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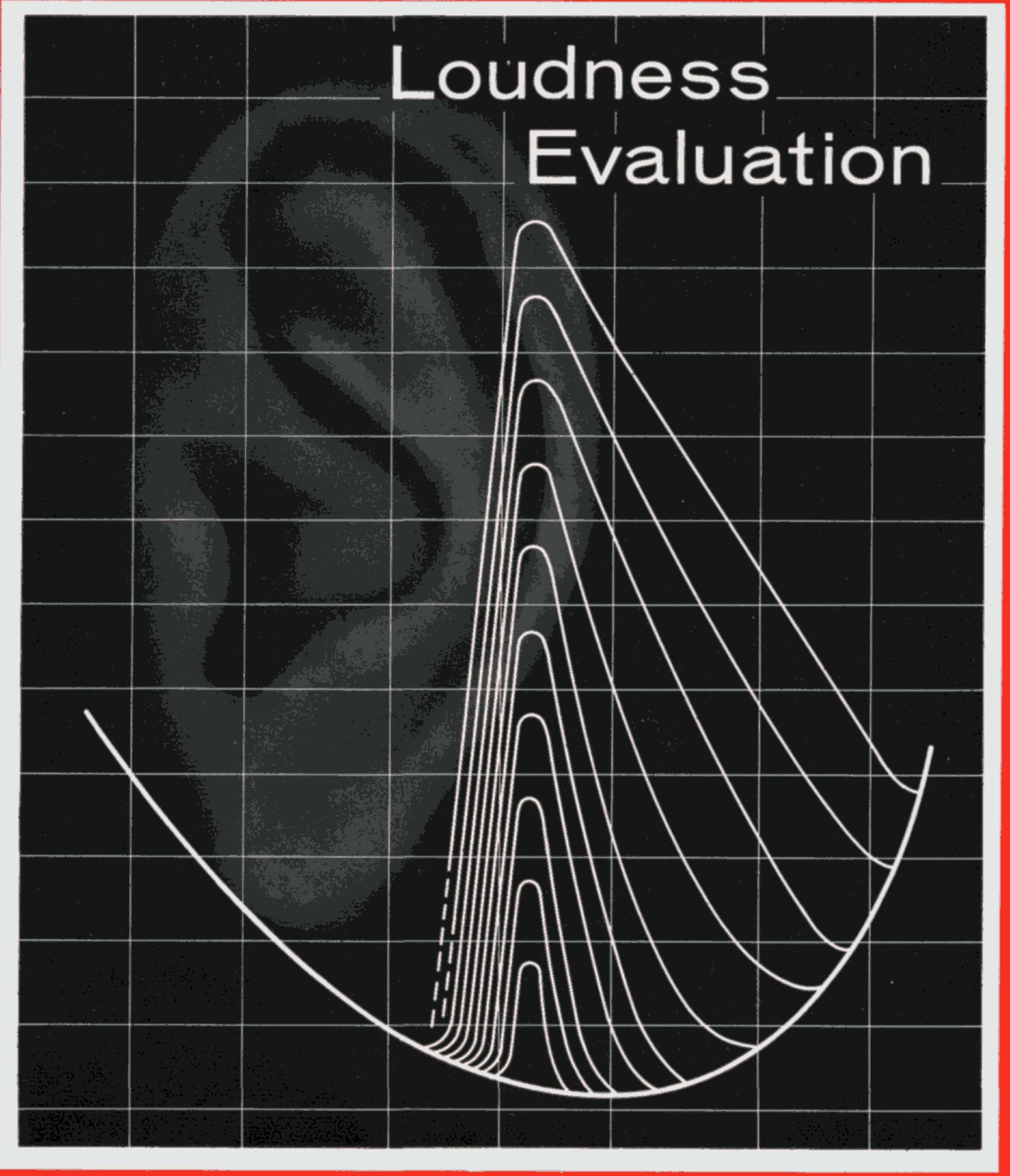

Loudness Evaluation

No. 2

1962

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TECHNICAL REVIEW

No. 2 – 1962

K. LARSEN & SØN - LYNGBY

Loudness Evaluation

A REVIEW OF CURRENT METHODS

by *Jens T. Broch,* Dipl.ing. E.T.H.

