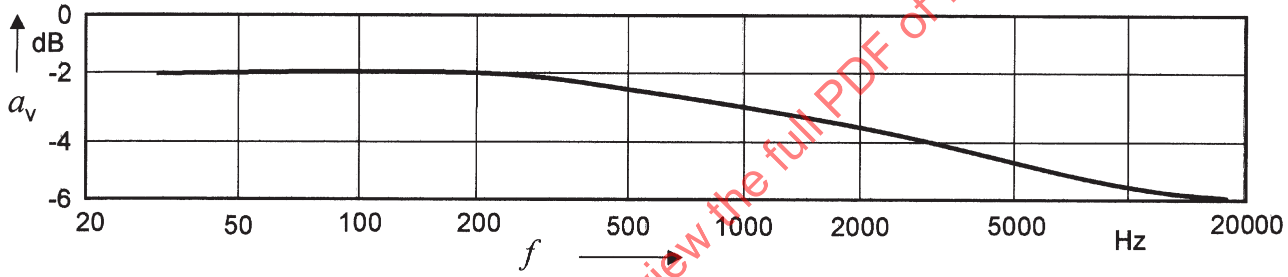


Figure C.1 — Masking index, a_v, as a function of frequency, f

The masking index, a_v, is given by Formula (C.1):

$$a_v = \left\{ -2 - \lg \left[1 + \left(\frac{f/\text{Hz}}{502} \right)^{2,5} \right] \right\} \text{dB} \tag{C.1}$$

where

f is the frequency, in Hertz (Hz).

Annex D
(informative)

Iterative method for the determination of the audibility, ΔL

Figure D.1 shows an iterative method for calculation of the tonal audibility.

