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Acoustics — Normal equal-loudness-level contours

Acoustique — Lignes isosoniques normales

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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 of 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 www.iso.org/iso/foreword.html.

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

This third edition cancels and replaces the second edition (ISO 226:2003), which has been technically revised.

The main changes are as follows:

— clarification of the scope in the introduction;

— updated bibliography;

— alignment with ISO 389-7 regarding the 0 phon data;

— correction of systematic errors that lead to minor changes in the entire data up to 0,6 dB.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Curves defining combinations of pure tones in terms of frequency and sound pressure level, which are perceived as equally loud, express a fundamental property of the human auditory system and are of basic importance in the field of psychoacoustics. Such equal-loudness-level contours were specified in the previous editions of this document.

NOTE 1   In this document, only the equal-loudness-level contours for pure tones are specified because of insufficient equal-loudness-level data for other sounds. Nevertheless, this International Standard could be applicable to one-third-octave or narrower bands of noise. It may be less valid for broader bands of noises or noises with prominent tones.

NOTE 2   For the calculation of loudness of arbitrary signals or the calculation of the tonal loudness other standards must be applied (e.g., for loudness of arbitrary stationary and non-stationary (time-varying) sounds: ISO 532-1[2], for loudness of arbitrary stationary sounds: ISO 532-2[3], for tonal loudness and tonality: ECMA-418-2[4]). The tonal loudness is the loudness of the tonal components of a complex sound as the basis for the tonality calculation in Reference [4].

During the technical revision of this document, it was decided to maintain separate documents for the specification of the threshold and supra-threshold data. The threshold values are specified in ISO 389 7[1], as a part of the series of International Standards concerning reference zero values for the calibration of audiometric equipment. The equal-loudness-level contours are presented in this document.

NOTE 3   The equal-loudness-level values given by this document differ from those of the previous edition of ISO 226, although the differences are small, i.e., up to 0,6 dB for the entire range of data. This change was caused by the application of an improved model for the perception of loudness as described in Reference [5]. The normal equal-loudness-level contours for pure tones in this document are essentially identical to those described in Reference [5] since both are based on the same equal-loudness-level data. The only difference is the low equal-loudness levels at 20 Hz caused by the revision of ISO 389-7 in 2019, which introduced a 0,4 dB change in the normative hearing threshold at that frequency.

Acoustics — Normal equal-loudness-level contours

1   Scope

This document specifies combinations of sound pressure levels and frequencies of pure continuous tones which are perceived as equally loud by human listeners. The specifications are based on the following conditions:

a)   the sound field in the absence of the listener consists of a free progressive plane wave;

b)   the source of sound is directly in front of the listener;

c)   the sound signals are pure tones;

d)   the sound pressure level is measured at the position where the centre of the listener's head would be, but in the absence of the listener;

e)   listening is binaural;

f)   the listeners are otologically normal persons in the age range from 18 years to 25 years inclusive.

The data are given in graphical form in Annex A and in numerical form in Annex B for the preferred frequencies in the one-third-octave series from 20 Hz to 12 500 Hz, inclusive, in accordance with ISO 266.

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.

ISO 266, *Acoustics — Preferred frequencies*

3   Terms and definitions

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

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

—   ISO Online browsing platform: available at https://www.iso.org/obp

—   IEC Electropedia: available at https://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

3.2
free field
sound field where the boundaries of the room exert a negligible effect on the sound waves

3.3
loudness level
value in phons that has the same numerical value as the sound pressure level in decibels of a reference sound, consisting of a frontally incident, free sinusoidal plane wave at a frequency of 1 000 Hz, which is judged as loud as the given sound

3.4
equal-loudness relationship
curve or function expressing, for a pure tone of a given frequency, the relationship between its *loudness level* (3.3) and its sound pressure level

3.5
equal-loudness-level contour
curve in the sound pressure level/frequency plane connecting points whose coordinates represent pure tones judged to be equally loud

3.6
normal equal-loudness-level contour
equal-loudness-level contour (3.5) that represents the average judgment of *otologically normal persons* (3.1) within the age limits from 18 years to 25 years inclusive

Note 1 to entry: The method for deriving the normal equal-loudness-level contours is described in Annex C.

3.7
threshold of hearing
level of a sound at which, under specified conditions, a person gives 50 % of correct detection responses on repeated trials

4 Formula for derivation of normal equal-loudness-level contours

4.1 Deriving sound pressure level from loudness level

The sound pressure level L_f in dB of a pure tone of frequency, f, which has a loudness level, L_N, in phon, is given by Formula (1) [see also Formula (C.3)]:

$$L_f = \frac{10}{\alpha_f} \cdot \lg\left\{\left[\left(\frac{p_o}{p_a}\right)^2\right]^{(\alpha_r - \alpha_f)} \left[10^{\left(\alpha_r \frac{L_N}{10\,\text{phon}}\right)} - 10^{\left(\alpha_r \frac{T_r}{10\,\text{dB}}\right)}\right] + 10^{\left(\alpha_f \frac{T_f + L_U}{10\,\text{dB}}\right)}\right\} \text{dB} - L_U$$

$$= \frac{10}{\alpha_f} \cdot \lg\left\{\left(4 \cdot 10^{-10}\right)^{(0,3 - \alpha_f)} \cdot \left[10^{\left(0,03 \frac{L_N}{\text{phon}}\right)} - 10^{0,072}\right] + 10^{\left(\alpha_f \frac{T_f + L_U}{10\,\text{dB}}\right)}\right\} \text{dB} - L_U \tag{1}$$

where

T_f is the threshold of hearing in dB as in Reference [1];

T_r is the threshold of hearing at 1 000 Hz in dB;

α_f is the exponent for loudness perception;

α_r is the exponent for loudness perception at 1 000 Hz;

L_U is a magnitude of the linear transfer function normalized at 1 000 Hz in dB

p_0 is 20 µPa.

