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Acoustics — Methods for calculating loudness —

Part 1:
Zwicker method

Acoustique — Méthode de calcul du niveau d'isosonie —
Partie 1: Méthode de Zwicker

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html

This document was prepared by Technical Committee ISO/TC 43, *Acoustics*.

This first edition cancels and replaces ISO 532:1975, which has been technically revised.

A list of all parts in the ISO 532 series can be found on the ISO website.

This corrected version of ISO 532-1:2017 incorporates the following correction:

- Table A.9 has been corrected.

Introduction

Loudness and loudness level are two perceptual attributes of sound, describing absolute and relative sensations of sound strength perceived by a person under specific listening conditions. Due to inherent individual differences among people, both loudness and loudness level have the nature of statistical estimators characterized by their respective measures of central tendency and dispersion determined for a specific sample of the general population.

The object of the ISO 532 series is to specify calculation procedures based on physical properties of sound for estimating loudness and loudness level of sound as perceived by persons with otologically normal hearing under specific listening conditions. Each procedure provides single numbers that can be used in many scientific and technical applications to estimate the perceived loudness and loudness level of sound, without conducting separate human observer studies for each application. Because loudness is a perceived quantity, the perception of which may vary among people, any calculated loudness value represents only an estimate of the average loudness as perceived by a group of individuals with otologically normal hearing.

ISO 532-1 and ISO 532-2 specify two different methods for calculating loudness which may yield different results for given sounds. Since no general preference for one or the other method can presently be stated, it is up to the user to select the method which appears most appropriate for the given situation. Some major features of each of the methods are described below to facilitate the choice.

The first method of this document describes the calculation of loudness and loudness level of stationary sounds and is based on DIN 45631:1991. The second method of this document covers the procedures for calculation of loudness and loudness level of arbitrary non-stationary (time-varying) sounds, including stationary sounds as a special case, and is based on DIN 45631/A1:2010.

This document also includes a program code for both methods leading to estimates of loudness and loudness level for stationary and time-varying sounds. An executable computer program is also provided for both methods. The applied software is normative for calculating loudness values, against which other implementations can be checked subject to stated tolerances, and provides additional functionality for the convenience of the user.

The method for stationary sounds in this document differs slightly from the methods included in the previous ISO 532:1975, method B, by specifying corrections for low frequencies and by restricting the description of the approach to numerical instructions only, thus allowing a unique software description. For reasons of continuity, the method given in this document is in accordance with ISO 226:1987 instead of the later revised version, ISO 226:2003.

Based on the general concept of the method for stationary sounds, the method for time-varying sounds incorporates a generalization of the Zwicker approach to arbitrary, non-stationary sounds. Of course, this generalization is compatible with the method for stationary sounds in that it gives the same loudness values as the method for stationary sounds if applied to stationary sounds.

The Moore-Glasberg method as implemented in ISO 532-2 is limited to stationary sounds and can be applied to tones, broadband noises and complex sounds with sharp line spectral components. The method in ISO 532-2 differs from those in ISO 532:1975. ISO 532:1975, method A (Stevens loudness), was removed as this method was not often used and its predictions were not accurate for sounds with strong tonal components. The method described in ISO 532-2 also improves the precision of calculated loudness in the low frequency range and allows for calculation of loudness under conditions where the sound differs at the two ears. It has been shown that this method provides a good match to the contours of equal loudness level as defined in ISO 226:2003 and the reference threshold of hearing as defined in ISO 389-7:2005.

NOTE Equipment or machinery noise emissions/immissions can also be judged by other quantities defined in various International Standards (see e.g. ISO 1996-1, ISO 3740, ISO 9612 and ISO 11200).

Acoustics — Methods for calculating loudness —

Part 1:
Zwicker method

1 Scope

This document specifies two methods for estimating the loudness and loudness level of sounds as perceived by otologically normal persons under specific listening conditions. The first method is intended for stationary sounds and the second method for arbitrary non-stationary (time-varying) sounds, including stationary sounds as a special case.

The methods can be applied to any sound recorded as single-channel measurements using a microphone, or as multi-channel measurements, for example by means of a head and torso simulator (see Annex D). Since most important technical sounds are time-varying, a model of time-varying loudness is preferable.