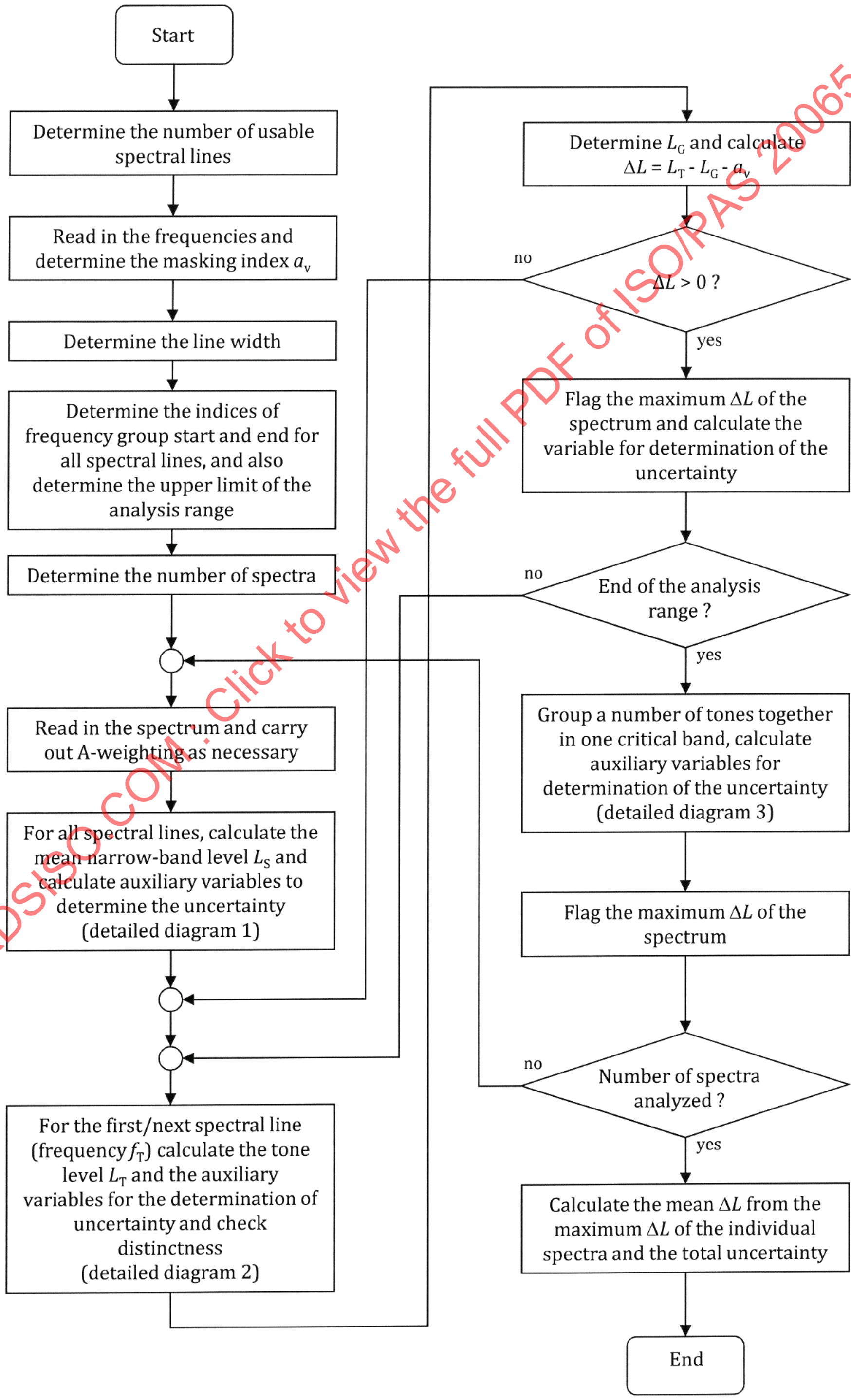


Figure D.1 — Iterative method

Detailed diagram 1

The mean narrow-band level, L_S, and auxiliary quantities to determine the uncertainty are calculated for all spectral lines (see Figure D.2).