These values are all given in [Table 1](#) for the preferred third-octave frequencies defined in ISO 266.

[Formula (1)](#) applies, at each frequency, for values from a lower limit of 20 phon to the following upper limits:

    20 Hz to 4 000 Hz: 90 phon

    5 000 Hz to 12 500 Hz: 80 phon

[Formula (1)](#) is only informative for loudness levels below 20 phon because of the lack of experimental data between 20 phon and the hearing thresholds. The same holds for loudness levels above 90 phon up to 100 phon from 20 Hz to 1 000 Hz because data from only one institute are available at 100 phon.

4.2 Deriving loudness levels from sound pressure levels

The loudness level L_N in phon of a pure tone of frequency f, which has a sound pressure level L_f in dB, is given by [Formula (2)](#):

$$L_N = \frac{100}{3} \cdot \lg \left[\frac{10^{\left(\alpha_f \frac{L_f + L_U}{10\,\text{dB}} \right)} - 10^{\left(\alpha_f \frac{T_f + L_U}{10\,\text{dB}} \right)}}{\left(4 \cdot 10^{-10} \right)^{\left(0,3 - \alpha_f \right)}} + 10^{0,072} \right] \text{phon} \tag{2}$$

where T_f, α_f and L_U are the same as in [4.1](#).

The same restrictions, which apply to [Formula (1)](#), also apply to [Formula (2)](#).

Table 1 — Parameters of [Formula (1)](#) used to calculate the normal equal-loudness-level contours

Frequency f Hz	α_f	L_U dB	T_f dB
20	0,635	−31,5	78,1
25	0,602	−27,2	68,7
31,5	0,569	−23,1	59,5
40	0,537	−19,3	51,1
50	0,509	−16,1	44,0
63	0,482	−13,1	37,5
80	0,456	−10,4	31,5
100	0,433	−8,2	26,5
125	0,412	−6,3	22,1
160	0,391	−4,6	17,9
200	0,373	−3,2	14,4
250	0,357	−2,1	11,4
315	0,343	−1,2	8,6
400	0,330	−0,5	6,2
500	0,320	0,0	4,4
630	0,311	0,4	3,0
800	0,303	0,5	2,2
1 000	0,300	0,0	2,4
1 250	0,295	−2,7	3,5
1 600	0,292	−4,2	1,7
2 000	0,290	−1,2	−1,3
2 500	0,290	1,4	−4,2
3 150	0,289	2,3	−6,0
4 000	0,289	1,0	-5,4
5 000	0,289	−2,3	−1,5
6 300	0,293	−7,2	6,0
8 000	0,303	−11,2	12,6
10 000	0,323	−10,9	13,9
12 500	0,354	−3,5	12,3

For a graphical and numerical representation of the data for the preferred frequencies in the one-third-octave series from 20 Hz to 12 500 Hz, inclusive, in accordance with ISO 266, information according to [Annex A](#) and [Annex B](#) shall be used.

Annex A
(informative)

Normal equal-loudness-level contours for pure tones under free-field listening conditions
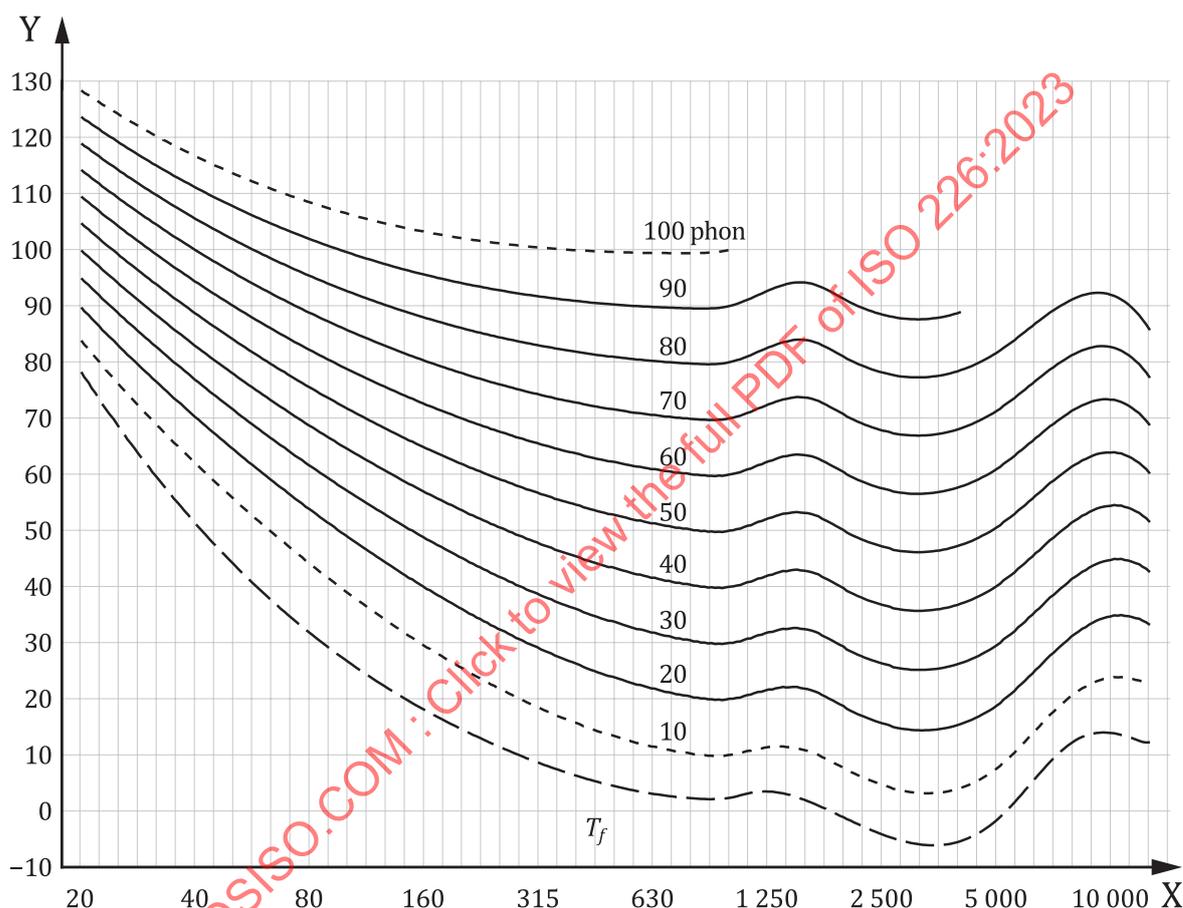
Key

