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Acoustics — Methods for calculating loudness —

Part 2: **Moore-Glasberg method**

Acoustique — Méthode de calcul d'isosonie —

Partie 2: Méthode Moore-Glasberg

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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*.

A list of all parts in the ISO 532- series, published under the general title *Acoustics — Methods for calculating loudness*, can be found on the ISO website.

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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 seeks 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.

This document is limited to calculation of loudness and loudness level of stationary sounds and the calculations are based on the spectral properties of a sound. This calculation method is based on Moore-Glasberg loudness calculation algorithms [14-17]. It starts by converting a specified signal spectrum into a series of sinusoidal components representing that spectrum. This series is then transformed into a specific loudness pattern by applying four consecutive transformations, each of which is directly related to physiological and psychological characteristics of the human hearing system. Loudness is calculated from the specific loudness pattern.

This document describes the calculation procedures leading to estimation of loudness and loudness level and provides an executable computer program and code. The software provided with this document is entirely informative and provided for the convenience of the user. Use of the provided software is not required for conformance with this document.

The Moore-Glasberg method is limited to stationary sounds and can be applied to tones, broadband noises and complex sounds with sharp line spectral components. The method in this document differs from those in ISO 532:1975. Method A of ISO 532:1975 (Stevens loudness[18]) 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 this document 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.

The Zwicker method in ISO 532-1 can be applied for stationary and arbitrary non-stationary sounds. The method for stationary sounds in ISO 532-1 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 ISO 532-1 is in accordance with ISO 226:1987 instead of the later revised version, ISO 226:2003.

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).

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Acoustics — Methods for calculating loudness —

Part 2:
Moore-Glasberg method

1 Scope

This document specifies a method for estimating the loudness and loudness level of stationary sounds as perceived by otologically normal adult persons under specific listening conditions. It provides an algorithm for the calculation of monaural or binaural loudness for sounds recorded using a single microphone, using a head and torso simulator, or for sounds presented via earphones. The method is based on the Moore-Glasberg algorithm.

NOTE 1 Issues of binaural calculations are discussed in Annex A.

NOTE 2 Users who wish to study the details of the calculation method can review or implement the source code, which is entirely informative and provided with this document for the convenience of the user.

This method can be applied to tones, broadband noises and complex sounds with sharp line spectral components, for example transformer hum or fan noise.

NOTE 3 It has been shown (see Reference [15]) 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.

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*

IEC/TS 60318-7, *Electroacoustics — Simulators of human head and ear — Part 7: Head and torso simulator for the measurement of hearing aids*

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/

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3.1
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, in gases 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* (3.2) 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* (3.17) calculation using the current procedure.

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

3.2
frequency band
continuous set of frequencies lying between 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]

3.3
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

3.4
cut-off frequency
lowest (f_l) or highest (f_h) frequency beyond which the response of the *filter* (3.3) to a sinusoidal signal does not exceed −3 dB relative to the maximum response measured between (f_l) and (f_h)

3.5
one-third-octave band
frequency band (3.2) 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.

3.6
band-reject filter
filter (3.3) that rejects signal energy within a certain *frequency band* (3.2) 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.

3.7
band level
$L_{p\mathrm{b}}$
sound pressure level (3.1) of sound contained within a restricted frequency band (b)

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3.8
one-third-octave-band level
L_T
sound pressure level (3.1) of sound contained within a *frequency band* (3.2) with the width of one-third of an octave

3.9
sound spectrum
representation of the magnitudes (and sometimes of the phases) of the components of a complex sound as a function of frequency

3.10
spectrum density level
spectrum level
level of the limit, as the width of the *frequency band* (3.2) approaches zero, of the quotient of a specified quantity distributed within a frequency band, by the width of the band, expressed in decibels

Note 1 to entry: The words "spectrum level" should be preceded by a descriptive modifier describing the measured quantity.

Note 2 to entry: For illustration, the sound pressure spectrum level L_{ps} at the midband frequency is obtained practically by

$$L_{pbs} = 10\lg\left[\left(p_b^2 / \Delta f\right) / \left(p_0^2 / \Delta_0 f\right)\right]\mathrm{dB}$$

where $p_b{}^2$ is the time-mean-square sound pressure measured through a *filter* (3.3) system, p_0 the reference sound pressure, Δf the bandwidth of the filter system, and $\Delta_0 f$ the reference bandwidth of 1 Hz. For computational purposes, with L_{pb} for the band *sound pressure level* (3.1) observed through the filter, the above relation becomes

$$L_{pbs} = L_{pb} - 10\lg\left[\Delta f / \Delta_0 f\right]\mathrm{dB}$$

3.11
auditory filter
filter (3.3) within the human cochlea describing the frequency resolution of the auditory system, with characteristics that are usually estimated from the results of masking experiments

3.12
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]

3.13
equivalent rectangular bandwidth of the auditory filter for otologically normal persons
ERB_n
auditory filter (3.11) bandwidth determined by measuring tone detection thresholds in wideband noise passed through band-reject (notch) filters of various bandwidths

Note 1 to entry: The subscript n indicates that the value applies for persons with otologically normal hearing.

Note 2 to entry: The multi-letter abbreviated term presented in italics and with a subscript is used here instead of a symbol to maintain an established notation and to avoid confusion.

Note 3 to entry: Bandwidth is measured in Hertz (Hz).

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3.14
equivalent rectangular bandwidth number scale
ERB_n-number scale
transformation of the frequency scale constructed so that an increase in frequency equal to one ERB_n leads to an increase of one unit on the ERB_n-number scale

Note 1 to entry: ERB_n is measured in Hertz (Hz).

Note 2 to entry: The unit of the ERB_n-number scale is the Cam. For example, the value of ERB_n for a centre frequency of 1 000 Hz is approximately 132 Hz, so an increase in frequency from 934 Hz to 1 066 Hz corresponds to a step of one Cam. The equation relating ERB_n-number to frequency is given in 7.4.

3.15
loudness level
sound pressure level (3.1) of a frontally incident, sinusoidal plane progressive wave, presented binaurally at a frequency of 1 000 Hz that is judged by otologically normal persons as being as loud as the given sound

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

3.16
calculated loudness level
L_N
loudness level (3.15) calculated following the procedure of a predictive model

3.17
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

Note 1 to entry: Loudness is expressed in sones.

Note 2 to entry: Loudness depends primarily upon the *sound pressure level* (3.1) 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* (3.15) 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.

3.18
calculated loudness
N
loudness (3.17) calculated following the procedure of a predictive model

3.19
excitation
E
output of an *auditory filter* (3.11) centred at a given frequency, specified in units that are linearly related to power

Note 1 to entry: An excitation of 1 unit is produced at the output of an auditory filter centred at 1 000 Hz by a tone with a frequency of 1 000 Hz with a *sound pressure level* (3.1) of 0 dB presented in a free field with frontal incidence.

3.20
excitation level
L_E
ten times the logarithm to the base 10 of the ratio of the *excitation* (3.19) at the output of an *auditory filter* (3.11) centred at the frequency of interest to the reference excitation E_0

$$L_E = 10\lg\frac{E}{E_0}\,\mathrm{dB}$$

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where the reference excitation, E_0, is the excitation produced by a 1 000 Hz tone with a *sound pressure level* (3.1) of 0 dB presented in a free field with frontal incidence

3.21
specific loudness
N ʹ
calculated loudness (3.18) evoked over a *frequency band* (3.2) with a bandwidth of one ERB_n (3.13) centred on the frequency of interest

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

Note 2 to entry: The definition together with the stated unit are different from those in ISO 532-1.

