INTERNATIONAL STANDARD

ISO 226

Second edition
2003-08-15

Acoustics — Normal equal-loudness-level contours

Acoustique — Lignes isosoniques normales

Reference number
ISO 226:2003(E)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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.

ISO 226 was prepared by Technical Committee ISO/TC 43, *Acoustics*.

This second edition cancels and replaces the first edition (ISO 226:1987), which has been technically revised.

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. Together with data on the threshold of hearing under free-field and diffuse-field listening conditions, such equal-loudness-level contours were specified in ISO 226:1987.

NOTE 1 Equal-loudness levels can also be determined for bands of noise. However, only the equal-loudness-level contours for pure tones are specified in this International Standard because insufficient data for bands of noise are available. Nevertheless, this International Standard could be applicable to one-third-octave-bands of noise.

During the technical revision of this International Standard, it was decided to separate threshold and supra-threshold data into two separate documents because the available equal-loudness-level data were not sufficient and hearing thresholds were needed. The threshold values were specified in ISO 389-7:1996, *Acoustics — Reference zero for the calibration of audiometric equipment — Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions*, 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 International Standard. They have been revised relative to the data in ISO 226:1987.

NOTE 2 ISO 389-7:1996 is presently under revision in order to align the threshold data with this edition of ISO 226.

Acoustics — Normal equal-loudness-level contours

1 Scope

This International Standard 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 referenced documents are indispensable for the application 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.

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 sound 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, sinusoidal plane progressive 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 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 that represents the average judgment of otologically normal persons within the age limits from 18 years to 25 years inclusive

NOTE 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_p of a pure tone of frequency f, which has a loudness level L_{N}, is given by:

$$L_p = \left(\frac{10}{\alpha_f} \cdot \lg A_f \right) \mathrm{dB} - L_U + 94\ \mathrm{dB} \tag{1}$$

where

$$A_f = 4{,}47 \times 10^{-3} \times (10^{0{,}025 L_{\mathrm{N}}} - 1{,}15) + \left[0{,}4 \times 10^{\left(\frac{T_f + L_U}{10} - 9 \right)} \right]^{\alpha_f}$$

T_f is the threshold of hearing;

α_f is the exponent for loudness perception;

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

These values are all given in Table 1.

Equation (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

Equation (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 of a pure tone of frequency f, which has a sound pressure level L_p, is given by:

$$L_N = \left(40 \cdot \lg B_f\right) \text{phon} + 94 \text{ phon} \tag{2}$$

where

$$B_f = \left[0{,}4 \times 10^{\left(\frac{L_p + L_U}{10} - 9\right)}\right]^{\alpha_f} - \left[0{,}4 \times 10^{\left(\frac{T_f + L_U}{10} - 9\right)}\right]^{\alpha_f} + 0{,}005\,135$$

and T_f, α_f and L_U are the same as in 4.1.

The same restrictions which apply to Equation (1) also apply to Equation (2).

Table 1 — Parameters of Equation (1) used to calculate the normal equal-loudness-level contours