ABSTRACT

After a brief review of some of the known facts about the acoustic-mechanical functioning of the ear, the most important methods of loudness determination in use to-dav are outlined. The graphical method due to ZWICKER, the arithmetic loudness addition method due to STEVENS, and the determination of PN db (perceived noise level) due to KRYTER are described and applied to two different types of noise spectra. The use of weighting networks for sound level measurements and a special N-curve for the measurement of PN db are briefly discussed. Finally some important noise and hearing damage criteria are summarized.

SOMMAIRE

Après un bref rappel du quelques unes des propriétés mécaniques de l'oreille, les principales méthodes actuelles de détermination de la sensation auditive sont passées en revue — La méthode graphique de ZWICKER, la sommation arithmétique de STEVENS, et la détermination des db PN (niveau de bruit perçu) de KRYTER sont décrites et appliquées à deux types différents de spectre. L'emploi des filtres de pondération donnant le niveau sonore en db A, B ou C et celui d'une caractéristique N spéciale pour la mesure en db PN est discuté brièvement. Finalement, des critères de détermination de la baisse d'audition sont résumés.

ZUSAMMENFASSUNG

Nach einer kurzen Behandlung einiger bekannter Tatsachen der akustisch-mechanischen Funktion des Ohrs werden die wichtigsten Berechnungsmethoden zur Bestimmung der Lautstärke angegeben. Die graphische Methode nach ZWICKER, die arithmetische Lautheitsaddition nach STEVENS und die Berechnungsmethode nach KRYTER (PN dB) werden auf 2 verschiedene Geräuschspektren angewendet. Die Benutzung von Bewertungsfiltern für Schallpegelmessungen und eine besondere N-Kurve für Messungen nach der KRYTER-Methode werden diskutiert. Abschließend werden die wichtigsten Geräusch-Kriterien und Kriterien für Hörschädigung angegeben.

Introduction.

The perception of sound by the human ear is a very complicated mechanism. Even though the basic works of Helmholtz, v. Békésy, Fletcher and a number of other investigators have greatly helped to clarify its functioning, many details are still not completely understood.

It is therefore quite natural that a variety of methods have, in the course of time, been devised which try to relate physical measurements of sound to the human perception. The purpose of this article is to describe the main methods of loudness determination in use to-day, to briefly explain the background on which they are based, and to summarize certain noise criteria which may guide the practicing noise abatement engineer in his work.

As a logical starting point some of the known facts about the hearing should be briefly reviewed.