The methods are based on the Zwicker algorithm.[14] The method for stationary sounds is provided for reasons of continuity and also offers the use of measured one-third-octave-band levels as input. The more general method for arbitrary sounds calculates the specific loudness pattern based on measured time signals by applying a signal processing model that is directly related to physiological and psychological characteristics of the human hearing system. Loudness is calculated from the specific loudness pattern. It has been shown that this method provides a good match to the results of many loudness experiments using synthetic and technical sounds.

No prior knowledge about the properties of the sound (e.g. broadband or narrowband noise, tonal content) and no user interactions are required for the fully automated application of the method.

The evaluation of the harmful effect of sound events is outside the scope of this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61260-1:2014, *Electroacoustics — Octave-band and fractional-octave-band filters — Part 1: Specifications*

IEC 61672-1:2013, *Electroacoustics — Sound level meters — Part 1: Specifications*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at http://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

3.1
otologically normal person

person in a normal state of health who is free from all signs or symptoms of ear disease and from obstructing wax in the ear canals, and who has no history of undue exposure to noise, exposure to potentially ototoxic drugs or familial hearing loss

[SOURCE: ISO 226:2003, 3.1]

3.2
sound pressure level

L_p

ten times the logarithm to the base 10 of the ratio of the square of the sound pressure, p, to the square of a reference value, p_0, expressed in decibels

$$L_p = 10 \lg \frac{p^2}{p_0^2} \text{ dB}$$

where the reference value, p_0, is 20 µPa

Note 1 to entry: Because of practical limitations of the measuring instruments, p^2 is always understood to denote the square of a frequency-weighted, frequency-band-limited or time-weighted sound pressure. If specific frequency and time weightings as specified in IEC 61672-1 and/or specific *frequency bands* (3.3) are applied, this should be indicated by appropriate subscripts, for example, $L_{p,\mathrm{AS}}$ denotes the A-weighted sound pressure level with time weighting S (slow). Frequency weightings such as A-weighting should not be used when specifying sound pressure levels for the purpose of *loudness* (3.18) calculation using the current procedure.

Note 2 to entry: This definition is technically in accordance with ISO 80000-8:2007, 8-22.

3.3
frequency band

continuous set of frequencies in the range of two specified limiting frequencies

Note 1 to entry: A frequency band is characterized by two values that define its position in the frequency spectrum, for instance its lower and upper cut-off frequencies.

Note 2 to entry: Frequency is expressed in Hz.

[SOURCE: IEC 60050-702:1992, 702-01-02]

3.4
filter

device or mathematical operation that, when applied to a complex signal, passes energy of signal components of certain frequencies while substantially attenuating energy of signal components of all other frequencies

3.5
cut-off frequency

lowest (f_l) or the highest (f_h) frequency beyond which the response of the *filter* (3.4) to a sinusoidal signal does not exceed −3 dB relative to the maximum response measured between f_l and f_h

3.6
band-pass filter

filter (3.4) that passes signal energy within a certain *frequency band* (3.3) and rejects most of the signal energy outside of this frequency band

3.7
filter bandwidth

Δf

difference between f_h and f_l for a *band-pass filter* (3.6)

3.8
one-third-octave band

frequency band (3.3) with the centre frequency f_T and the width of one-third of an octave

Note 1 to entry: The subscript T instead of c is used to specify the centre frequency in the special case of a one-third-octave band.

Note 2 to entry: Width of one-third of an octave as specified in IEC 61260-1.

3.9
band-reject filter

filter (3.4) that rejects signal energy within a certain *frequency band* (3.3) and passes most of the signal energy outside of this frequency band

Note 1 to entry: A narrow band-reject filter is also called a notch filter.

3.10
one-third-octave-band level

L_T

sound pressure level (3.2) of sound contained within a *frequency band* (3.3) with the width of one-third of an octave

3.11
sound spectrum

representation of the magnitudes (and sometimes of the phases) of the components of a complex sound as a function of frequency

3.12
critical band
auditory filter

filter (3.4) within the human cochlea describing the frequency resolution of the auditory system with characteristics that are usually estimated from the results of masking experiments

3.13
critical bandwidth
auditory filter bandwidth

bandwidth of a *critical band* (3.12)

Note 1 to entry: The critical bandwidth values in Hz are as specified in Reference [22].