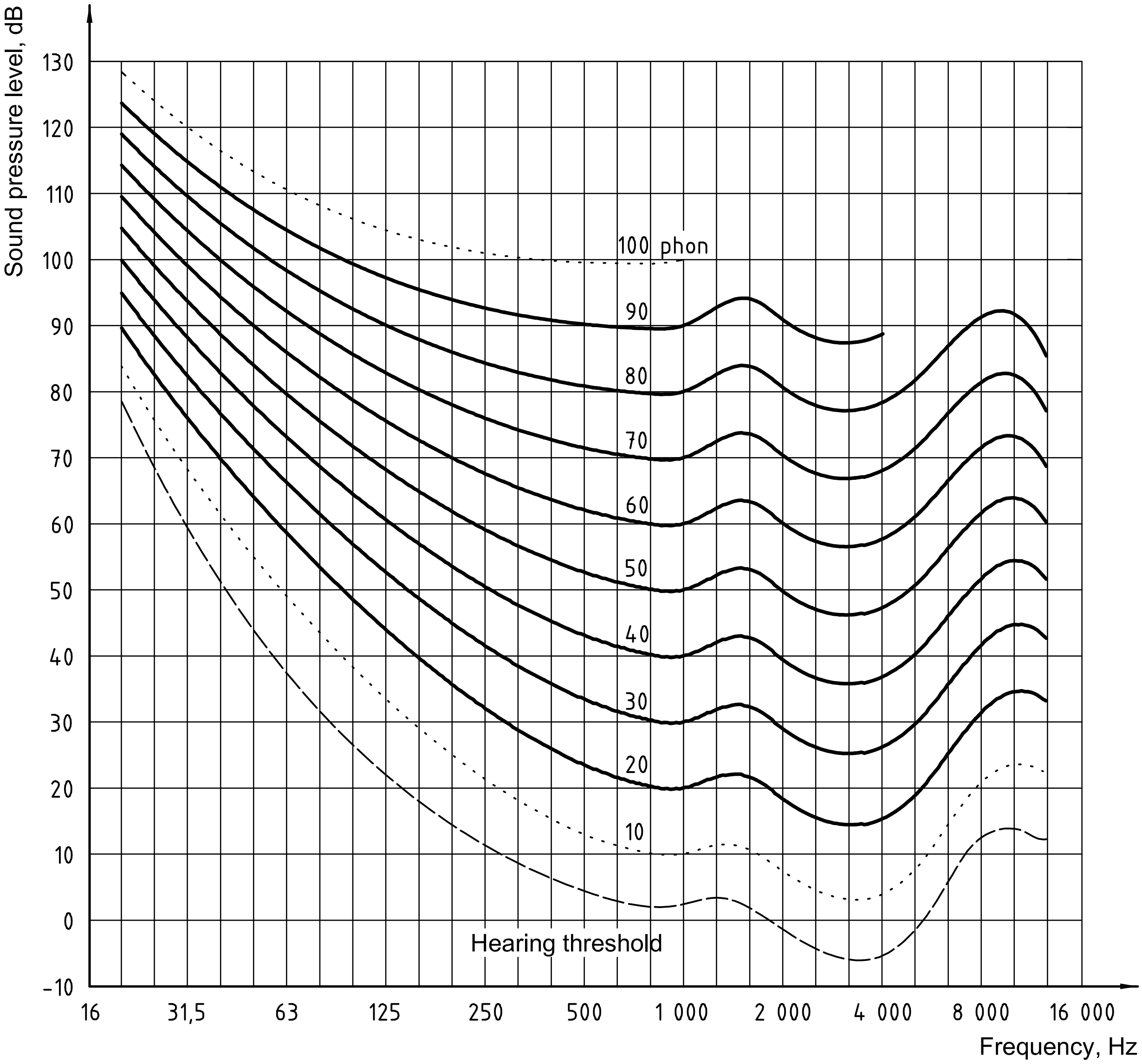
Frequency, f Hz	α_f	L_U dB	T_f dB
20	0,532	–31,6	78,5
25	0,506	–27,2	68,7
31,5	0,480	–23,0	59,5
40	0,455	–19,1	51,1
50	0,432	–15,9	44,0
63	0,409	–13,0	37,5
80	0,387	–10,3	31,5
100	0,367	–8,1	26,5
125	0,349	–6,2	22,1
160	0,330	–4,5	17,9
200	0,315	–3,1	14,4
250	0,301	–2,0	11,4
315	0,288	–1,1	8,6
400	0,276	–0,4	6,2
500	0,267	0,0	4,4
630	0,259	0,3	3,0
800	0,253	0,5	2,2
1 000	0,250	0,0	2,4

Table 1 (*continued*)

Frequency, f Hz	α_f	L_U dB	T_f dB
1 250	0,246	−2,7	3,5
1 600	0,244	−4,1	1,7
2 000	0,243	−1,0	−1,3
2 500	0,243	1,7	−4,2
3 150	0,243	2,5	−6,0
4 000	0,242	1,2	−5,4
5 000	0,242	−2,1	−1,5
6 300	0,245	−7,1	6,0
8 000	0,254	−11,2	12,6
10 000	0,271	−10,7	13,9
12 500	0,301	−3,1	12,3

Annex A
(normative)

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



NOTE 1 The hearing threshold under free-field listening condition, T_f, is indicated by a dashed line.