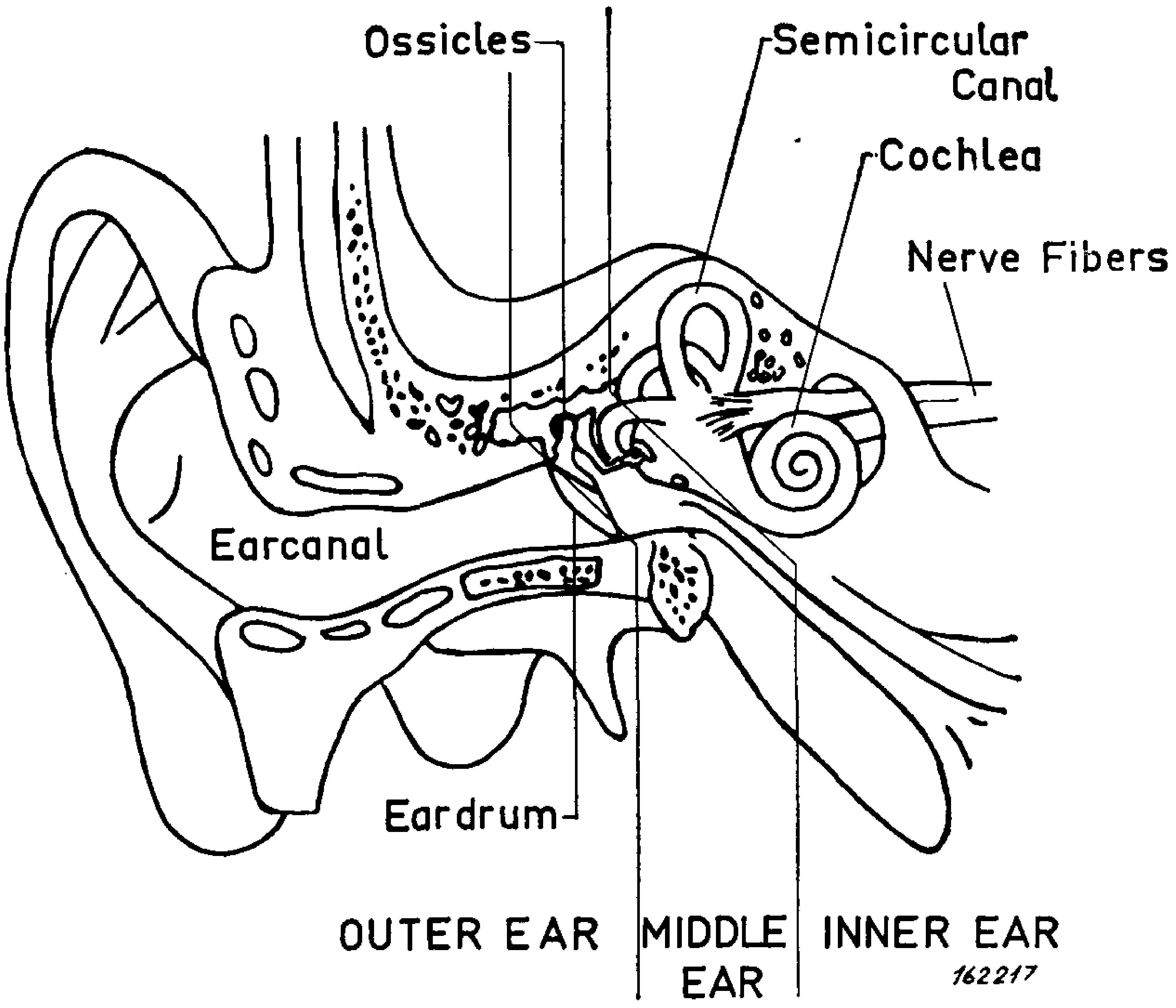

Fig. 1. Drawing illustrating the three "main" parts of the ear: The outer ear, the middle ear, and the inner ear with cochlea.

Human Hearing.

The human ear consists of three "main" parts, the outer ear, the middle ear and the inner ear, see Fig. 1.

The outer ear "matches" the impedance of the ear-drums to the air; a matching which is remarkly good at 800 c/s and remains fairly good even at higher frequencies. Only at frequencies below some 400 c/s is the matching rather poor.

The vibrations of the ear-drums are in the middle ear mechanically transferred to the inner ear. Because the inner ear is filled with lymph, there is a further impedance "matching" here. At the same time the vibration amplitudes of the ear drum are transformed to the much smaller vibration amplitudes but higher pressures in the inner ear.

The perception of the sound by the nerves finally takes place along the basilar membrane of cochlea in the inner ear. Here also a sort of frequency analysis of the sound is made. Sounds of various frequencies set the basilar membrane into "maximum" vibrations at different distances from the oval window. The "maxima" are rather broad and the lower frequency maxima occurs furthest away from the oval window, see Fig. 2.