4 General

The method described in the main part of this document specifies a method for calculating loudness and loudness level based on the Moore-Glasberg procedure.

The procedure involves a sequence of stages. Each stage is described below. However, it is envisaged that those wishing to calculate loudness using this procedure will use the computer program (see Annex C) provided with this document that implements the described procedure. It is not expected that the procedure will be implemented by hand. Such computations would be very time consuming. The source code provided in Annex C gives an example of the implementation of the method. Other implementations using different software are possible.

NOTE 1 The computational procedure described in this document is an updated version of procedures published earlier elsewhere[14-17].

NOTE 2 Uncertainties are addressed in Clause 9.

5 Specifications of signals

5.1 General

The spectrum of the signal whose loudness is to be determined shall be specified at each ear. The spectrum can be specified exactly using the methods described in 5.2, 5.3 and 5.4 for the case of a complex tone, noise consisting of bands of pink or white noise of defined width, or sounds having a mixture of discrete sinusoidal components or bands of pink or white noise. The sound spectrum can be specified approximately using one-third-octave-band levels specified in the method described in 5.5. For this, one-third-octave bands according to IEC 61260-1:2014 should be used. The methods described in 5.2 to 5.4 may be of interest for synthetic signals or signals analysed by discrete Fourier transform techniques. The method described in 5.5 will be usually used for practical signals. If the spectrum is specified exactly, the predicted loudness will be more accurate than when the spectrum is approximated using one-third-octave-band levels.

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5.2 Complex tone

This is a sound with a spectrum that consists of discrete sinusoidal components. The spectrum can be specified in terms of frequency components that are either harmonically or non-harmonically spaced. The frequency and sound pressure level of each component shall be specified.

5.3 Noise consisting of bands of pink or white noise of defined width

The number of noise bands and their widths shall be specified. Each band can be composed of either filtered white noise (with a constant spectrum level within the passband) or filtered pink noise (with a spectrum level within the passband that decreases with increasing centre frequency at a rate of 3 dB/octave). For each band, the following shall be specified: the lower cut-off frequency, the upper cut-off frequency and the spectrum level. In the case of pink noise, the frequency at which the spectrum

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level is determined shall also be specified. Within the procedure, the spectra of bands of noise are approximated by a series of discrete sinusoidal components. When the bandwidth of the noise exceeds 30 Hz, the components are spaced at 10 Hz intervals, and the level of each component is set 10 dB higher than the spectrum level at the corresponding frequency. When the bandwidth of the noise is less than 30 Hz, the components are spaced at 1 Hz intervals, and the level of each component is set equal to the spectrum level at the corresponding frequency.

EXAMPLE 1 A band of white noise extending from 200 Hz to 500 Hz with a spectrum level of 50 dB would be approximated by sinusoidal components with frequencies 205 Hz, 215 Hz, 225 Hz, 235 Hz .... 475 Hz, 485 Hz, 495 Hz, each component having a sound pressure level of 60 dB.

EXAMPLE 2 A band of pink noise having lower and upper cut-off frequencies of 100 Hz and 115 Hz, respectively, with a spectrum level of 65 dB would be approximated by sinusoidal components with frequencies 101 Hz, 102 Hz, 103 Hz, 104 Hz .... 113 Hz, 114 Hz, 115 Hz, with the components having sound pressure levels increasing progressively from 64,7 dB at 101 Hz to 65,3 dB at 115 Hz.

NOTE The spacing of the components (10 Hz as in Example 1 or 1 Hz as in Example 2) is not a property of the input signal. The 1 Hz spacing is used to ensure sufficient accuracy in the computation of loudness when the bandwidth of the spectrum of the signal is narrow, i.e. less than 30 Hz. For signals with wider bandwidth, i.e. 30 Hz or greater, then a 10 Hz spacing will result in sufficient accuracy for the purpose of the computation of loudness.

5.4 Mixture of discrete sinusoidal components and bands of pink or white noise

For the case of mixtures of sounds, which each have a spectrum consisting of discrete sinusoidal components, 5.2 is applied for each discrete sinusoidal component that the mixed sound comprises. For the case of a mixture of bands of pink or white noise, the spectrum of each component of the mixture can be specified exactly using 5.3. This method is mainly applicable to synthetic signals, although it could be applicable to signals with strong line components in a noise background.

5.5 Sound specified in terms of the sound pressure levels in 29 adjacent one-third-octave bands

The nominal centre frequencies of the 29 adjacent one-third-octave bands are as defined by IEC 61260-1:2014 within the range 25 Hz to 16 000 Hz. Within each band, the spectrum is assumed to be flat, and, as described for noise bands in 5.3, the spectrum is approximated as a series of sinusoidal components spaced at 10 Hz intervals or (for centre frequencies of 125 Hz and below) at 1 Hz intervals. The level of each component is calculated as follows. Let the width of a one-third-octave band at a given centre frequency be W (e.g. 230 Hz for a centre frequency of 1 000 Hz). The sound pressure level in that band, L_T, is converted to the spectrum level in that band as $L_T - 10\lg(W/1\text{ Hz})$ dB. The level of each component in the approximation is then set 10 dB above the spectrum level, i.e. to $L_T - 10\lg(W/1\text{ Hz})$ dB + 10 dB.

NOTE The 1/3 octave filters, as defined by IEC 61260–1:2014, to analyse the spectrum of the input signal can have errors in their outputs of up to ± 0,7 dB. In a worst-case scenario, if all filter outputs were 0,7 dB higher than the correct values, this would lead to an error in the estimated loudness (in sones) of approximately +4 % for a typical broadband sound. If all filter outputs were 0,7 dB lower than the correct values, this would lead to an error in the estimated loudness of approximately −4 % for a typical broadband sound.

EXAMPLE Consider the one-third-octave band centred at 1 000 Hz, and assume that the band sound pressure level is 63 dB. The spectrum level is then 63 dB – 10lg(230) dB = 39,4 dB. The spectrum of that one-third-octave band would thus be approximated by components at 890 Hz, 900 Hz, 910 Hz, 920 Hz .... 1 080 Hz, 1 090 Hz, 1 100 Hz, 1 110 Hz, each with a sound pressure level of 49,4 dB.

6 Instrumentation

For the input signals used in 5.2 to 5.4 instrumentation is not necessarily required as these levels can be specified without the use of measurement instrumentation. If the input signals from these three methods are acquired with instrumentation, or if one-third-octave-band sound pressure levels as described in 5.5 are determined in a sound field, this shall be done through the use of a sound acquisition system that conforms to IEC 61672-1, in conjunction with one-third-octave filters that conform to

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IEC 61260-1:2014. Equipment used to present the one-third-octave spectrum in real time shall meet the requirements of IEC 61672-1:2013, class 1, or IEC 61260-1:2014, class 1. The microphone(s) shall have an omnidirectional characteristic or a free-field characteristic, corresponding to the method being used in 7.2.2. If a head and torso simulator is used it shall conform to IEC/TS 60318-7. For signals acquired using a head and torso simulator, the transfer function of the simulator shall be allowed for, as described in 7.2.5. It should be noted that the following procedure described in this document applies to the sound that has been already acquired.