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
(normative)

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 phon	**Sound pressure level**, dB									
	Frequency, Hz									
	20	**25**	**31,5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**
10	(83,8)	(75,8)	(68,2)	(61,1)	(55,0)	(49,0)	(43,2)	(38,1)	(33,5)	(28,8)
20	89,6	82,7	76,0	69,6	64,0	58,6	53,2	48,4	43,9	39,4
30	94,8	88,5	82,4	76,5	71,3	66,2	61,2	56,8	52,6	48,4
40	99,9	93,9	88,2	82,6	77,8	73,1	68,5	64,4	60,6	56,7
50	104,7	99,1	93,7	88,5	84,0	79,6	75,4	71,6	68,2	64,7
60	109,5	104,2	99,1	94,2	90,0	85,9	82,1	78,7	75,6	72,5
70	114,3	109,2	104,4	99,8	95,9	92,2	88,6	85,6	82,9	80,2
80	119,0	114,2	109,6	105,3	101,7	98,4	95,2	92,5	90,1	87,8
90	123,7	119,2	114,9	110,9	107,5	104,5	101,7	99,3	97,3	95,4
100	(128,4)	(124,2)	(120,1)	(116,4)	(113,4)	(110,6)	(108,2)	(106,2)	(104,5)	(103,0)

Table B.1 (*continued*)

Loudness level phon	**Sound pressure level**, dB									
	Frequency, Hz									
	200	**250**	**315**	**400**	**500**	**630**	**800**	**1 000**	**1 250**	**1 600**
10	(24,8)	(21,3)	(18,1)	(15,1)	(13,0)	(11,2)	(10,0)	10,0	(11,3)	(10,4)
20	35,5	32,0	28,7	25,7	23,4	21,5	20,1	20,0	21,5	21,4
30	44,8	41,5	38,4	35,5	33,4	31,5	30,1	30,0	31,6	32,0
40	53,4	50,4	47,6	45,0	43,1	41,3	40,1	40,0	41,8	42,5
50	61,7	59,0	56,5	54,3	52,6	51,1	50,0	50,0	52,0	52,9
60	69,9	67,5	65,4	63,5	62,1	60,8	59,9	60,0	62,2	63,2
70	77,9	75,9	74,2	72,6	71,5	70,5	69,8	70,0	72,3	73,5
80	85,9	84,3	82,9	81,7	80,9	80,2	79,7	80,0	82,5	83,7
90	93,9	92,6	91,6	90,8	90,2	89,8	89,6	90,0	92,6	94,0
100	(101,8)	(101,0)	(100,3)	(99,8)	(99,6)	(99,5)	(99,4)	100,0	—	—

Table B.1 (*continued*)

Loudness level phon	Sound pressure level, dB								
	Frequency, Hz								
	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)	(3,8)	(7,5)	(14,3)	(21,0)	(23,4)	(22,3)
20	18,2	15,4	14,3	15,1	18,6	25,0	31,5	34,4	33,0
30	28,8	26,0	25,0	26,0	29,4	35,5	41,7	44,6	42,5
40	39,2	36,5	35,6	36,6	40,0	45,8	51,8	54,3	51,5
50	49,6	46,9	46,1	47,1	50,5	56,1	61,8	63,8	60,1
60	60,0	57,3	56,4	57,6	60,9	66,4	71,7	73,2	68,6
70	70,3	67,6	66,8	68,0	71,3	76,6	81,5	82,5	77,0
80	80,6	77,9	77,1	78,3	81,6	86,8	91,4	91,7	85,4
90	90,9	88,2	87,4	88,7	—	—	—	—	—
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 dB	Loudness level, phon									
	Frequency, Hz									
	20	25	31,5	40	50	63	80	100	125	160
0	—	—	—	—	—	—	—	—	—	—
10	—	—	—	—	—	—	—	—	—	—
20	—	—	—	—	—	—	—	—	—	—
30	—	—	—	—	—	—	—	(4,3)	(7,3)	(11,1)
40	—	—	—	—	—	—	(7,5)	(11,6)	(16,0)	20,7
50	—	—	—	—	(6,0)	(10,9)	(16,5)	21,9	26,9	31,9
60	—	—	—	(8,9)	(15,2)	21,8	28,4	34,2	39,3	44,1
70	—	—	(12,1)	20,6	28,2	35,5	42,2	47,8	52,5	56,8
80	(4,4)	(15,9)	26,2	35,7	43,6	50,7	57,0	62,0	66,1	69,8
90	20,8	32,7	43,3	52,7	60,1	66,5	72,1	76,4	79,9	82,9
100	40,3	51,7	61,8	70,4	77,1	82,7	87,5	(91,0)	(93,8)	(96,1)
110	61,1	71,6	80,7	88,5	(94,3)	(99,0)	—	—	—	—
120	82,2	(91,7)	(99,8)	—	—	—	—	—	—	—