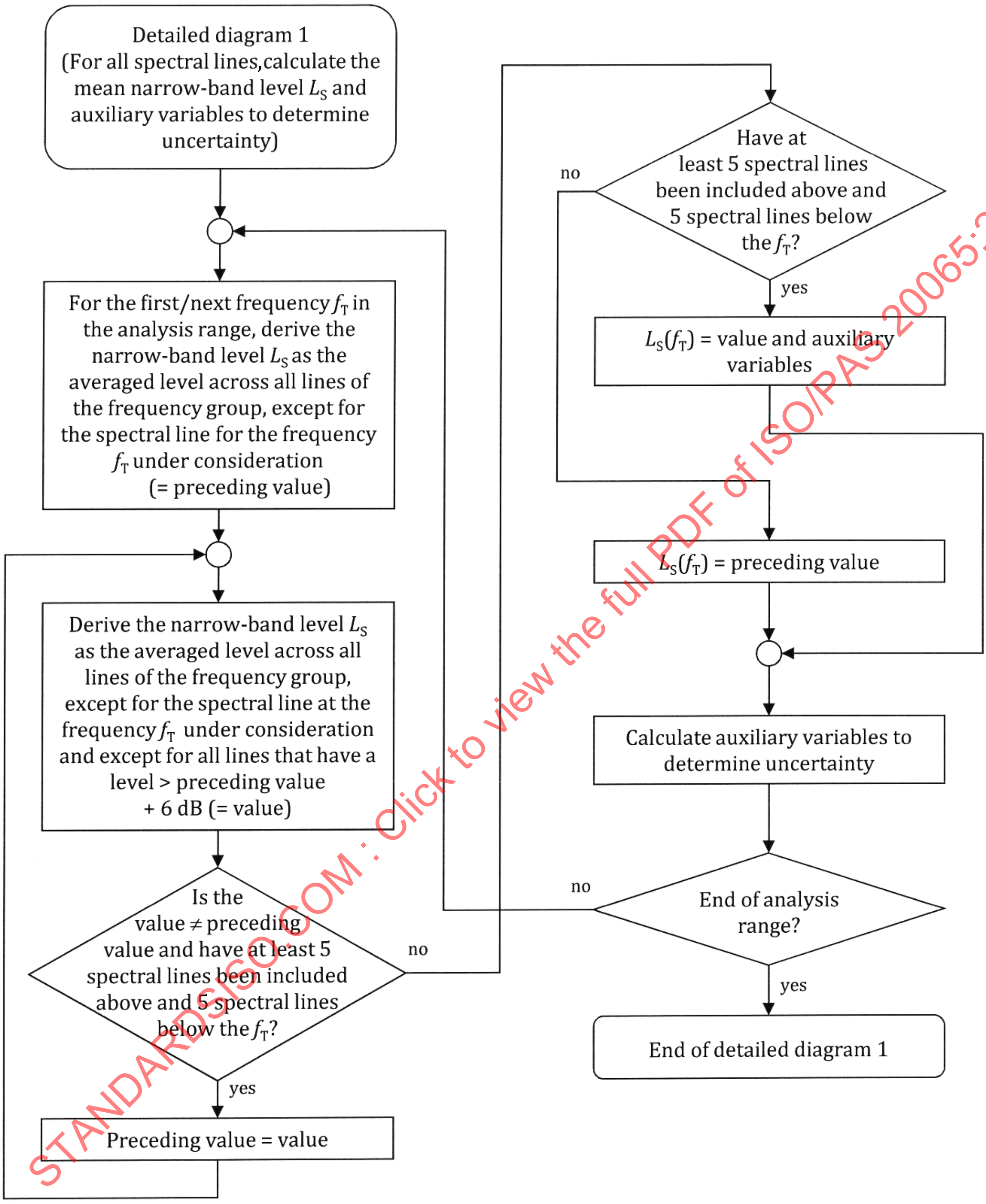


Figure D.2 — Detailed diagram 1

Detailed diagram 2

The tone level, L_T, and the auxiliary quantities to determine the uncertainty is calculated for the first/next spectral line of frequency, f_T. In addition, the tone is checked for distinctness (see Figure D.3).

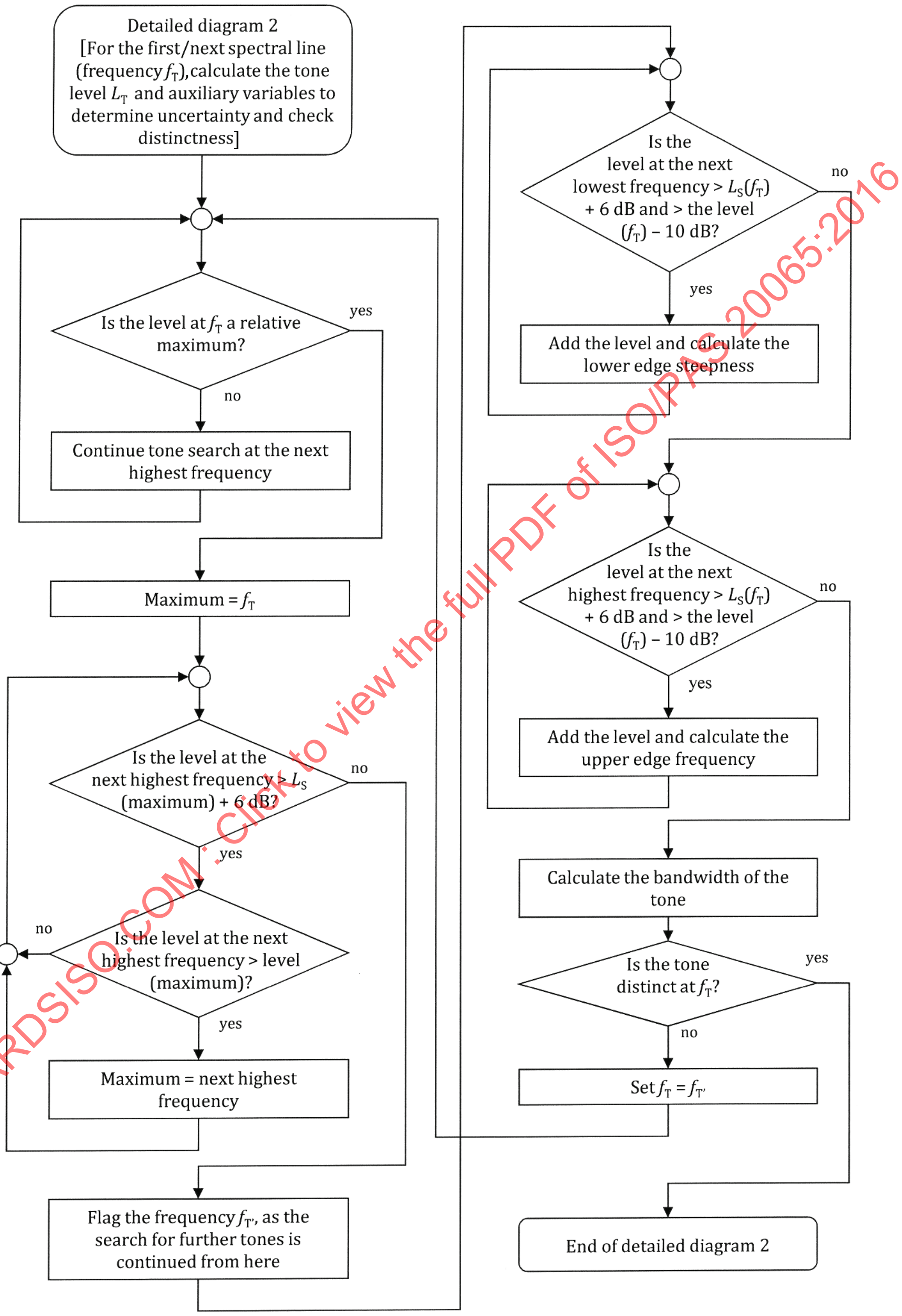


Figure D.3 — Detailed diagram 2

Detailed diagram 3

A number of tones in one critical band are grouped together and auxiliary quantities for determination of uncertainty are calculated. The maximum ΔL of the spectrum is identified (see Figure D.4).