7 Description of the method

7.1 Introduction

The method of calculating loudness consists of the following discrete steps:

(a) transformation of the recorded sound spectrum into the sound spectrum at the tympanic membrane for each ear;

(b) transformation of the sound spectrum at the tympanic membrane into the sound spectrum at the oval window;

(c) transformation of the sound spectrum at the oval window into an excitation pattern on the basilar membrane;

(d) transformation of the excitation pattern into a specific loudness pattern;

(e) calculation of monaural and binaural loudness using the concept of binaural inhibition.

These steps are illustrated in the flow chart in Figure 1 and are described sequentially in 7.2 to 7.5.

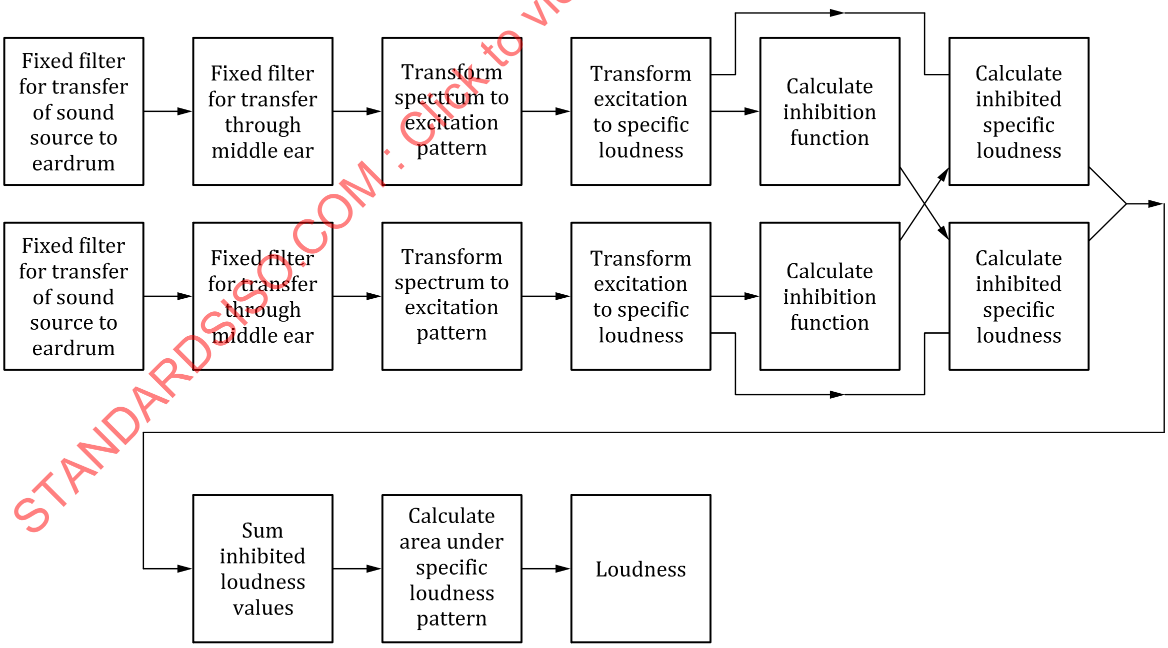

Figure 1 — Flow chart illustrating the sequence of the method

7.2 Determination of sound spectrum at the tympanic membrane

7.2.1 General

The spectrum specified in Clause 5 is transformed to the spectrum of sound reaching the tympanic membrane. This is done by applying one of the transfer functions specified in 7.2.2 to 7.2.5. Several

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different listening situations are possible and the transfer function chosen depends on the situation. The methods listed are not mutually exclusive.

7.2.2 Free field and diffuse field transfer functions for sound picked up by a single microphone

These transfer functions are applicable when the sound is picked up via a microphone placed at the centre of the position where the listener's head would be. The acoustical effects of the head/torso and outer ear on transmission of sound to the tympanic membrane are represented by two standard transfer functions. The first, applicable to free field listening with frontal incidence of the sound source, is specified in column 2 of Table 1. The second, applicable to listening in a diffuse field, is specified in column 3 of Table 1. The transfer functions represent the mean for adult humans[19-21].

The diffuse field transfer function can also be used for sounds presented via earphones that are designed to have a diffuse field response (see 7.2.3).

The transfer functions given in Table 1 are based on data known to provide good predictions of the equal loudness contours given in ISO 226:2003 and the absolute threshold values given in ISO 389-7:2005. It is acknowledged that these transfer functions do not comply with those specified in ISO 11904-1:2002.

7.2.3 Earphones

It is possible to calculate loudness for sounds transmitted via earphones. Note that the sensitivity level of the earphones (the sound pressure level produced for a given applied voltage) shall be taken into account when determining the spectra at the tympanic membrane. The transfer function of the earphones to the tympanic membrane shall be specified. This is done by specifying the deviations from a flat response at several frequencies. A file containing these deviations is called an “earphone correction file”. The transfer function of the earphone can be measured using a microphone close to the tympanic membrane or using the method described in ISO 11904-1:2002.

7.2.4 Signal recorded at eardrum

Spectra at the tympanic membrane can be recorded using a probe microphone in the ear canal. For sounds with no strong components above 3 000 Hz, a microphone should be within 10 mm of the tympanic membrane (eardrum). For sounds with strong components above 3 000 Hz, the microphone should be within 5 mm of the eardrum. In this case, no transfer function is needed. This case is treated as being equivalent to presentation of the sound via earphones with a flat response at the tympanic membrane.

7.2.5 Head and torso simulator

Sounds may be recorded using the microphones of a head and torso simulator. If the head and torso simulator represents an accurate acoustical model of an average adult listener, no transfer function needs to be specified. Otherwise, this is treated as a special case of earphone presentation, and the transfer function from the sound field to the microphones of the head and torso simulator shall be specified in a correction file.

7.2.6 Interpolation and extrapolation

The transfer functions described in 7.2 are specified at discrete frequencies. Linear interpolation on a decibel versus linear frequency scale is used to determine values at intermediate frequencies. In the case of earphone correction files, if the lowest frequency specified (f_l) is above 20 Hz then the value of the transfer function for frequencies between 20 Hz and f_l is set to the value specified at f_l. If the highest frequency specified (f_h) is below 18 000 Hz then the value of the transfer function for frequencies between f_h and 18 000 Hz is set to the value specified at f_h.

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7.3 Determination of sound spectrum at the oval window

The transmission of sound through the middle ear from the tympanic membrane to the oval window (the cochlea) is taken into account by a middle ear transfer function specified in column 4 of Table 1. The shape of the function represents the difference between the sound pressure level in the cochlea and the sound pressure level at the tympanic membrane. The whole function is scaled so that an input signal consisting of a 1 000 Hz sinusoid presented in a free field with frontal incidence at a sound pressure level of 0 dB leads to a sound pressure level at the cochlea of 0 dB. The interpolation procedure described in 7.2.6 is used to determine values at intermediate frequencies. The values for frequencies above 12 500 Hz are based on extrapolation and have not been validated, so they are shown in italics in Table 1. They are included for the user who wishes to predict the loudness of sounds with frequency components above 12 500 Hz. The end result of this stage is a specification of the spectrum of the pressure variation applied to the cochlea.