Table B.2 (*continued*)

Sound pressure level dB	Loudness level, phon									
	Frequency, Hz									
	200	250	315	400	500	630	800	1 000	1 250	1 600
0	—	—	—	—	—	—	—	—	—	—
10	—	—	—	(5,5)	(7,3)	(8,9)	(10,0)	10,0	(8,8)	(9,6)
20	(6,2)	(8,9)	(11,8)	(14,5)	(16,7)	(18,6)	(19,9)	20,0	(18,6)	(18,7)
30	(14,6)	(18,0)	21,3	24,4	26,6	28,5	29,9	30,0	28,4	28,1
40	24,8	28,4	31,8	34,7	36,9	38,7	40,0	40,0	38,2	37,6
50	36,0	39,6	42,7	45,4	47,3	48,9	50,0	50,0	48,1	47,3
60	47,9	51,2	53,9	56,3	57,9	59,2	60,1	60,0	57,9	56,9
70	60,2	63,0	65,3	67,2	68,5	69,5	70,3	70,0	67,8	66,7
80	72,6	74,9	76,7	78,2	79,1	79,9	80,4	80,0	77,6	76,4
90	85,2	86,9	88,2	89,2	89,8	(90,2)	(90,5)	90,0	87,4	86,1
100	(97,7)	(98,9)	(99,7)	—	—	—	—	100,0	—	—
110	—	—	—	—	—	—	—	—	—	—
120	—	—	—	—	—	—	—	—	—	—

Table B.2 (*continued*)

Sound pressure level dB	Loudness level, phon								
	Frequency, Hz								
	2 000	2 500	3 150	4 000	5 000	6 300	8 000	10 000	12 500
0	—	(6,1)	(7,4)	(6,8)	—	—	—	—	—
10	(12,5)	(15,1)	(16,2)	(15,4)	(12,3)	(6,0)	—	—	—
20	21,8	24,3	25,3	24,5	21,3	(15,3)	(9,1)	(7,1)	(8,1)
30	31,2	33,8	34,7	33,8	30,6	24,8	(18,6)	(15,9)	(17,0)
40	40,8	43,4	44,2	43,2	40,0	34,4	28,3	25,5	27,3
50	50,4	53,0	53,8	52,8	49,6	44,1	38,2	35,6	38,3
60	60,1	62,7	63,5	62,4	59,2	53,8	48,3	46,0	49,9
70	69,8	72,4	73,2	72,0	68,8	63,6	58,4	56,7	61,7
80	79,5	82,1	82,9	81,7	78,5	73,4	68,5	67,4	73,6
90	89,2	—	—	—	—	—	78,6	78,2	—
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 [1] to [12]. In most of the cases, the experimental conditions, such as the stimuli and subject criterion, satisfied the preferred test conditions (see reference [13]). 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 Equation (1) and Equation (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 was applied here:

$$l = c(p^{2\theta} - p_{\mathrm{t}}^{2\theta}) \tag{C.1}$$

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 [14] and [15], 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 [16]).