X   frequency, expressed in Hz

Y   sound pressure level, expressed in dB

T_f hearing threshold

NOTE 1   The hearing threshold under free-field listening condition, T_f, is indicated by a dashed line as defined in ISO 389-7[1].

NOTE 2   The contour at 10 phon is drawn by dotted lines because of the lack of experimental data between 20 phon and the hearing thresholds. Moreover, the 100-phon contour is also described by a dotted line because data from only one institute are available at this loudness level.

**Figure A.1 — Normal equal-loudness-level contours for pure tones
(binaural, free-field listening, frontal incidence)**

Annex B
(informative)

Tables for normal equal-loudness-level contours for pure tones under free-field listening conditions

Table B.1 — Sound pressure level corresponding to a given loudness level of pure tones ranging in frequency from 20 Hz to 12 500 Hz

Loudness level	Sound pressure level, dB									
	Frequency, Hz									
phon	20	25	31,5	40	50	63	80	100	125	160
10	(83,7)	(76,1)	(68,7)	(61,7)	(55,5)	(49,5)	(43,7)	(38,6)	(33,9)	(29,2)
20	89,5	82,9	76,3	69,9	64,3	58,8	53,4	48,6	44,1	39,6
30	94,8	88,6	82,5	76,6	71,4	66,2	61,2	56,7	52,6	48,4
40	99,7	93,9	88,2	82,7	77,8	73,0	68,3	64,2	60,4	56,6
50	104,6	99,1	93,7	88,5	83,9	79,4	75,2	71,4	68,0	64,6
60	109,4	104,2	99,1	94,2	89,9	85,8	81,9	78,5	75,4	72,4
70	114,1	109,2	104,4	99,8	95,9	92,1	88,5	85,5	82,8	80,1
80	118,9	114,2	109,7	105,4	101,8	98,3	95,1	92,5	90,1	87,8
90	123,6	119,2	115,0	111,0	107,7	104,6	101,7	99,4	97,4	95,5
100	(128,3)	(124,2)	(120,2)	(116,6)	(113,6)	(110,8)	(108,3)	(106,3)	(104,7)	(103,2)
Loudness level	Sound pressure level, dB									
	Frequency, Hz									
phon	200	250	315	400	500	630	800	1 000	1 250	1 600
10	(25,1)	(21,5)	(18,3)	(15,4)	(13,2)	(11,3)	(10,0)	10,0	(11,2)	(10,5)
20	35,6	32,1	28,9	25,9	23,6	21,6	20,1	20,0	21,4	21,5
30	44,7	41,4	38,4	35,7	33,5	31,6	30,0	30,0	31,6	32,1
40	53,3	50,3	47,6	45,1	43,1	41,4	40,0	40,0	41,8	42,6
50	61,6	58,9	56,5	54,3	52,6	51,1	49,9	50,0	52,0	52,9
60	69,7	67,4	65,4	63,5	62,1	60,8	59,8	60,0	62,1	63,2
70	77,8	75,9	74,2	72,6	71,5	70,4	69,7	70,0	72,3	73,5
80	85,9	84,3	82,9	81,8	80,9	80,1	79,6	80,0	82,5	83,8
90	94,0	92,7	91,7	90,9	90,2	89,7	89,5	90,0	92,6	94,1
100	(102,0)	(101,1)	(100,4)	(99,9)	(99,6)	(99,4)	(99,4)	100,0	—	—

Loudness level	Sound pressure level, dB									
	Frequency, Hz									
phon	2 000	2 500	3 150	4 000	5 000	6 300	8 000	10 000	12 500	
10	(7,3)	(4,5)	(3,0)	(3,9)	(7,6)	(14,4)	(20,9)	(23,7)	(22,4)	
20	18,2	15,5	14,2	15,3	18,7	25,0	31,4	34,7	33,0	
30	28,7	26,1	24,9	26,1	29,5	35,5	41,6	44,7	42,4	
40	39,2	36,6	35,5	36,7	40,1	45,8	51,6	54,4	51,3	
50	49,6	47,0	45,9	47,2	50,5	56,1	61,6	63,9	60,0	
60	60,0	57,4	56,4	57,7	61,0	66,4	71,5	73,2	68,6	
70	70,4	67,8	66,8	68,1	71,4	76,6	81,4	82,6	77,1	
80	80,7	78,1	77,2	78,5	81,8	86,9	91,3	91,9	85,6	
90	91,1	88,5	87,5	88,8	—	—	—	—	—	
100	—	—	—	—	—	—	—	—	—	
NOTE Values in brackets are for information only.										