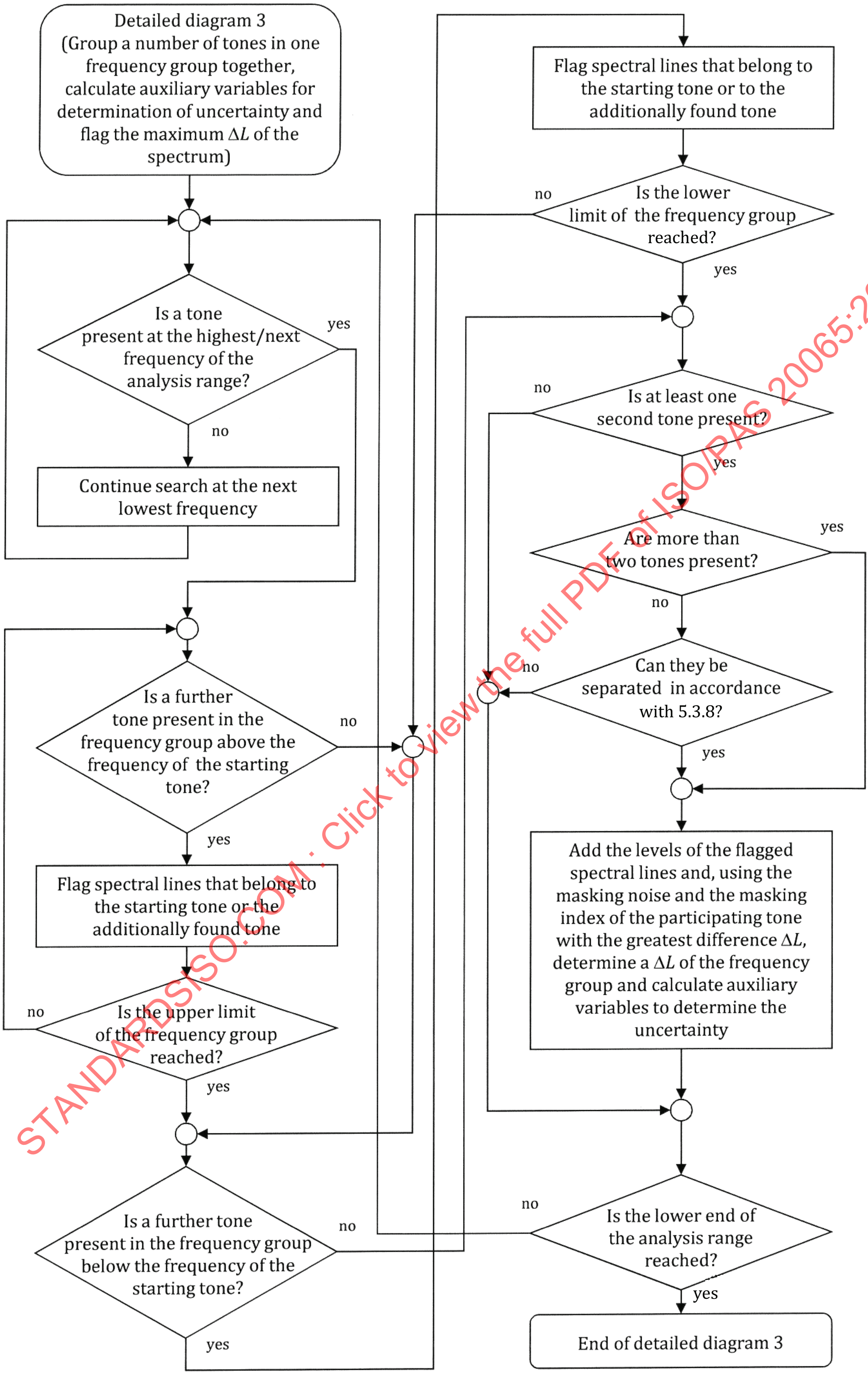


Figure D.4 — Detailed diagram 3