Furthermore, it was pointed out in reference [17] 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. 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 Equation (C.1) is given as follows:

$$l = b\left[c\left\{(Up)^{2\alpha} - (Up_{\mathrm{t}})^{2\alpha}\right\}\right]^{\beta} \tag{C.2}$$

where

U is an extended linear transfer function;

c and α are an extended dimensional constant and an exponent for the “loudness perception process,” respectively;

b and β are those for the “number assignment process,” respectively;

p and p_{t} are as defined in Equation (C.1).

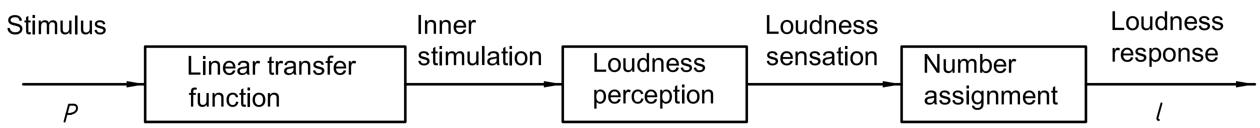


Figure C.1 — Block diagram of a loudness-rating-process model

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 equation can be derived from Equation (C.2):

$$p_f{}^2 = \frac{1}{U_f{}^2}\left[\left(p_{\mathrm{r}}^{2\alpha_{\mathrm{r}}} - p_{\mathrm{tr}}^{2\alpha_{\mathrm{r}}}\right) + \left(U_f p_{\mathrm{t}f}\right)^{2\alpha_f}\right]^{1/\alpha_f} \tag{C.3}$$

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},

$p_{\mathrm{t}f}$ is the threshold of hearing at a frequency of f Hz;

p_{tr} is the threshold of hearing at 1 000 Hz;

α_f and α_{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.

Equation (C.3) can be transformed into Equation (1) by substituting

$$p_f^{\,2},\ p_{\mathrm{r}}^{\,2}, p_{\mathrm{t}f}^{\,2}, p_{\mathrm{tr}}^{\,2} \text{ and } U_f^{\,2}$$

by

$$p_f^{\,2} = p_0^{\,2} 10^{L_f/10},\ p_{\mathrm{r}}^{\,2} = p_0^{\,2} 10^{L_{\mathrm{N}}/10},\ p_{\mathrm{t}f}^{\,2} = p_0^{\,2} 10^{T_f/10},\ p_{\mathrm{tr}}^{\,2} = p_0^{\,2} 10^{T_{\mathrm{r}}/10} \text{ and } U_f^{\,2} = 10^{L_U/10},$$

respectively, where p_0 is 20 μPa, and 0,25 is substituted for α_{r} and the threshold value of 2,4 dB is substituted for T_{r}.

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

The exponent α_{r}, which is the exponent at 1 000 Hz, is set to 0,25 for the following reason. The typical value obtained by means of the AME (Absolute Magnitude Estimation) method was 0,27 (0,54 for sound pressure) (see reference [15]). 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 $\alpha_{\mathrm{r}}\beta$ in the equations, where β = 1,08. This value of β was determined in reference [18]. Therefore, the exponent at 1 000 Hz, α_{r}, is assumed to be 0,25 (= 0,27/1,08).

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 Equation (1) are obtained. The values were calculated from the experimental data according to the following procedure.