Note 2 to entry: Each critical bandwidth has a width of one unit on the *critical band rate scale* (3.14).

3.14
critical band rate scale

transformation of the frequency scale, constructed so that an increase in frequency equal to one *critical bandwidth* (3.13) leads to an increase of one unit on the critical band rate scale

Note 1 to entry: Frequencies on the critical band rate scale are expressed in Bark.

EXAMPLE The value of the critical bandwidth for a centre frequency of 1 000 Hz is approximately 160 Hz, so an increase in frequency from 920 Hz to 1 080 Hz corresponds to a step of one Bark.

3.15
critical band level

L_{CB}

sound pressure level (3.2) of sound contained within a *critical band* (3.12)

3.16
loudness level

sound pressure level (3.2) of a frontally incident, sinusoidal plane progressive wave, presented binaurally at a frequency of 1 000 Hz that is judged by *otologically normal persons* (3.1) as being as loud as the given sound

Note 1 to entry: Loudness level is expressed in phons.

3.17
calculated loudness level

L_N

loudness level (3.16) calculated following the procedure of a predictive model

3.18
loudness

perceived magnitude of a sound, which depends on the acoustic properties of the sound and the specific listening conditions, as estimated by *otologically normal persons* (3.1)

Note 1 to entry: Loudness is expressed in sones.

Note 2 to entry: Loudness depends primarily upon the *sound pressure level* (3.2), although it also depends upon the frequency, waveform, bandwidth, and duration of the sound.

Note 3 to entry: One sone is the loudness of a sound with a *loudness level* (3.16) of 40 phon.

Note 4 to entry: A sound that is twice as loud as another sound is characterized by doubling the number of sones.

3.19
calculated loudness

N

loudness (3.18) calculated following the procedure of a predictive model

Note 1 to entry: The calculated loudness is denoted N_F or N_D, expressed in sones. The letters F and D signify that the calculation assumes either free field frontal sound incidence (F) or diffuse field incidence (D).

Note 2 to entry: The calculated loudness corresponds to the loudness that would be experienced by an average of a group of persons with otologically normal hearing whose heads are centred at the position of the microphone. This is equivalent to diotic listening (same sound at each ear).

3.20
specific loudness

N'

loudness (3.18) evoked over a *frequency band* (3.3) with a bandwidth of a *critical band* (3.12) centred at the frequency of interest

Note 1 to entry: Specific loudness is expressed in sones/Bark.

Note 2 to entry: The definition together with the stated unit are different from those in ISO 532-2.

3.21
percentile loudness

N_X

loudness (3.18) that is reached or exceeded in X % of the measuring time intervals

Note 1 to entry: The percentile loudness is expressed in sones.

4 Specification of input signal and instrumentation

The input signal is measured using a sound acquisition system consisting of at least a microphone, pre-amplifier and amplifier. The instrumentation shall meet the requirements of IEC 61672-1:2013, class 1, as far as applicable. The waveform of the time signal is sampled with an A/D-converter. The test implementation in A.4 requires a sampling rate of 48 kHz. Signals with other sampling rates shall be resampled to 48 kHz when using this implementation. For the convenience of the user an additional source file containing an algorithm for up-sampling signals with sampling rates of 32 kHz or 44,1 kHz is provided (see '**// BLOCK Resampling**').

For reasons of convenience, the program code is extended to allow the use of time signals in the form of WAVE files for the calculation algorithm of loudness. The data format can be 16-bit integer or 32-bit float format (correct sound pressure values, no normalized data). For a 16-bit integer format, an appropriate calibration file and the corresponding calibration value shall be given. The corresponding algorithms are also contained in the additional source file.

The type of sound field [free (F) or diffuse (D)] shall be specified.

The one-third-octave-band sound pressure levels are determined using one-third-octave-band filters that conform to IEC 61260-1:2014, class 1 with centre frequencies spanning the range between 25 Hz and 12,5 kHz. In order to reduce uncertainties of loudness calculation the filter coefficients are provided (A.2). The one-third-octave-band filters are designed as 6th order Chebyshev filters using three 2nd order sections. These filters are optimized to provide a damping of 20 dB at the centre frequencies of the adjacent bands (except for 12,5 kHz only the lower band is considered). This means that, for example, a 1 kHz tone with a sound pressure level of 70 dB produces the following levels at different centre frequencies: 50 dB at 800 Hz, 70 dB at 1 kHz and 50 dB at 1,25 kHz.