NOTE The transfer function used corresponds to that in Reference [14]; it differs slightly from that in Reference [17]. The differences are especially noteworthy in the frequency region from 1 250 Hz to 1 600 Hz and in the region from 4 000 Hz to 6 300 Hz. The transfer function used here provides more accurate predictions of the reference thresholds of hearing in ISO 389-7:2005 and of the equal-loudness contours in ISO 226:2003.

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Table 1 — Transfer functions

Frequency in Hz	Difference between the sound pressure level at the tympanic membrane and the sound pressure level measured in the free field for frontal incidence (in the absence of a listener) in dB	Difference between the sound pressure level at the tympanic membrane and the sound pressure level measured in the diffuse field (in the absence of a listener) in dB	Scaled transfer function value for the middle ear in dB
20	0,0	0,0	−39,6
25	0,0	0,0	−32,0
31,5	0,0	0,0	−25,85
40	0,0	0,0	−21,4
50	0,0	0,0	−18,5
63	0,0	0,0	−15,9
80	0,0	0,0	−14,1
100	0,0	0,0	−12,4
125	0,1	0,1	−11,0
160	0,3	0,3	−9,6
200	0,5	0,4	−8,3
250	0,9	0,5	−7,4
315	1,4	1,0	−6,2
400	1,6	1,6	−4,8
500	1,7	1,7	−3,8
630	2,5	2,2	−3,3
750	2,7	2,7	−2,9
800	2,6	2,9	−2,6
1 000	2,6	3,8	−2,6
1 250	3,2	5,3	−4,5
1 500	5,2	6,8	−5,4
1 600	6,6	7,2	−6,1
2 000	12,0	10,2	−8,5

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Table 1 *(continued)*

Frequency in Hz	Difference between the sound pressure level at the tympanic membrane and the sound pressure level measured in the free field for frontal incidence (in the absence of a listener) in dB	Difference between the sound pressure level at the tympanic membrane and the sound pressure level measured in the diffuse field (in the absence of a listener) in dB	Scaled transfer function value for the middle ear in dB
2 500	16,8	14,9	−10,4
3 000	15,3	14,5	−7,3
3 150	15,2	14,4	−7,0
4 000	14,2	12,7	−6,6
5 000	10,7	10,8	−7,0
6 000	7,1	8,9	−9,2
6 300	6,4	8,7	−10,2
8 000	1,8	8,5	−12,2
9 000	−0,9	6,2	−10,8
10 000	−1,6	5,0	−10,1
11 200	1,9	4,5	−12,7
12 500	4,9	4,0	−15,0
14 000	2,0	3,3	−18,2 [a]
15 000	−2,0	2,6	−23,8 [a]
16 000	2,5	2,0	−32,3 [a]
20 000	2,5	2,0	−45,5 [a]
[a] Values are in a range that has not been validated.			

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7.4 Transformation of sound spectrum into excitation pattern

To obtain a representation of the distribution of excitation produced by the sound within the cochlea, the sound spectrum at the oval window (the cochlea) is transformed into an excitation pattern along the basilar membrane. The procedure used here is essentially the same as described by Reference [14]. Reference [14], pages 135 to 138, gives FORTRAN code implementing the procedure. The only change is that the constant D in Formula (5) of this document has the value 0,35, whereas in the FORTRAN code a value of 0,38 was used. The cochlea is modelled as an array of band pass auditory filters with overlapping pass bands. The bandwidths and shapes of the filters depend on both the input sound pressure level and the centre frequency, f_c, of the filter. The excitation pattern of a given sound is defined as the output of the auditory filters represented as a function of f_c. The output can be specified either as excitation ratio, E/E_0, or as excitation level, L_E.

The equivalent rectangular bandwidth, ERB_n in Hz, of the auditory filter for otologically normal persons and for an input sound pressure level to the cochlea of 51 dB, is specified as a function of the centre frequency of the band pass auditory filter, f_c, by Formula (1):

$$ERB_n = 24{,}673\ (0{,}004368\ f_c + 1\ \text{Hz}) \qquad (1)$$

The characteristics of the auditory filter for other input levels are derived as described below.

For a given auditory filter (with a specific f_c), the excitation is calculated by summing the power of the output in response to all of the different frequency components in the input. A first stage in this process is to sum the powers of the components of the input spectrum within each band which has a width

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as defined by Formula (1). The resulting power, converted to decibels (using the reference excitation defined in 3.20), is denoted X. It is assumed that the sharpness of the auditory filter depends on X.

The value of X is calculated using a rounded-exponential weighting function (called hereafter a filter) rather than a rectangular weighting function. The rounded-exponential filter is defined by

$$W(g, f_c) = (1 + pg)\exp(-pg) \tag{2}$$

where the value of g at frequency f is

$$g = |(f - f_c)| / f_c \tag{3}$$

and p is a dimensionless parameter determining the bandwidth and slope of the filter. For calculating X, the value of p in Formula (2) is set to $4f_c/ERB_n$. The output power of the rounded-exponential filter is calculated over the following ranges:

$$\begin{aligned} &\text{For } f < f_c \qquad g = 0 \text{ to } 1 \\ &\text{For } f > f_c \qquad g = 0 \text{ to } 4 \end{aligned} \tag{4}$$

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The calculation of X is performed with the filter centred in turn on every component in the input spectrum, as specified in Clause 5.

To calculate the output of a given auditory filter in response to a given group of frequency components, it is first necessary to specify the shape of the filter. Each side of the filter is specified to have the form given in Formula (2). The value of p for the lower side of the filter (frequencies below the centre frequency) is denoted p_l, while the value of p for the upper side of the filter (frequencies above the centre frequency) is denoted p_u. The value of p_u is invariant with level and is equal to $4f_c / ERB_n$. The value of p_l is calculated as follows.

The value of p_l for $X = 51$ dB is set equal to $4f_c / ERB_n$. Let $p_l(X, f_c)$ denote the value of p_l at level X and centre frequency f_c. Then

$$p_l(X, f_c) = p_l(51\text{ dB}, f_c) - D\,[p_l(51\text{ dB}, f_c) / p_l(51\text{ dB}, 1\text{ kHz})]\,(X - 51\text{ dB}) \tag{5}$$

where $p_l(51, f_c)$ is the value of p_l at centre frequency f_c for $X = 51$ dB, $p_l(51, 1\text{ kHz})$ denotes the value of p_l at 1 kHz for $X = 51$ dB and D is a constant with unit 1/dB and a value of 0,35.

Figure 2 shows the shape of the auditory filter centred at 1 kHz for sound pressure levels in each ERB_n from 20 dB to 100 dB in 10 dB steps.

The final excitation pattern is plotted with the scale of centre frequency (f_c) transformed to an ERB_n-number scale. An increase in frequency equal to 1 ERB_n corresponds to a step of one unit on the ERB_n-number scale. For brevity, the unit of the ERB_n-number scale is denoted the Cam, and the scale is denoted the Cam scale.

EXAMPLE According to Formula (1), the value of ERB_n for f_c = 1 000 Hz is approximately 132 Hz, so an increase in frequency from 934 Hz to 1 066 Hz corresponds to a step of one Cam.

The relationship of ERB_n-number i to f_c is given by an equation derived from Formula (1)

$$i = 21{,}366\ \lg(0{,}004\ 368\, f_c / \text{Hz} + 1) \tag{6}$$

Figure 3 shows excitation patterns for a 1000 Hz sine wave for sound pressure levels ranging from 20 dB to 100 dB in 10 dB steps. In this figure, the excitation ratio, E/E_0, has been converted to excitation level, L_E, in decibels.