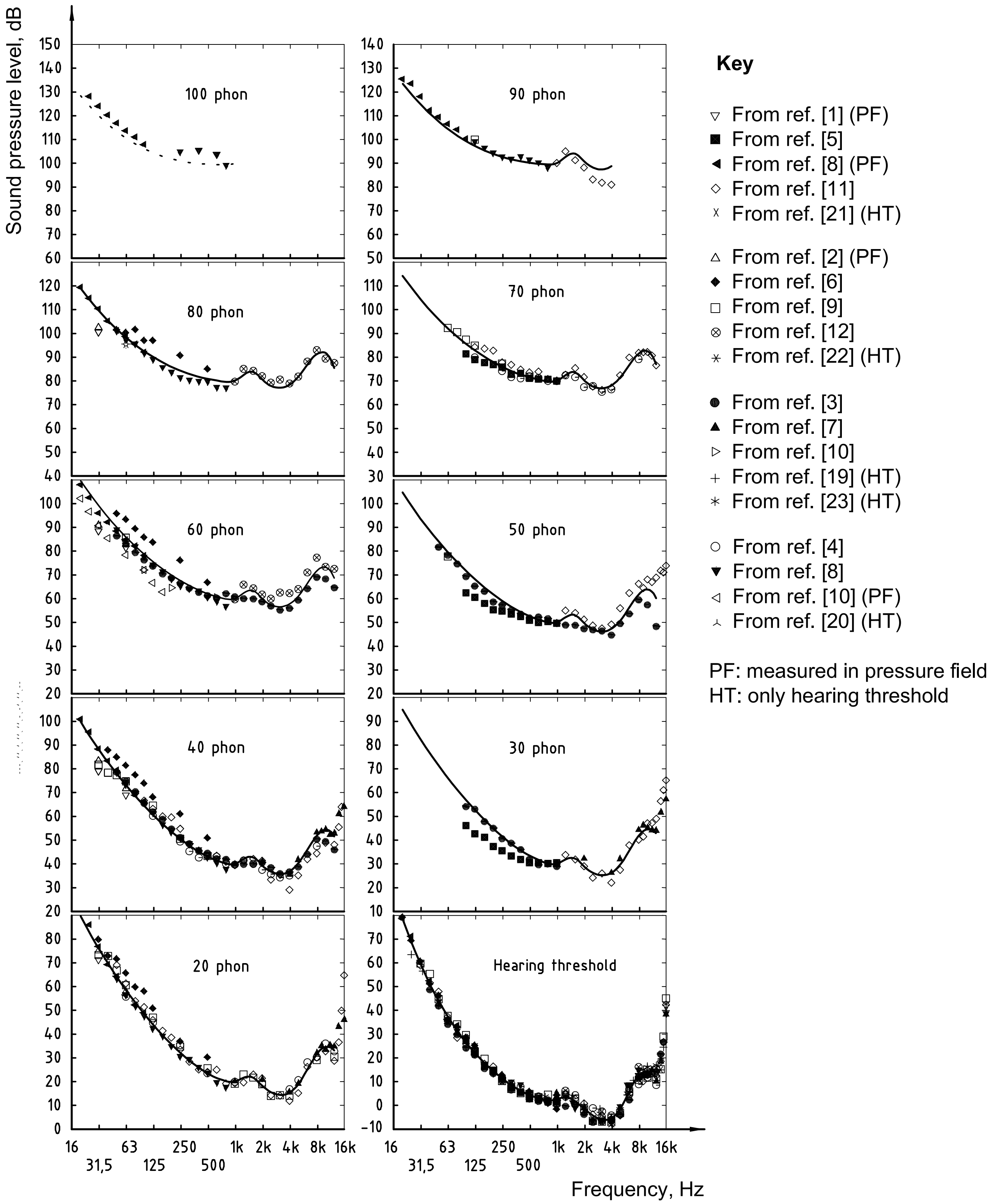
a) With the exception of the two studies (references [19, 21]) where the mean values were used, thresholds of hearing from 20 Hz to 12 500 Hz (references [3-9, 11, 12, 20, 22, 23]) are represented by taking the mean of the median results of the individual studies for each frequency and then smoothed 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) Equation (1) was fitted to the mean results of the individual studies (references [1-12]) 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 Equation (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 [1] to [12] and from [19] to [23], 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 Equation (1).