Table B.2 — Loudness levels corresponding to a given sound pressure level of pure tones ranging in frequency from 20 Hz to 12 500 Hz

Sound pressure level	Loudness level, phon									
	Frequency, Hz									
dB	20	25	31,5	40	50	63	80	100	125	160
0	—	—	—	—	—	—	—	—	—	—
10	—	—	—	—	—	—	—	—	—	—
20	—	—	—	—	—	—	—	—	—	(3,5)
30	—	—	—	—	—	—	—	(4,1)	(7,0)	(10,7)
40	—	—	—	—	—	(3,5)	(7,1)	(11,2)	(15,7)	20,4
50	—	—	—	—	(5,6)	(10,4)	(16,2)	21,7	26,8	31,9
60	—	—	(2,7)	(8,4)	(14,7)	21,6	28,4	34,3	39,4	44,2
70	—	(3,5)	(11,5)	20,1	28,0	35,6	42,4	48,0	52,7	56,9
80	(4,7)	(15,5)	25,8	35,5	43,6	50,9	57,2	62,1	66,2	69,8
90	20,8	32,6	43,2	52,6	60,1	66,7	72,2	76,5	79,9	82,8
100	40,5	51,8	61,8	70,3	76,9	82,6	87,4	(90,9)	(93,6)	(95,8)
110	61,3	71,6	80,6	88,1	(93,9)	(98,7)	—	—	—	—
120	82,4	(91,6)	(99,5)	—	—	—	—	—	—	—

Sound pressure level	Loudness level, phon									
	Frequency, Hz									
dB	200	250	315	400	500	630	800	1 000	1 250	1 600
0	—	—	—	—	—	—	—	—	—	—
10	—	—	(3,4)	(5,4)	(7,1)	(8,8)	(10,0)	10,0	(8,8)	(9,5)
20	(6,0)	(8,7)	(11,5)	(14,2)	(16,4)	(18,4)	19,9	20,0	(18,6)	(18,6)
30	(14,4)	(17,9)	21,1	24,1	26,4	28,4	30,0	30,0	28,4	28,0
40	24,7	28,4	31,7	34,6	36,7	38,6	40,0	40,0	38,2	37,5
50	36,1	39,7	42,7	45,3	47,2	48,9	50,1	50,0	48,1	47,2
60	48,1	51,3	53,9	56,2	57,8	59,2	60,2	60,0	57,9	56,9
70	60,3	63,0	65,3	67,1	68,4	69,6	70,3	70,0	67,7	66,6
80	72,7	74,9	76,7	78,1	79,1	79,9	80,4	80,0	77,6	76,3
90	85,1	86,8	88,1	89,1	89,7	(90,3)	(90,5)	90,0	87,4	86,0
100	(97,5)	(98,7)	(99,5)	—	—	—	—	100,0	—	—
110	—	—	—	—	—	—	—	—	—	—
120	—	—	—	—	—	—	—	—	—	—

Sound pressure level	Loudness level, phon								
	Frequency, Hz								
dB	2 000	2 500	3 150	4 000	5 000	6 300	8 000	10 000	12 500
0	(3,5)	(6,0)	(7,4)	(6,7)	(3,6)	—	—	—	—
10	(12,5)	(14,9)	(16,2)	(15,3)	(12,1)	(6,0)	—	—	—
20	21,7	24,2	25,4	24,3	21,2	(15,2)	(9,1)	(7,0)	(8,0)
30	31,2	33,7	34,8	33,6	30,5	24,7	(18,6)	(15,6)	(17,0)
40	40,8	43,3	44,3	43,1	39,9	34,4	28,4	25,2	27,4
50	50,4	52,9	53,9	52,7	49,5	44,1	38,4	35,4	38,5
60	60,0	62,5	63,5	62,3	59,1	53,8	48,4	45,9	50,0
70	69,7	72,2	73,1	71,9	68,7	63,5	58,5	56,5	61,7
80	79,3	81,8	82,7	81,5	78,3	73,3	68,6	67,3	73,4
90	89,0	—	—	—	—	—	78,7	78,0	—
100	—	—	—	—	—	—	—	—	—
110	—	—	—	—	—	—	—	—	—
120	—	—	—	—	—	—	—	—	—

NOTE   Values in brackets are for information only.

Annex C
(informative)

Notes on the derivation of the normal equal-loudness-level contours

C.1 Experimental data

Normal equal-loudness-level contours for pure tones under free-field listening conditions specified in ISO 226 are obtained from the results of twelve independent experimental investigations as given in References [6] to [17] as summarized in Reference [5]. In most of the cases, the experimental conditions, such as the stimuli and subject criterion, satisfied the preferred test conditions (see Reference [18]). The deviation from the preferred test conditions can be regarded as negligible. Brief descriptions of the investigations are given in Table C.1.

C.2 Derivation of Formula (1) and Formula (2)

Equal-loudness-level contours are drawn in the two-dimensional plane described by frequency and sound pressure level axes. Since experimental data to draw the contours are given discretely, the data must be appropriately smoothed and interpolated. To this end, a model function representing the equal-loudness relations is derived. Values of the parameters of the function are obtained by fitting the function to the experimental data using the method of least squares.