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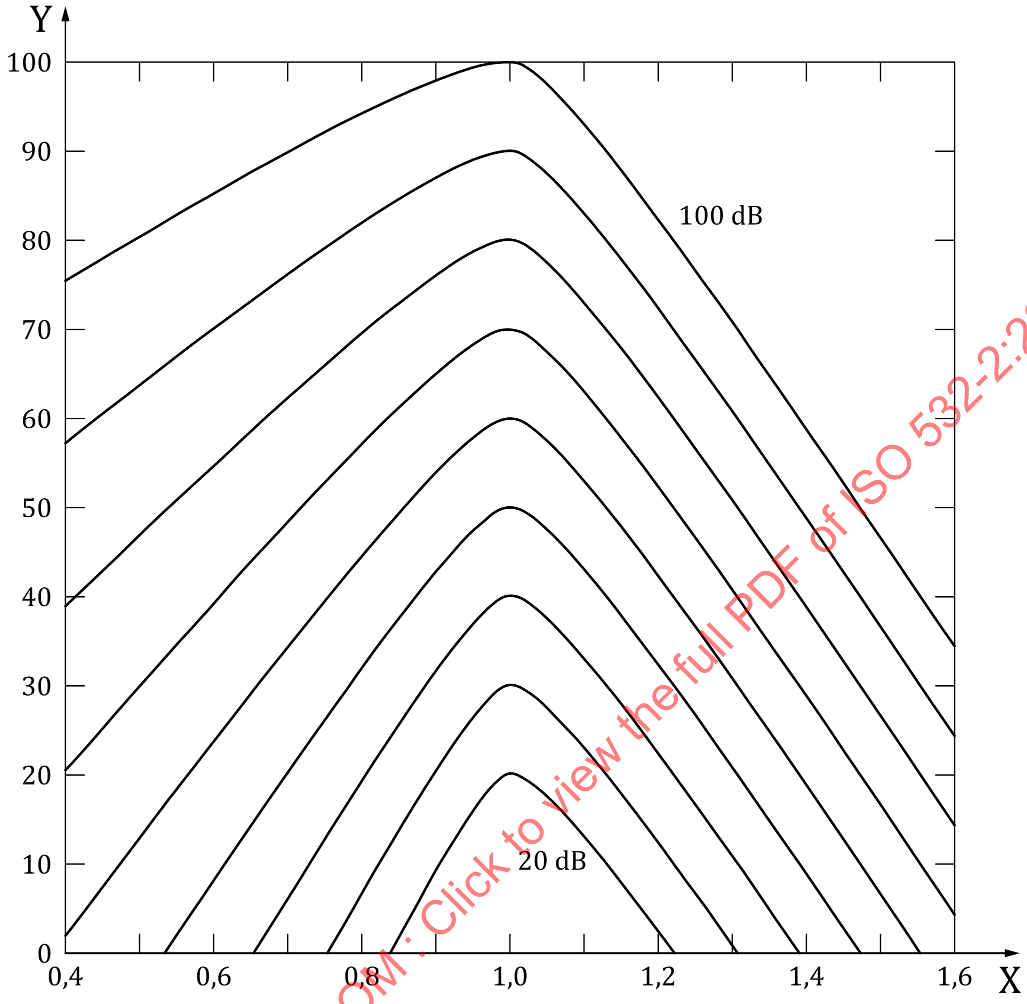
The excitation pattern is calculated for ERB_n-numbers i from 1,8 to 38,9 in steps of 0,1. The use of fine steps ensures high accuracy, which is important when the input spectrum contains sharp line spectral components.



Key

X frequency, in kHz

Y output level, in dB

NOTE The output level of the filter is plotted as a function of the frequency of the input.

Figure 2 — The shape of the auditory filter centred at 1 kHz for sound pressure levels in each ERB_n from 20 dB to 100 dB in 10 dB steps

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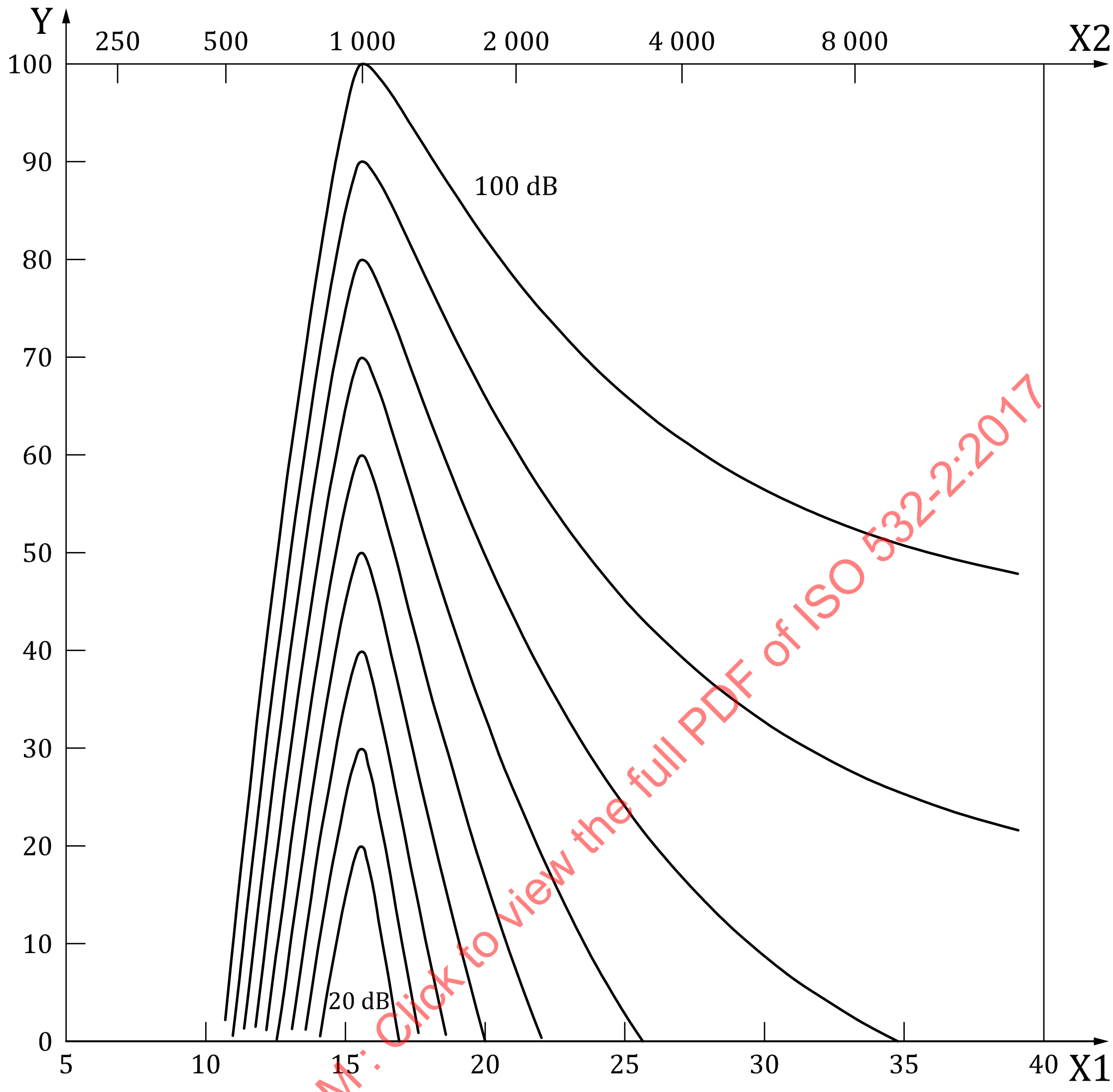

Key

X1 ERB_n-number, in Cam

X2 frequency, in Hz

Y excitation level, in dB

NOTE The frequency scale has been transformed to an ERB_n-number scale, as defined by Formula (6). The lower abscissa shows the ERB_n-number; the corresponding frequency is shown at the top.