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

Table C.1 — Investigations of normal equal-loudness-level contours for pure tones

Investigation	Reference [1]	Reference [2]	Reference [3]	Reference [4]
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	

Table C.1 (*continued*)

Investigation	Reference [5]	Reference [6]	Reference [7]
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 [24])	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

Table C.1 (*continued*)

Investigation	Reference [8]		Reference [9]	Reference [10]	
Year	1997		1997	1999	
Country	Denmark		Japan	Germany	
Sound field	Free field	Pressure field[b]	Free field	Free field	Pressure field[b]
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		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 $\mu\pm2\sigma$ 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	N. A.	
Sequence in a tone pair	Random		Random	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 $\times$ 20 = 180 judgments	When the sequence of step size 2 dB was finished	
PSE estimation	Maximum likelihood estimation		Maximum likelihood estimation	N. A.	
Note		Individual equal-loudness level for 100 Hz measured in the free field was used as Reference tone level			Individual equal-loudness level for 100 Hz measured in the free field was used as Reference tone level

Table C.1 (*continued*)

Investigation	Reference [11]	Reference [12]
Year	2000	2002
Country	Japan	Japan
Sound field	Free field	Free field
Measured range[a]	Threshold: 31,5 Hz to 18 000 Hz 20 phon: 50 Hz to 16 000 Hz 30 phon: 1 000 Hz to 16 000 Hz 40 phon: 80 Hz to 15 000 Hz 50 phon: 1 000 Hz to 16 000 Hz 70 phon: 125 Hz to 12 500 Hz 90 phon: 1 000 Hz to 4 000 Hz	Threshold: 1 000 Hz to 12 500 Hz 60 phon: 1 000 Hz to 12 500 Hz 80 phon: 1 000 Hz to 6 300 Hz
Number of subjects (age)	7 to 32 (18 to 25)	21 (20 to 25)
Experimental method	Randomized maximum likelihood sequential procedure	Randomized maximum likelihood sequential procedure
Reference tone	1 000 Hz at a fixed level	1 000 Hz at a fixed level
Test tone level	Chosen randomly from μ, μ±2 dB, μ±4 dB and μ±6 dB[c]	Chosen randomly from μ, μ±2 dB, μ±4 dB μ±6 dB and μ±8 dB[c]
Duration of a tone	1 s	1 s
Sequence in a tone pair	Random	Random
Number of judgments in a single run/termination criterion	When 50 pairs of tones were presented	When 60 pairs of tones were presented
PSE estimation	Maximum likelihood estimation	Maximum likelihood estimation
Note	First and second presentation levels were ±20 dB from the authors' best guess of PSE	First and second presentation levels were ±20 dB from the authors' best guess of PSE

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 [9] but in reference [25] along with those in reference [4].

Bibliography

[1] KIRK, B. Hørestyrke og genevirkning af infralyd. *Institute of Electronic Systems*, Aalborg University, Aalborg, Denmark, 1983, pp. 1-111 (in Danish) ISSN 0106-0791

[2] MØLLER, H., ANDRESEN, J. Loudness of pure tones at low and infrasonic frequencies. *J. Low Freq. Noise and Vib.*, **3**, 1984, pp. 78-87

[3] BETKE, K. and MELLERT, V. New measurements of equal-loudness level contours. *Proc. Inter-noise 89*. 1989, pp. 793-796

[4] SUZUKI, S., SUZUKI, Y., KONO, S., SONE, T., KUMAGAI, M., MIURA, H. and KADO, H. Equal-loudness level contours for pure tone under free field listening condition (I) — Some data and considerations on experimental conditions. *J. Acoust. Soc. Jpn. (E)*, **10**, 1989, pp. 329-338

[5] FASTL, H., JAROSZEWSKI, A., SHORER, E. and ZWICKER, E. Equal loudness contours between 100 and 1000 Hz for 30, 50, and 70 phon. *Acustica*, **70**, 1990, pp. 197-201

[6] WATANABE, T. and MØLLER, H. Hearing threshold and equal loudness contours in free field at frequencies below 1 kHz. *J. Low Freq. Noise and Vib.*, **9**, 1990, pp. 135-148; WATANABE, T, MØLLER, H. Low frequency hearing thresholds in pressure field and in free field. *J. Low Freq. Noise Vibr.*, **9**, 1990, pp. 106-115

[7] POULSEN, T. and THØGERSEN, L. Hearing threshold and equal loudness level contours in a free sound field for pure tones from 1 kHz to 16 kHz. *Proc. Nordic Acoust. Meeting*, 1994, pp. 195-198