The method for stationary sounds also offers the use of one-third-octave-band levels measured with a sound level meter according to IEC 61672-1:2013, class 1, and a filter according to IEC 61260-1:2014, class 1, as input.

NOTE A software package including the listing of the program code can be freely downloaded from http://standards.iso.org/iso/532/-1/ed-1/en

5 Method for stationary sounds

5.1 General

This specifies a method for calculating loudness and loudness level of stationary sounds using objective measurement data and a calculation procedure developed by E. Zwicker and his colleagues.[14] The calculated data allow the loudness to be specified and thus different stationary sounds to be quantitatively evaluated according to their individual expected perceived loudness. The procedure applies to all stationary sounds.

The method for stationary sounds given in this document is an updated version of method B as given in ISO 532:1975, providing a modified treatment of low-frequency energy. The calculation is based on an algorithmic approach as opposed to a graphical method. The modified treatment for frequencies below 300 Hz strictly follows the approach given by DIN 45631:1991, introduced to improve the accuracy of the calculated loudness. Since then, this modified version has achieved widespread use and thus frequently replaced previous applications of ISO 532:1975, method B. It therefore can be seen as the direct continuation of the frequently used Zwicker method.

It is this aim of maximum continuity which has prevented any other changes because the benefit of some smaller adoptions was seen to be smaller than the loss of continuity and comparability of data. For reasons of continuity, the method given in this document is in accordance with ISO 226:1987 instead of the later revised version ISO 226:2003.

The procedure involves a sequence of steps. For a precise definition of each step the user is referred to a detailed description in 5.2 and the program code in A.4. Both descriptions of the procedure are provided in order to facilitate the comprehension of the procedure. It is envisaged that those wishing to calculate loudness using the method for stationary sounds will use an implementation of the algorithm given by the computer program of A.4 or other implementations in conformance with the tolerances given in the paragraph below.

The implementation given in Annex A shall be used as the test method against which other implementations shall be tested to determine compliance with this document.

Any specific implementation is permitted if, for all stationary test signals given in B.2 and B.3,

— their calculated specific loudness values differ by not more than ± 5 % of the specific loudness values calculated by the test implementation or ± 0,1 sone/Bark, and if

— the deviation for total loudness is not more than ± 5 % or ± 0,1 sone.

The supplier of any specific implementation shall provide a declaration of conformance with this document, indicating the results achieved using the test signals given in Annex B, e.g. as part of the solution's user manual. For convenience, the test signals and the tables of the results from the test implementation (including tolerances) are supplied electronically (as WAVE and EXCEL files). Modifying the test signals is not allowed.

NOTE A software package including the WAVE and EXCEL files can be freely downloaded from http://standards.iso.org/iso/532/-1/ed-1/en

5.2 Description of the method

The method for calculating loudness consists of three steps. These steps provide a means of combining and converting the one-third-octave-band levels to give the total loudness level. These steps are described below and illustrated by a block diagram in Figure 1. An example for factory noise in a diffuse sound field is also given for further explanation (see Figure 2). Even though the abscissa gives cut-off or centre frequencies, Figure 2 is scaled according to critical band rate. At each one-third-octave band, "ladders" can be seen, the rungs of which represent possible values of the respective one-third-octave-band levels.

Step 1

This step accounts for the fact that the human hearing system is less sensitive at low frequencies below 300 Hz than at higher frequencies. This is done by appropriately decreasing the respective one-third-octave- band levels before entering them into the diagram of Figure 2. The details of these corrections can be taken from Table A.3.

Step 2

The approximation of critical bands by one-third-octave bands is only acceptable for frequencies above about 300 Hz. For lower frequencies, one-third-octave bands are smaller than the critical bands, so two or more one-third-octave bands shall be added in order to approximate critical bands. This is the case for all evaluated one-third-octave bands between 20 Hz and 90 Hz ($L_{\text{CB}'\,1}$), for the three one-third-octave bands between 90 Hz and 180 Hz ($L_{\text{CB}'\,2}$), and for the two one-third-octave bands between 180 Hz and 280 Hz ($L_{\text{CB}'\,3}$). In these cases, the critical band level shall be approximated by power summation in the given one-third-octave bands. The thick horizontal lines shown in Figure 2 with the width of about a critical band at low centre frequencies were produced in this way from the smaller horizontal thin bars which correspond to the measured one-third-octave-band levels.