Figure 3 — Excitation patterns for 1 kHz sine waves with sound pressure levels ranging from 20 dB to 100 dB in 10 dB steps

7.5 Transformation of excitation pattern into specific loudness

7.5.1 Introduction

The excitation ratio E/E_0 is transformed to specific loudness N' in sone/Cam. The calculation of specific loudness depends on two properties of the cochlea:

— excitation at the reference threshold of hearing, and

— gain of the cochlear amplifier for inputs with low sound pressure levels,

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which are described in 7.5.2 and 7.5.3. The following sub-clauses, 7.5.4 to 7.5.7, describe the calculation procedure based on the excitation ratio E/E_0.

7.5.2 Reference excitation at the reference threshold of hearing

The reference threshold of hearing is the lowest detectable sound pressure level of a sound in the absence of any other sounds. The function relating the excitation level at the reference threshold of hearing to frequency for monaural listening is specified in column 2 of Table 2 (binaural listening is considered in 8.1). Interpolation of the same form as described in 7.2.6 is used to determine values at frequencies between those shown in the table. The values given in Table 2 are values at the peak of the excitation pattern for sinusoidal signals, i.e. values at the output of the auditory filter centred at the signal frequency. Above 500 Hz, the excitation ratio at the reference threshold of hearing is constant. The peak excitation ratio produced by a sinusoidal signal at threshold (for monaural listening) is denoted E_{THRQ}/E_0. For frequencies of 500 Hz and above, the value of E_{THRQ}/E_0 is 2,065 (equivalent to an excitation level, L_E, of 3,15 dB).

Table 2 — Excitation level and value of 10lg$G$ at the reference threshold of hearing for monaural listening

Centre frequency in Hz	Excitation level at reference threshold (constant for all values above 500 Hz) in dB	10lg$G$ at reference threshold in dB
50	27,46	−24,31
63	23,45	−20,30
80	18,47	−15,32
100	15,13	−11,98
125	11,97	−8,82
160	9,34	−6,19
200	7,43	−4,28
250	5,75	−2,60
315	4,73	−1,58
400	3,92	−0,77
500	3,15	0
630	3,15	0
750	3,15	0
800	3,15	0
1 000	3,15	0

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7.5.3 Gain of the cochlear amplifier for inputs with low sound pressure levels

The term G represents the gain of the cochlear amplifier for inputs with low sound pressure levels at a specific frequency, relative to the gain at 500 Hz and above (which is assumed to be constant). The product of G and E_{THRQ}/E_0 at a specific frequency is independent of frequency. Table 2 shows the value of G, expressed in decibels, for different frequencies.

EXAMPLE If E_{THRQ}/E_0 is a factor of 10 higher than the value at 500 Hz and above, then G is equal to 0,1. More generally, if E_{THRQ}/E_0 is a factor K higher than the value at 500 Hz and above, then G is equal to $1/K$.

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7.5.4 Calculation of specific loudness from excitation when $E_{THRQ}/E_0 \le E/E_0$

When the excitation evoked by the signal of interest at a specific centre frequency is greater than or equal to the value of E_{THRQ}/E_0 for that frequency, but less than or equal to 10^{10}, which covers the range of most practical applications, the specific loudness is calculated by Formula (7) (see Reference [17]):

$$N' = C\left[\left(GE/E_0 + A\right)^{\alpha} - A^{\alpha}\right] \tag{7}$$

where C = 0,0617 sone/Cam. E/E_0 as specified in 3.20 is dimensionless. For frequencies of 500 Hz and above, the value of α is equal to 0,2 and the value of A is equal to 2 E_{THRQ}/E_0. A is dimensionless. Below 500 Hz, the values of α and A are related to the value of G. The relationship of α to G is specified in Table 3. The relationship of A to G is specified in Table 4. In these tables, G has been converted to decibels. Interpolation of the same form as described in 7.2.6 is used to determine values at frequencies between those shown in the table.

7.5.5 Calculation of specific loudness from excitation when $E_{THRQ}/E_0 > E/E_0$

When the excitation evoked by the signal of interest at a specific centre frequency is less than the value of E_{THRQ}/E_0 for that frequency, the specific loudness is calculated as

$$N' = C\left(\frac{2E}{\left(E + E_{THRQ}\right)}\right)^{1,5}\left[\left(G\frac{E}{E_0} + A\right)^{\alpha} - A^{\alpha}\right] \tag{8}$$

7.5.6 Calculation of specific loudness from excitation when $E > 10^{10}$

When the excitation ratio evoked by the signal of interest at a specific centre frequency is greater than 10^{10}, the specific loudness is calculated as

$$N' = C\left(\frac{E/E_0}{1,0707}\right)^{0,2} \tag{9}$$

Note that this corresponds to sound pressure levels greater than 100 dB, and there are few data on loudness perception for such high levels. The procedure has not been validated for such high levels.

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Table 3 — Value of the parameter α as a function of the parameter G, converted to decibels

10 lg G in dB	α
−25,0	0,266 92
−20,0	0,250 16
−15,0	0,236 79
−10,0	0,222 28
−5,0	0,210 55
0,0	0,200 00

Table 4 — Value of the parameter *A* as a function of the parameter *G*, with *G* expressed in decibels

10 lg *G* in dB	*A*	**10 lg *G*** (continued) in dB	*A* (continued)
−25,0	7,784	−12,0	5,437
−24,5	7,667	−11,5	5,364
−24,0	7,551	−11,0	5,291
−23,5	7,435	−10,5	5,218
−23,0	7,318	−10,0	5,145
−22,5	7,210	−9,5	5,086
−22,0	7,103	−9,0	5,027
−21,5	6,996	−8,5	4,972
−21,0	6,889	−8,0	4,918
−20,5	6,782	−7,5	4,863
−20,0	6,675	−7,0	4,808
−19,5	6,596	−6,5	4,754
−19,0	6,517	−6,0	4,699
−18,5	6,438	−5,5	4,644
−18,0	6,360	−5,0	4,590
−17,5	6,281	−4,5	4,542
−17,0	6,202	−4,0	4,496
−16,5	6,124	−3,5	4,451
−16,0	6,047	−3,0	4,405
−15,5	5,975	−2,5	4,359
−15,0	5,902	−2,0	4,314
−14,5	5,823	−1,5	4,268
−14,0	5,744	−1,0	4,222
−13,5	5,665	−0,5	4,177
−13,0	5,587	0,0	4,131
−12,5	5,510		

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8 Calculation of loudness and loudness level

8.1 Calculation of monaural and binaural loudness (diotic and dichotic stimuli)

The overall (total) loudness of a sound in sones for monaural presentation is obtained by integrating across the specific loudness pattern from i = 1,8 to 38,9, which is equivalent to summing the values of N' across the whole ERB_n-number scale when the pattern is sampled at 1 Cam intervals. In practice, to achieve greater accuracy, the specific loudness is calculated at intervals of 0,1 Cam, and in this case the sum is divided by 10. When a sound is presented to both ears, the loudness is less than that predicted from summing the loudness values from the two ears[16]. When the sound is identical at the two ears (diotic presentation), the loudness is close to 1,5 times that evoked by the sound at each ear alone[16]. This effect is implemented using the concept of inhibitory interactions between the two ears. For further discussion of this, see Annex A.