[8] LYDOLF, M. and MØLLER, H. New measurements of the threshold of hearing and equal-loudness contours at low frequencies. *Proceedings of the 8th International meeting on Low Frequency Noise and Vibration*, Gothenburg, Sweden, 1997, pp. 76-84

[9] TAKESHIMA, H., SUZUKI, Y., KUMAGAI, M., SONE, T., FUJIMORI, T. and MIURA, H. Equal-loudness level measured with the method of constant stimuli — Equal-loudness level contours for pure tone under free-field listening condition (II). *J. Acoust. Soc. Jpn. (E)*, **18**, 1997, pp. 337-340

[10] BELLMANN, M.A., MELLERT, V., RECKHARDT, C. and REMMERS, H. Sound and vibration at low frequencies. Joint meeting of ASA, EAA and DAGA, 1999, Berlin, Germany. *J. Acoust. Soc. Am.*, **105**, 1999, p. 1297

[11] TAKESHIMA, H., SUZUKI, Y., FUJII, H., KUMAGAI, M., ASHIHARA, K., FUJIMORI, T. and SONE, T. Equal-loudness contours measured by the randomized maximum likelihood sequential procedure. *Acustica — acta acustica*, **87**, 2001, pp. 389-399

[12] TAKESHIMA, H., SUZUKI, Y., ASHIHARA, K. and FUJIMORI, T. Equal-loudness contours between 1 kHz and 12.5 kHz for 60 and 80 phons. *Acoust. Sci. Tech.*, **23**, 2002, pp. 106-109

[13] ISO/TC 43/WG 1 Threshold of hearing, Preferred test conditions for determining hearing thresholds for standardization. *Scand. Audiol.*, **25**, 1996, pp. 45-52

[14] ZWISLOCKI, J.J. and HELLMAN, R.P. On the psychophysical law. *J. Acoust. Soc. Am.*, **32**, 1960, p. 924

[15] LOCHNER, J.P.A. and BURGER, J.F. Form of the loudness function in the presence of masking noise. *J. Acoust. Soc. Am.*, **33**, 1961, pp. 1705-1707

[16] HUMES, L.E. and JESTEADT, W. Models of the effects of threshold on loudness growth and summation. *J. Acoust. Soc. Am.*, **90**, 1991, pp. 1933-1943

[17] ATTENEAVE, F. *Perception and related areas. A study of science*. Vol. 4, S. Koch (ed.), McGraw Hill, New York, 1962

[18] ZWISLOCKI, J.J. Group and individual relations between sensation magnitudes and their numerical estimates. *Perception Psychophysics*, **33**, 1983, pp. 460-468

[19] ROBINSON, D.W. and DADSON, M.A. A re-determination of the equal-loudness relations for pure tones. *British J. Appl. Phy.*, **7**, 1956, pp. 166-181

[20] TERANISHI, R. Study about measurement of loudness on the problems of minimum audible sound. *Researches of the Electrotechnical laboratory*, No. 658, Tokyo, Japan, 1965

[21] BRINKMANN, K. Audiometer-Bezugsschwelle und Freifeld-Hörschwelle. *Acustica*, **28**, 1973, pp. 147-154

[22] VORLÄNDER, M. Freifeld-Hörshwellen von 8 kHz -16 kHz. *Fortschritte der Akustik — DAGA '91*, Bad Honnef, DPG-GmbH, 1991, pp. 533-536

[23] POULSEN, T. and HAN, L.A. The binaural free field hearing threshold for pure tones from 125 Hz to 16 kHz. *Acustica — acta acustica*, **86**, 2000, pp. 333-337

[24] ZWICKER, E. *Psychoakustik*. Hochschultext, Springer, Berlin 1982

[25] TAKESHIMA, H., SUZUKI, Y., KUMAGAI, M., SONE, T., FUJIMORI, T. and MIURA, H. Threshold of hearing for pure tone under free-field listening conditions. *J. Acoust. Soc. Jpn. (E)*, **15**, 1994, pp. 159-169

ICS 13.140

Price based on 18 pages