Step 3

Before entering the corrected one-third-octave-band levels into the diagram (in order to transform the levels into their corresponding core loudness, see A.3), it shall be ascertained whether the spectrum was obtained under diffuse or free field conditions. In the example of Figure 2, this was done by using the appropriate ladder structure assigning spectral values to specific loudness values. Graphical representations of different ladder structures for a wide range of one-third-octave-band levels in diffuse or free field were given in ISO 532:1975 and DIN 45631:1991. In practice, however, the appropriate values of the ladder structure currently are defined within numerical tables. For reasons of simplicity and convenience, this document uses a C-implementation of the algorithm instead of particular tables to specify all numerical allocations. The letters "D" for diffuse and "F" for free field shall be used to specify the algorithm applied.

Then, for each band a slope towards the higher critical band is added, and the area below the distribution of specific loudness is summed. The specific value of the slope to be added depends on the respective one-third-octave-band levels and centre frequencies. Again, detailed information can be found in the above mentioned graphical representations or in the tables of A.3, respectively. Having entered the corrected one-third-octave-band levels into the diagram, the shape of the specific loudness pattern starts with a vertical rise to the one-third-octave-band level measured, stays at the main value corresponding to the one-third-octave-band level in question and then falls with a slope unless the level is higher in the next one-third-octave band, in which case the pattern rises vertically to the level appropriate for the next one-third-octave band. Both the one-third-octave-band spectrum and the loudness pattern are highlighted by solid curves in the diagram of Figure 2.

If the next one-third-octave-band level is lower, the decrease of the specific loudness towards higher centre frequencies follows the broken lines, corresponding to the upper slope. In this way, the final specific loudness versus critical band rate pattern, shortened to “loudness pattern”, is determined and indicated by the highest thick solid lines in Figure 2. For narrow-band sounds, this upper slope contributes strongly to the total loudness, i.e. to the total area below the curve. Therefore, it contributes especially to the total loudness of pure tones. An example is given in Figure 2 by the dotted line for a 1 kHz tone with a sound pressure level of 70 dB. Generally, one-third-octave-band filters show a leakage towards neighbouring filters of about −20 dB. This means that a 1 kHz tone with a sound pressure level of 70 dB produces the following levels at different centre frequencies: 50 dB at 800 Hz, 70 dB at 1 kHz and 50 dB at 1,25 kHz. Therefore, the lower slope of the loudness pattern becomes less steep.

The solid curve in Figure 2 shows the loudness pattern of a factory noise. An area is formed extending from low to high frequencies. It is bordered by the straight line upwards at the left and right sides of the overall diagram, and also by the horizontal lower abscissa. The area within these boundaries is marked by hatching. To calculate the area quantitatively, a rectangular surface of equal area is drawn, which has the width of the diagram as a basis. The height of this rectangle is a measure of the total area, which is marked by shading from upper left to lower right. Using this height (the dashed-dotted line), the loudness or the loudness level can be read from the scales on the right or the left of the diagram. In the diffuse field example shown in Figure 2, a calculated loudness N_D of 24 sone and a corresponding loudness level $L_{N,D}$ of 86 phon is found. The sound under test has a relatively broad spectrum. Therefore there is quite a large difference between the measured sound pressure level of 73 dB or the A-weighted sound pressure level of 68 dB on the one hand, and the calculated loudness level of 86 phon on the other hand.

The graphical procedure which finally leads to a loudness pattern has the advantage that partial areas in the diagram correspond to specific parts of the loudness. Therefore, in many cases the diagram clearly shows which partial area is dominant or which part contributes strongly to the total loudness. In many applications it is often very important to first reduce that part of the noise which produces the largest area in the loudness pattern. On the other hand, the diagram shows which parts of the spectrum are so small in relation to the neighbouring parts that they are partially or even totally masked. In Figure 2, for example, the one-third-octave-band level of 51 dB at the centre frequency of 630 Hz does not contribute to loudness because it is totally masked, as indicated by the fact that this one-third-octave-band level lies below the shaded curve limiting the total area and arising, at this frequency, from the one-third-octave-band level at 500 Hz.

