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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):

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

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, $L_{\mathrm{T}i}$, 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):

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

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:

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

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

$$f_2 = f_1 + \Delta f_c \qquad (5)$$

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):

$$L_\mathrm{S} = \left[10 \lg \left(\frac{1}{M} \sum\nolimits_{i=1}^{M} 10^{0{,}1 L_i/\mathrm{dB}} \right) + 10 \lg \left(\frac{\Delta f}{\Delta f_\mathrm{e}} \right) \right] \mathrm{dB} \tag{6}$$

where

L_i is the narrow-band level of the *i*th 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 $K = 1$:

$$L_\mathrm{T} = L_\mathrm{T} \tag{7}$$

In case $K > 1$:

$$L_\mathrm{T} = \left[10 \lg \left(\sum\nolimits_{i=1}^{K} 10^{0{,}1 L_i/\mathrm{dB}} \right) + 10 \lg \left(\frac{\Delta f}{\Delta f_e} \right) \right] \mathrm{dB} \tag{8}$$