The interpolation along the sound pressure level axis was based on a model loudness function. A loudness function denotes the loudness of a sound as a function of the sound pressure level of the sound. While several functions have been proposed as the model loudness function for a pure tone, l, the following function, given by Formula (C.1), was applied here (see Reference [19]):

$$l = c\left[\left(\frac{p}{\mathrm{Pa}}\right)^{2\theta} - \left(\frac{p_{\mathrm{t}}}{\mathrm{Pa}}\right)^{2\theta}\right] \tag{C.1}$$

where

c is a dimensional constant;

p is the sound pressure of the pure tone;

θ is the exponent of the loudness-perception process;

p_{t} is the threshold of hearing in terms of sound pressure.

This function was given in References [20] and [21] and is known to describe very well the loudness function of a pure tone in the absence of masking noise, in spite of its simple form (see Reference [22]).

Furthermore, it was pointed out in Reference [23] that there are two different processes in assessing loudness: one is a "loudness perception process"; the other is a "number assignment process." Based on this idea, a two-stage model was proposed in which the outputs of both processes are described by separate power transformations (see Reference [5]). Moreover, in an actual hearing system, the sound emitted from a sound source is transformed by a linear transfer function such as a head-related transfer function and transfer functions of the outer ear, the middle ear, and the linear mechanical part of the inner ear. The linear transfer function describes a comprehensive transfer function between a

sound source and the stage just before the loudness perception process. According to these ideas, the process of loudness rating consists of three parts:

— a linear transfer function,

— a loudness perception, and

— a number assignment.

Figure C.1 shows a block diagram describing this model. The loudness response on the basis of this model together with the loudness function of Formula (C.1) is given by Formula (C.2):

$$l = b \left\{ c \left[(U \frac{p}{\text{Pa}})^{2\alpha} - (U \frac{p_\text{t}}{\text{Pa}})^{2\alpha} \right] \right\}^{\beta}$$

(C.2)

where

U is an extended linear transfer function;

c, α are extended dimensional constants and an exponent for the "loudness perception process," respectively;

b, β are those for the "number assignment process," respectively;

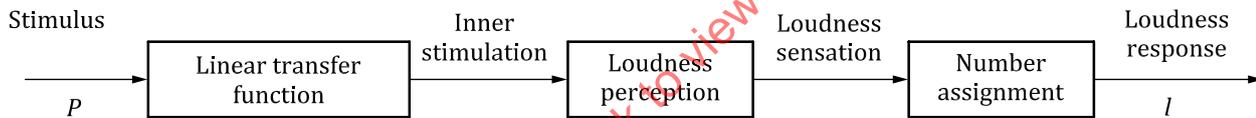p, p_t are as defined in Formula (C.1).

Figure C.1 — Block diagram of a loudness-rating-process model

In addition to sound pressure, the equal-loudness relationship along the frequency axis must be also expressed by a function. When the loudness of a 1 000 Hz pure tone is equal to the loudness of an f Hz pure tone, the following Formula (C.3) can be derived from Formula (C.2):

$$\left(\frac{p_f}{\text{Pa}} \right)^2 = \frac{1}{U_f{}^2} \left\{ \left[\left(\frac{p_\text{r}}{\text{Pa}} \right)^{2\alpha_r} - \left(\frac{p_\text{tr}}{\text{Pa}} \right)^{2\alpha_r} \right] + \left(U_f \frac{p_\text{tf}}{\text{Pa}} \right)^{2\alpha_f} \right\}^{\frac{1}{\alpha_f}}$$

(C.3)

where

p_f is the sound pressure of an f Hz pure tone when its loudness is equal to that of a 1 000 Hz pure tone with a sound pressure, p_r;

p_tf is the threshold of hearing at a frequency of f Hz;

p_tr is the threshold of hearing at 1 000 Hz;

$\alpha_f, \alpha_\text{r}$ are the exponents for the f Hz and 1 000 Hz pure tones, respectively;

U_f is a magnitude of the linear transfer function normalized at 1 000 Hz.

That is, U at 1 000 Hz is set to 1. In these derivations, it is assumed that the variables for the "number assignment process", b and β, do not depend on frequency. With these equations, the sound pressure level of an f Hz pure tone whose loudness is equal to that of a 1 000 Hz pure tone can be calculated.

Formula (C.3) can be transformed into Formula (1) by substituting $\left(\dfrac{p_f}{\text{Pa}}\right)^2, \left(\dfrac{p_r}{\text{Pa}}\right)^2, \left(\dfrac{p_{tf}}{\text{Pa}}\right)^2, \left(\dfrac{p_{tr}}{\text{Pa}}\right)^2$ by

$$\left(\frac{p_f}{\text{Pa}}\right)^2 = \left(\frac{p_0}{\text{Pa}}\right)^2 10^{\left(\frac{L_f}{10\,\text{dB}}\right)}, \left(\frac{p_r}{\text{Pa}}\right)^2 = \left(\frac{p_0}{\text{Pa}}\right)^2 10^{\left(\frac{L_N}{10\,\text{phon}}\right)}, \left(\frac{p_{tf}}{\text{Pa}}\right)^2 = \left(\frac{p_0}{\text{Pa}}\right)^2 10^{\left(\frac{T_f}{10\,\text{dB}}\right)}, \left(\frac{p_{tr}}{\text{Pa}}\right)^2 = \left(\frac{p_0}{\text{Pa}}\right)^2 10^{\left(\frac{T_{rf}}{10\,\text{dB}}\right)}$$

and $U_f^2 = 10^{\frac{L_U}{10\,\text{dB}}}$, respectively, where p_0 is 20 µPa and 0,3 is substituted for α_r and the threshold value of 2,4 dB is substituted for T_r.