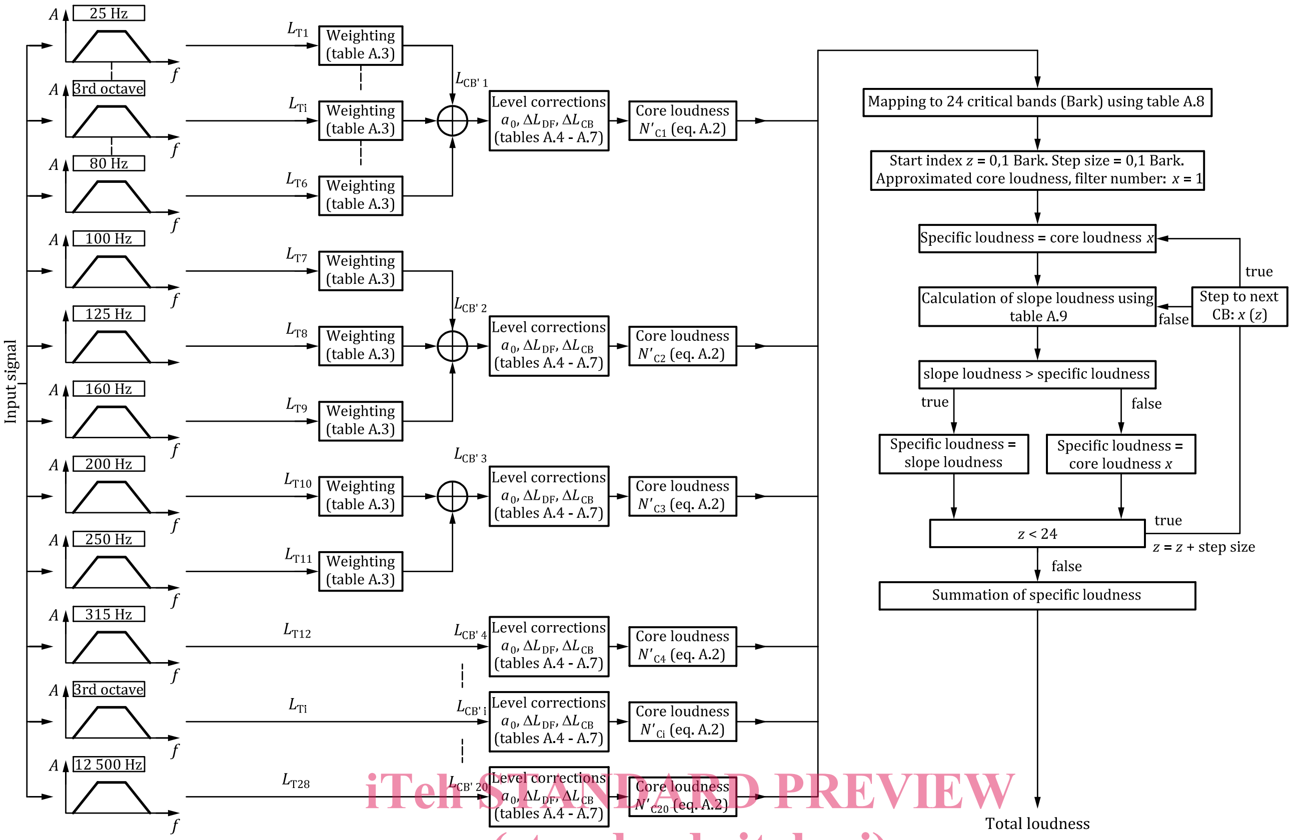
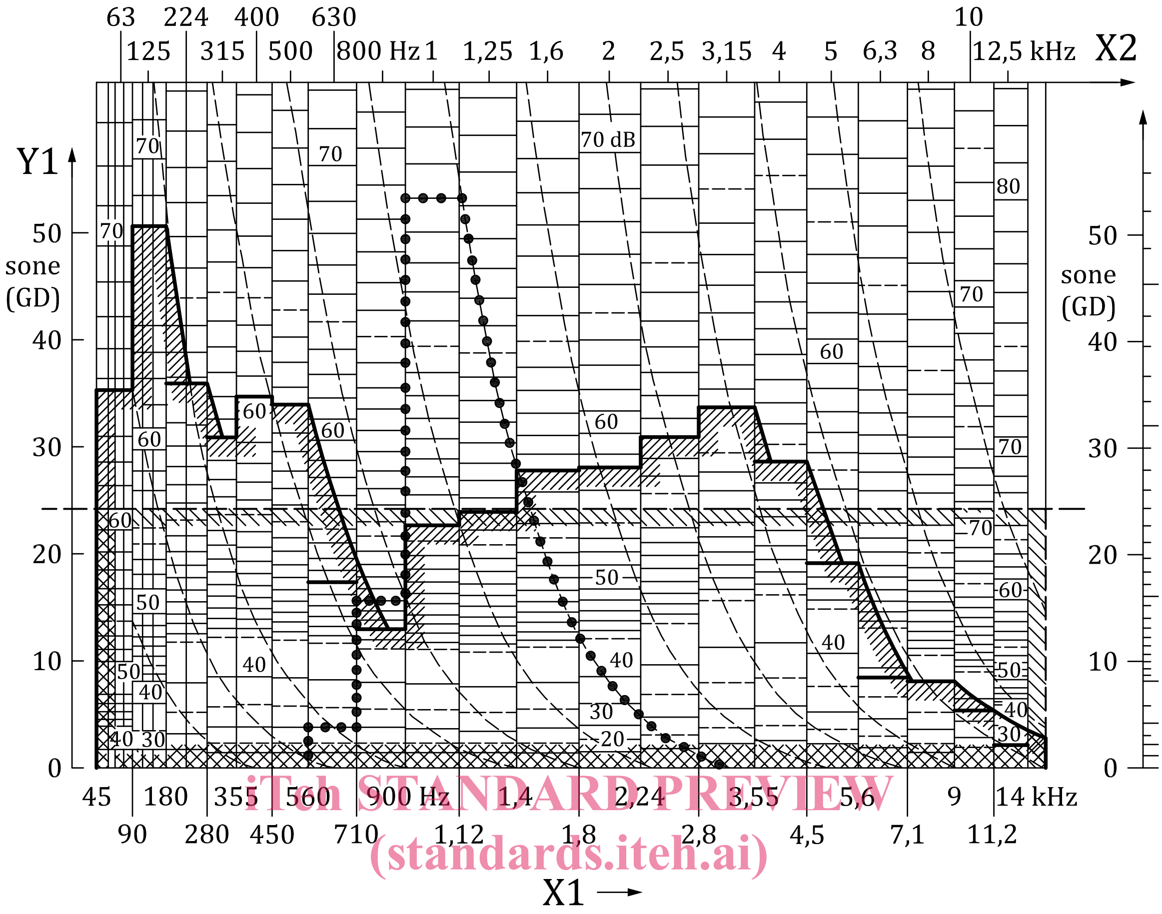