Let $N'_L(i)$ and $N'_R(i)$ be the specific loudness values evoked at the left and right ears, respectively, at a given frequency expressed by ERB_n-number i. It is assumed that there are inhibitory interactions between the two ears, such that a signal at the left ear inhibits (reduces) the loudness evoked by a signal

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at the right ear, and vice versa. It is assumed further that these inhibitory interactions are relatively broadly tuned.

To implement the broad tuning of the inhibition, the specific loudness pattern at each ear is initially smeared or smoothed by a process resembling convolution with a Gaussian-shaped weighting function.

The smoothed result at i Cam for the left ear is calculated as:

$$N'_{\mathrm{L}}(i)_{\mathrm{smoothed}} = \sum_{D_i=-18}^{D_i=+18} N'_{\mathrm{L}}(i-D_i)\exp\left[-(BD_i)^2\right] \tag{10}$$

where D_i is the deviation from the given i and B is a parameter determining the degree of spread of inhibition along the ERB_{n}-number scale. The value of B is 0,08. D_i is changed in steps of 0,1. This equation results in an increase in overall magnitude after smoothing, but this is irrelevant because only ratios of the smoothed specific loudness patterns for the two ears are used subsequently. When $i + D_i$ is less than 1,8 Cam and greater than 38,9 Cam, N_{L}' is set to 0.

Similarly for the right ear, the smoothed specific loudness at i Cam is given by:

$$N'_{\mathrm{R}}(i)_{\mathrm{smoothed}} = \sum_{D_i=-18}^{D_i=+18} N'_{\mathrm{R}}(i-D_i)\exp\left[-(BD_i)^2\right]. \tag{11}$$

The values determined by Formulae (10) and (11) are determined for i = 1,8 to 38,9 at intervals of 0,1.

Let $INH_{\mathrm{L}}(i)$ denote the factor by which the specific loudness evoked by the signal at the left ear is reduced after inhibition produced by the signal at the right ear. Let $INH_{\mathrm{R}}(i)$ denote the factor by which the specific loudness evoked by the signal at the right ear is reduced after inhibition produced by the signal at the left ear. The inhibition is modelled by Formula (12) and Formula (13):

$$INH_{\mathrm{L}}(i) = 2\Big/\left[1+\left\{\mathrm{sech}\left(N'_{\mathrm{R}}(i)_{\mathrm{smoothed}} / N'_{\mathrm{L}}(i)_{\mathrm{smoothed}}\right)\right\}^{\theta}\right] \tag{12}$$

$$INH_{\mathrm{R}}(i) = 2\Big/\left[1+\left\{\mathrm{sech}\left(N'_{\mathrm{L}}(i)_{\mathrm{smoothed}} / N'_{\mathrm{R}}(i)_{\mathrm{smoothed}}\right)\right\}^{\theta}\right] \tag{13}$$

where sech represents the mathematical function hyperbolic secant, and θ = 1,597 8.

To prevent problems associated with dividing by zero when $N'_{\mathrm{L}}(i)_{\mathrm{smoothed}}$ or $N'_{\mathrm{R}}(i)_{\mathrm{smoothed}}$ are zero, a small number (10^{-13}) is added to the values of $N'_{\mathrm{L}}(i)_{\mathrm{smoothed}}$ and $N'_{\mathrm{R}}(i)_{\mathrm{smoothed}}$ prior to entering them in Formula (12) and Formula (13).

The gain values calculated using Formula (12) and Formula (13) are applied to the original specific loudness values in each ear to give inhibited specific loudness values. Specifically, the value of $N'_{\mathrm{L}}(i)$ is divided by $INH_{\mathrm{L}}(i)$, and the value of $N'_{\mathrm{R}}(i)$ is divided by $INH_{\mathrm{R}}(i)$. The loudness for each ear is then calculated by summing the inhibited specific loudness values over centre frequency on the Cam scale, and the overall binaural loudness is obtained by summing the (inhibited) loudness values across the two ears.

8.2 Relationship between loudness level and loudness

The procedure can be used to determine the relationship between loudness level in phons and loudness in sones. This is done by using as input to the procedure a 1 000 Hz sinusoid, and specifying the conditions as binaural listening in a free field with frontal incidence. The input level of the 1 000 Hz tone is then equal to its loudness level in phons and the output of the procedure gives the corresponding calculated loudness, N, in sones. The relationship between loudness level in phons and loudness in sones is specified in Table 5.

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Table 5 — Relationship between loudness level in phons and calculated loudness, *N*, in sones

Loudness level phon	Calculated loudness, *N* sone
0,0	0,001
2,2	0,004
4,0	0,008
5,0	0,010
7,5	0,019
10,0	0,031
15,0	0,073
20,0	0,146
25,0	0,26
30,0	0,43
35,0	0,67
40,0	1,00
45,0	1,46
50,0	2,09
55,0	2,96
60,0	4,14
65,0	5,77
70,0	8,04
75,0	11,2
80,0	15,8
85,0	22,7
90,0	32,9
95,0	47,7
100,0	69,6
105,0	102,0
110,0	151,0
115,0	225,0
120,0	337,6

8.3 Calculation of the reference threshold of hearing

The reference threshold of hearing of a sound is taken to correspond to the level at which the procedure gives a calculated loudness of 0,004 sone. This value corresponds to a loudness level of 2,2 phon. The procedure can be used to calculate the reference threshold of hearing of a given sound by determining the input level that leads to a calculated loudness level of 2,2 phon. Thus calculated, the reference thresholds of hearing for sinusoids are within 0,2 dB of those specified in ISO 389-7:2005 for all frequencies from 0,05 kHz to 12,5 kHz.

9 Uncertainty of calculated loudness for stationary sounds

The calculation of loudness of stationary sounds using the loudness model described in this document is based on psychoacoustic experiments. The use of the method will produce results with uncertainty comparable to the uncertainty of perceived loudness assessed in a psychoacoustic experiment, assuming that the loudness data are averaged for a sample of at least 10 otologically normal persons.

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Since sufficient information needed to calculate uncertainty of the loudness calculation described in this document by applying the approach described in ISO/IEC Guide 98-3 is not currently available, the determination of uncertainty has been based on the reproducibility of the data obtained across a large number of loudness assessment studies conducted in various laboratories.

The uncertainty of loudness calculation for stationary sounds described in this document has been based on reproducibility of loudness matching judgements and judgements relating loudness to loudness level for a number of simple and complex input sounds. This uncertainty is based on the results of several studies conducted with $n \geq 10$ otologically normal persons.