Formula (2) can be derived from Formula (C.3) with the same replacements.

The exponent α_r, which is the exponent at 1 000 Hz, is set to 0,3 for the following reasons.

The loudness function based on a method of magnitude estimation and production is determined by the output of the "number assignment process." On the other hand, loudness functions based on other methods based on the additivity of loudness are determined by the output of the "loudness perception process." Since judgment of equal loudness between two sounds must be based on the comparison of the output of the "loudness perception process," the exponent value based on the loudness additivity may be used as it is in Reference [5].

The typical value obtained by means of the AME (Absolute Magnitude Estimation) method was 0,27 (0,54 for sound pressure) (see Reference [21]). Loudness obtained by an AME experiment seems to be suitable for the output of the two-stage model. Thus, the exponent of 0,27 is adopted as the value that corresponds to $\alpha_r\beta$ in the equations, where β = 1,08. This value of β was determined in Reference [24]. Therefore, the exponent at 1 000 Hz, α_r, is assumed to be 0,25 (= 0,27/1,08) for values from experiments based on the method of magnitude estimation and production. This value was used in the previous edition of ISO 226.

On the other hand, loudness functions based on other methods based on the additivity of loudness are determined by the output of the "loudness perception process". Since judgment of equal loudness between two sounds must be based on the comparison of the output of the "loudness perception process" where the exponent value based on the loudness additivity may be used as it is.

The average of all available data for the α_r values achieved by the different procedures is 0,296, as described in Reference [5], rounded to a value of 0,30.

## C.3 Derivation of the frequency dependent parameters shown in Table 1

The equal-loudness-level contours can be drawn if the values of the frequency dependent parameters, α_f, L_U, and T_f in Formula (1) are obtained. The values were calculated from the experimental data according to the following procedure.

a) With the exception of the two studies (References [25][27]) where the mean values were used, thresholds of hearing from 20 Hz to 12 500 Hz (References [8] to [14][16][17][26][28][29]) are represented by taking the mean of the median results of the individual studies for each frequency and then smoothed and interpolated by a cubic B-spline function. The resulting values are shown as T_f in Table 1. The number of subjects was not taken into account in the calculation of the spline function.

b) Formula (1) was fitted to the mean results of the individual studies (References [6] to [17]) at each frequency by the nonlinear least-squares method for estimating α_f and L_U. The obtained values of α_f were then smoothed and interpolated by a cubic B-spline function. The resultant values are shown as α_f in Table 1.

c) L_U values were then re-estimated by using Formula (1) with the values of α_f. The re-estimated L_U values were smoothed and interpolated by a cubic B-spline function. The resultant values are shown as L_U in Table 1.

C.4 Comparison between equal-loudness-level contours and experimental data

The estimation of the contours was carried out for the frequency range from 20 Hz to 12 500 Hz, because available data at frequencies above 12 500 Hz exhibit large variability. Figure C.2 shows the data from References [6] to [17] and from Reference [25] to [29] together with the fitted normal equal-loudness-level contours and the curve for the threshold of hearing.
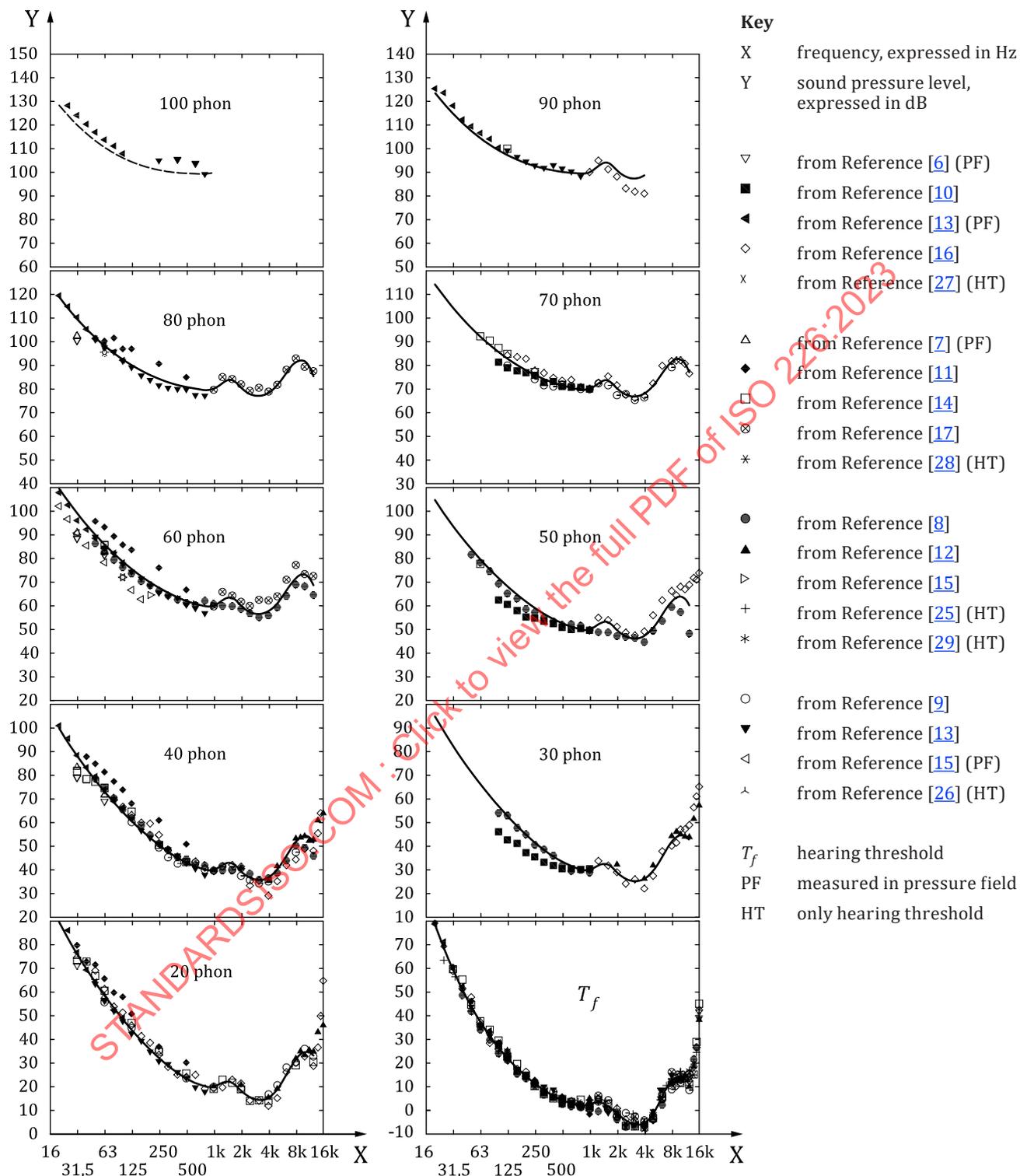
NOTE 1   The data measured in pressure field (PF) are only for low frequencies [see also Table C.1 and footnote b)].