Figure 1 — Block diagram of the calculation method by this document, method for stationary sounds

Figure 2 shows a schematic diagram of the graphical calculation algorithm as implemented in this document, method for stationary sounds, according to DIN 45631:1991.



Key

X1	cut-off frequency of third-octave bands
X2	centre frequency
Y1	scale of total loudness
Y2	scale of corresponding loudness level

Figure 2 — Example of the loudness calculation procedure using charts indicating the measured one-third-octave-band levels of a factory noise in a diffuse field (see Annex A)

Explanation of Figure 2: Specific loudness is on the ordinate while the critical band rate expressed as cut-off frequencies of the one-third-octave bands is on the abscissa. The area surrounded by the *thick solid line* and hatched from *lower left* to *upper right* indicates the total loudness of the noise. This area is approximated by a rectangular area of the same width but with a height indicated by the area hatched from *upper left* to *lower right.* The height of this rectangular area marks the total loudness on the left scale and the corresponding loudness level on the right scale. The dotted curve represents the loudness pattern of a 1 kHz tone with a sound pressure level of 70 dB.

5.3 Calculation of loudness and loudness level

The loudness calculation can be performed from provided one-third-octave-band sound pressure levels (function ‘f_loudness_from_levels’ in A.4) or from calculated one-third-octave-band levels based on time signals (function ‘f_loudness_from_signal’ in A.4). The one-third-octave-band levels or the time signal (as WAVE file) can be easily input using the command line or the graphical user interface of the