Since the perceptual loudness data are normally distributed, the maximum deviation of the data has been defined as the [-3σ; +3σ] range corresponding to 99,6 % of all the data, where σ is the standard deviation of the sample distribution. Based on a number of studies, this maximum deviation is approximately equivalent to a change in loudness level of 4 phon (e.g References [26,27,30–32]). This uncertainty indicates that sounds that differ in “true” loudness level by ± 4 phon may result in the same loudness estimate. Alternatively, it indicates that a sound of a given loudness may cause loudness level judgements that differ up to ± 4 phon.

The standard deviation (standard uncertainty) of such reproducibility of the data is 1,4 phon and the expanded uncertainty for a stated coverage probability of 95 % is two times the standard deviation of the reproducibility, i.e. 2,8 phon. The expanded uncertainty of loudness calculation is the maximum uncertainty permitted for demonstration of conformance to the requirements of this document. It is the uncertainty of the loudness calculation that the user needs to take into account.

Additionally, the random error estimated by expanded uncertainty may be compounded by a systematic error resulting from methodological differences between a given study and the studies that were used as the basis for the development of the loudness calculation procedure described in this document. Such systematic errors, if present, can increase the overall deviation of the loudness calculated according to this document from the perceived loudness, but cannot be a priori estimated, since they may be different in each study.

10 Data reporting

The following information shall be reported:

a) a reference to this document, i.e. ISO 532-2;

b) the sound under consideration;

c) the manner of sound presentation, for example, free field, diffuse field or via headphones;

d) the method used to define or measure the sound, for example by specification of a synthetic signal, via a microphone at the centre of the listening position, or via a head and torso simulator;

e) for headphone presentation or for signals recorded from a head and torso simulator, whether any “correction file” has been used (see 7.2.3 and 7.2.5) and, if so, the contents of the correction file;

f) the method used to specify the spectrum, for example as the levels in one-third-octave bands or as the spectrum determined using discrete cosine-transform methods;

g) whether the sound was presented monaurally or binaurally;

h) the loudness in sones;

i) if required, the specific loudness in sones/Cam as a function of ERB_n-number, i;

j) if required, the loudness level in phons.

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Annex A
(informative)

Comments regarding binaural loudness

ISO 532:1975 provided two methods for calculating the loudness of sounds presented monaurally or diotically (the same sound to each ear). This facilitated the measurement of sound spectra using a single microphone. A limitation of these previous methods was that they did not reflect typical listening conditions in which sounds differ at the two ears (dichotic conditions). Modern instrumentation systems can facilitate the measurement of sound spectra at the left and right ears through the use of artificial heads. While there is a large body of literature on binaural summation of loudness, exact rules governing the calculation of binaural loudness from two monaural inputs do not exist, as binaural loudness summation may be dependent on the exposure situation. Examination of the literature does provide a reasonable consensus for studies conducted under the same sound exposure conditions and psychometric test methods. Recent studies of binaural loudness with otologically normal persons have used loudness matching, which can be made “bias-free” by using adaptive 2-Alternative-Forced-Choice (2-AFC) methods.

For headphone playback, the level difference required for equal loudness of monaural and diotic sounds is 3 –10 dB[16,33,35]. Other studies have shown that loudspeaker playback comparing a monaural sound to a binaural sound[36] or comparing loudspeaker playback with different level at each ear[35] gives a level difference of 3 dB to 5 dB. As in all listening tests, differences will exist between subjects. Some studies also show a level dependence of binaural loudness summation. While the present state of the art has not reached a consensus of the topic of binaural loudness summation, the model proposed in this standard is broadly consistent with the conclusions presented in the literature referenced above.

The method published in this standard predicts loudness for diotic and dichotic listening conditions, as well as for monaural conditions, based on an algorithm published by Moore and Glasberg[16]. For diotic conditions, the predictions of the method correspond well to standard measures of loudness. For example, the equal-loudness-level contours in ISO 226:2003 are predicted with good accuracy. The predictions for monaural and dichotic conditions are consistent with the general trends for loudness judgements found in the literature[16], but the predictions need to be treated with caution[37, 38].

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Annex B
(informative)

Results for specific test signals

B.1 Sinusoidal tones

B.1.1 Example 1

A 1 000 Hz tone presented binaurally in free field with a sound pressure level of 10 dB, 20 dB, 30 dB, 40 dB, 50 dB, 60 dB, 70 dB or 80 dB. Notice that, for sound pressure levels above 40 dB, the loudness roughly doubles for each 10 dB increase in sound pressure level.

Sound pressure level in dB	10	20	30	40	50	60	70	80
Calculated loudness N in sone	0,03	0,14	0,43	1,0	2,1	4,1	8,1	15,8
Calculated loudness level L_N in phon	10	20	30	40	50	60	70	80

B.1.2 Example 2

A 3 000 Hz tone presented binaurally in free field with a sound pressure level of 20 dB, 40 dB, 60 dB or 80 dB. Notice that the 3 000 Hz tone is louder than a 1 000 Hz tone of the same sound pressure level. This is a consequence of the free field to tympanic membrane transfer function.

Sound pressure level in dB	20	40	60	80
Calculated loudness N in sone	0,35	1,8	7,0	27,2
Calculated loudness level L_N in phon	28	48	68	87,5

B.1.3 Example 3

A 1 000 Hz tone presented monaurally via an earphone with a sound pressure level of 20 dB, 40 dB, 60 dB or 80 dB at the tympanic membrane.

Sound pressure level in dB	20	40	60	80
Calculated loudness N in sone	0,07	0,54	2,31	8,82
Calculated loudness level L_N in phon	14,7	32,7	51,5	71,4

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B.1.4 Example 4

A 100 Hz tone presented binaurally in free field with a sound pressure level of 50 dB.

Sound pressure level in dB	50
Calculated loudness N in sone	0,351
Calculated loudness level L_N in phon	28

B.1.5 Example 5

A 100 Hz tone presented binaurally via Telephonics TDH-39 earphones with a nominal output sound pressure level of 50 dB. The frequency response of the earphone at the tympanic membrane, relative to the nominal sensitivity, is specified in the file TDH 39.

Sound pressure level in dB	50
Calculated loudness N in sone	0,048
Calculated loudness level L_N in phon	12,5

Notice that the loudness is lower in this example than in Example 4. This happens because the response of the TDH 39 earphone at the tympanic membrane drops off at low frequencies; the response is about 13,8 dB down at 100 Hz relative to the nominal sensitivity.

NOTE Additional studies[22,23] have compared the results of using the method described in this document to the standardized equal loudness curves according to ISO 226:2003.

B.2 Filtered noise

B.2.1 EXAMPLE 1

A band of white noise arithmetically centred at 1 000 Hz, presented binaurally in free field, with a spectrum density level of 40 dB, and a bandwidth of 100 Hz (950 Hz to 1 050 Hz) or 1 000 Hz (500 Hz to 1 500 Hz).

Bandwidth	100 Hz	1 000 Hz
Calculated loudness N in sone	4,21	14,17
Calculated loudness level L_N in phon	60,2	78,4

B.2.2 EXAMPLE 2

A band of white noise arithmetically centred at 1 000 Hz, presented binaurally in free field, with an overall sound pressure level of 60 dB, and a bandwidth of 100 Hz (950 Hz to 1 050 Hz, spectrum density level 40 dB) or 1 000 Hz (500 Hz to 1 500 Hz, spectrum density level 30 dB). Notice that the noise with

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