NOTE 2   The symbols are the experimental data; the contours are calculated according to Formula (1).

Figure C.2 — Equal-loudness-level contours for pure tones under free-field listening conditions for normal hearing (frontal sound incidence)

Table C.1 — Investigations of normal equal-loudness-level contours for pure tones (frontal sound incidence)

Investigation	Reference [6]	Reference [7]	Reference [8]	Reference [9]
Year	1983	1984	1989	1989
Country	Denmark	Denmark	Germany	Japan
Sound field	Pressure field[b]	Pressure field[b]	Free field	Free field
Measured range[a]	20 phon: 2 Hz to 63 Hz 40 phon: 2 Hz to 63 Hz 60 phon: 2 Hz to 63 Hz 80 phon: 8 Hz to 63 Hz 100 phon: 31,5 Hz to 63 Hz	20 phon: 2 Hz to 63 Hz 40 phon: 2 Hz to 63 Hz 60 phon: 2 Hz to 63 Hz 80 phon: 4 Hz to 63 Hz 100 phon: 16 Hz to 63 Hz	Threshold: 40 Hz to 15 000 Hz 30 phon: 100 Hz to 1 000 Hz 40 phon: 50 Hz to 12 500 Hz 50 phon: 50 Hz to 12 500 Hz 60 phon: 50 Hz to 12 500 Hz	Threshold: 63, 125, 250 to 12 500 Hz 20 phon: 63, 125, 250, 500, 1 000, 2 000, 4 000 to12 500 Hz 40 phon: 125, 250 to 4 000, 8 000 Hz 70 phon: 125, 250 to 4 000, 8 000 Hz
Number of subjects (age)	14 (18 to 25)	20 (18 to 25)	13 to 49 (17 to 25)	9 to 32 (19 to 25)
Experimental method	Randomized maximum likelihood sequential procedure	Randomized maximum likelihood sequential procedure	Method of constant stimuli	Method of constant stimuli
Reference tone	63 Hz at a fixed level	63 Hz at a fixed level	1 000 Hz at a fixed level	1 000 Hz at a fixed level
Test tone level	Chosen randomly from μ and $\mu \pm \sigma$[c]	Chosen randomly from μ, $\mu \pm \sigma$ and $\mu \pm 2\sigma$[c]	7 levels separated by 5 dB each	9 levels separated by 1,5 dB to 4,5 dB each
Duration of a tone	2 s	2 s	1 s	1 s
Sequence in a tone pair	Reference tone was presented first	Random	Random	Random
Number of judgments in a single run/termination criterion	When the operator felt that the estimate of the PSE was sufficiently precise	When the five possible levels for a given trial already had been presented	7 test tone levels × 3 = 21 judgments	9 test tone levels × 20 = 180 judgments
PSE estimation	Maximum likelihood estimation	Maximum likelihood estimation	Where the ratio of louder response is 50 %	Maximum likelihood estimation
Note	Reference tone level was determined individually from the result of equal-loudness comparison between 1 000 Hz reference tone and 63 Hz test tone	Reference tone level was determined individually from the result of equal-loudness comparison between 1 000 Hz reference tone and 63 Hz test tone	Test tone levels were shifted by 2,5 dB between sessions	
Investigation	Reference [10]	Reference [11]	Reference [12]	Reference [12]

a Measured range "A Hz to B Hz" means frequencies of one-third-octave series specified in ISO 266 from A Hz to B Hz.

b Experiments in the "Pressure field" were conducted in a special small room in which a specified sound pressure is generated in the whole space. Experiments with this installation are limited to the very low frequency region. Such experiments have been confirmed to give results consistent with those obtained in free field in comparison investigations.

c μ and σ are estimated mean and standard deviation of the psychometric function with the method of maximum likelihood.

d The threshold of hearings were not reported in Reference [14] but in Reference [31] along with those in Reference [9].

Table C.1 *(continued)*

Year	1990	1990	1994
Country	Germany	Denmark	Denmark
Sound field	Free field	Free field	Free field
Measured range[a]	Threshold: 100 Hz to 1 000 Hz 30 phon: 100 Hz to 1 000 Hz 50 phon: 100 Hz to 1 000 Hz 70 phon: 100 Hz to 1 000 Hz	Threshold: 25 to 125, 250, 500, 1 000 Hz 20 phon: 31,5 to 125, 250, 500 Hz 40 phon: 40 to 125, 250, 500 Hz 60 phon: 50 to 125, 250, 500 Hz 80 phon: 50 to 125, 250, 500 Hz	Threshold: 1 000 to 16 000 Hz 20 phon: 1 000 to 16 000 Hz 30 phon: 1 000 to 16 000 Hz 40 phon: 1 000 to 16 000 Hz	
Number of subjects (age)	12 (21 to 25)	10 to 12 (18 to 30)	29 (18 to 25)	
Experimental method	Method of constant stimuli	Bracketing method	Bracketing method	
Reference tone	1 000 Hz at a fixed level	1 000 Hz at a fixed level	1 000 Hz at a fixed level	
Test tone level	±1,875 dB, ±4,875 dB, ±7,875 dB from equal-loudness level (Reference [28])	Changed by a 2 dB step	Changed by a 3 dB step	
Duration of a tone	1 s	1 s	1 s	
Sequence in a tone pair	Random	Random	Random	
Number of judgments in a single run/termination criterion	70 judgments (20 times for ±1,875 dB, 10 times for ±4,875 dB, 5 times for ±7,875 dB)	When 6 descending and 5 ascending were finished	When 4 descending and 4 ascending were finished	
PSE estimation	50 % of psychometric function	Average of the end level of the sequences excluding initial descents	Median of the end level of the sequences	
Note		Initial test tone level was 15 dB to 20 dB above the ISO 226:1987 level	Initial test tone level was 15 dB above the ISO 226:1987 level	
Investigation	Reference [13]	Reference [14]	Reference [15]	
Year	1997	1997	1999	
Country	Denmark	Japan	Germany	
Sound field	Free field / Pressure field[b]	Free field	Free field / Pressure field[b]	

[a] Measured range "*A* Hz to *B* Hz" means frequencies of one-third-octave series specified in ISO 266 from *A* Hz to *B* Hz.

[b] Experiments in the "Pressure field" were conducted in a special small room in which a specified sound pressure is generated in the whole space. Experiments with this installation are limited to the very low frequency region. Such experiments have been confirmed to give results consistent with those obtained in free field in comparison investigations.

[c] μ and σ are estimated mean and standard deviation of the psychometric function with the method of maximum likelihood.

[d] The threshold of hearings were not reported in Reference [14] but in Reference [31] along with those in Reference [9].

Table C.1 (continued)

Measured range[a]	Threshold: 50 Hz to 16 000 Hz 20 phon: 50 Hz to 800 Hz 40 phon: 50 Hz to 800 Hz 60 phon: 50 Hz to 800 Hz 80 phon: 50 Hz to 800 Hz 90 phon: 125 Hz to 800 Hz 100 phon: 250 Hz to 800 Hz	Threshold: 20 Hz to 100 Hz 20 phon: 20 Hz to 100 Hz 40 phon: 20 Hz to 100 Hz 60 phon: 20 Hz to 100 Hz 80 phon: 20 Hz to 100 Hz 90 phon: 20 Hz to 100 Hz 100 phon: 25 Hz to 100 Hz	Threshold: 31,5 Hz to 20 000 Hz[d] 20 phon: 31,5 to 63, 125, 250, 500, 1 000 to 4 000, 8 000, 12 500 Hz 40 phon: 31,5 to 63, 125, 250, 500 Hz 50 phon: 125 Hz 60 phon: 125 Hz 70 phon: 63 to 125, 250 to 4 000, 8 000 Hz 90 phon: 125 Hz	60 phon: 100, 200, 630, 1 000 Hz	60 phon: 16 Hz to 160 Hz
Number of subjects (age)	27 (19 to 25)	14 (19 to 25)	9 to 30 (19 to 25)	12 (Uncertain)	
Experimental method	Randomized maximum likelihood sequential procedure	Randomized maximum likelihood sequential procedure	Method of constant stimuli	Adaptive 1 up - 1 down method	
Reference tone	1 000 Hz at fixed level	100 Hz at a fixed level	1 000 Hz at a fixed level	1 000 Hz at a fixed level	100 Hz at a fixed level
Test tone level	Chosen randomly from μ, $\mu\pm\sigma$, and $\mu \pm 2\sigma$ randomly[c]		9 levels separated by 1,5 to 2,5 dB each	Initial step size was 8 dB and step size was halved until the final step size 2 dB at every second reversal in the responses	
Duration of a tone	1 s	1 s	1 s	N. A.	N. A.
Sequence in a tone pair	Random	Random	Random	N. A.	N. A.
Number of judgments in a single run/termination criterion	The method terminated when the five possible levels for a given trial already had been presented		9 test tone levels × 20 = 180 judgments	When the sequence of step size 2 dB was finished	
PSE estimation	Maximum likelihood estimation	Maximum likelihood estimation	Maximum likelihood estimation	N. A.	

a   Measured range "A Hz to B Hz" means frequencies of one-third-octave series specified in ISO 266 from A Hz to B Hz.

b   Experiments in the "Pressure field" were conducted in a special small room in which a specified sound pressure is generated in the whole space. Experiments with this installation are limited to the very low frequency region. Such experiments have been confirmed to give results consistent with those obtained in free field in comparison investigations.

c μ and σ are estimated mean and standard deviation of the psychometric function with the method of maximum likelihood.

d   The threshold of hearings were not reported in Reference [14] but in Reference [31] along with those in Reference [9].