Because the maxima are relatively broad the complete frequency analysis performed by the hearing mechanism—which is a very selective analysis—cannot be accounted for by the formation of these maxima only. It has

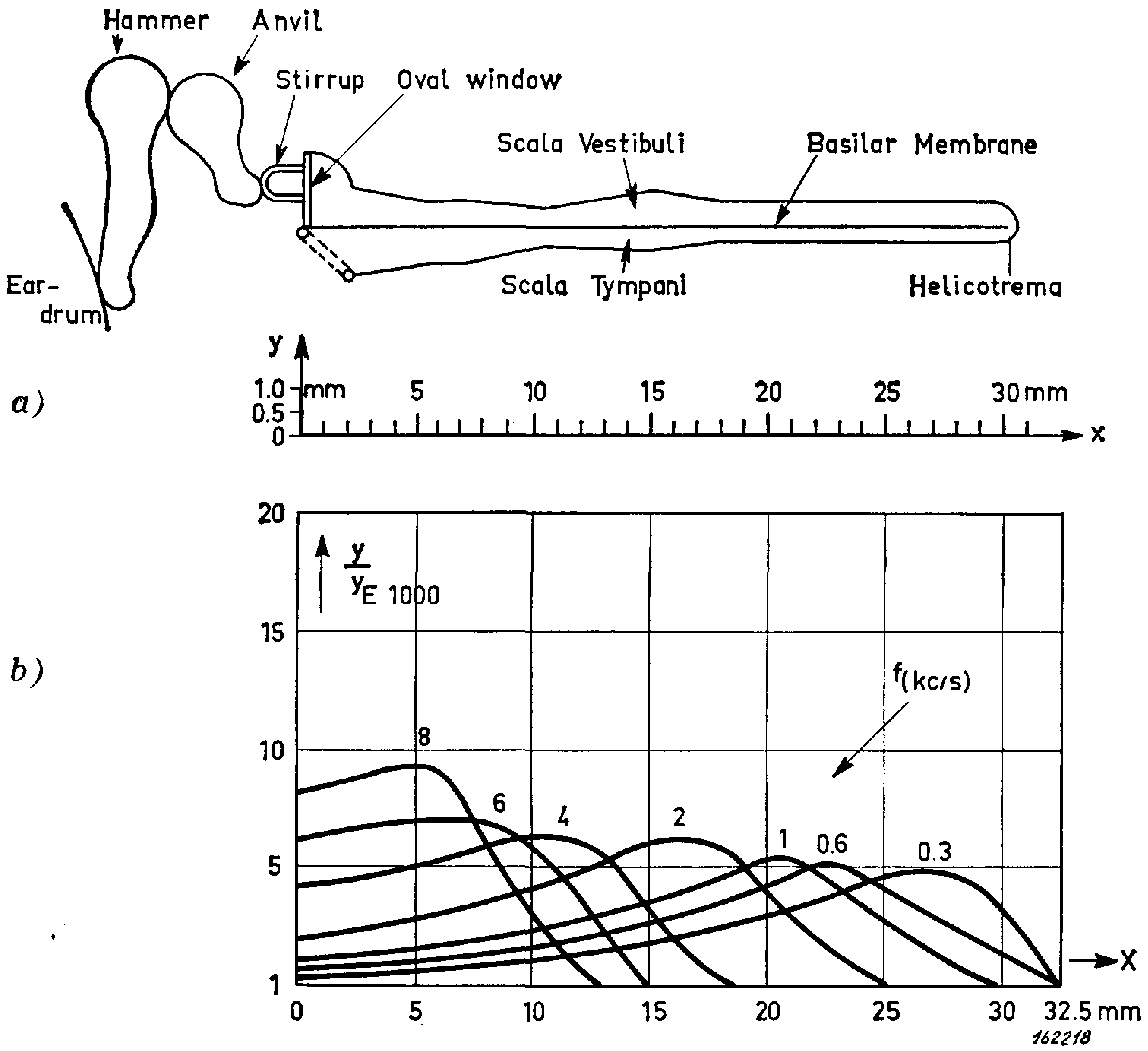

Fig. 2.

a) Sketch of the "folded out" cochlea.

b) Drawing indicating the vibrations of the basilar membrane during sound reception.

therefore been suggested (L. Cremer) that a "preliminary" analysis is made along the basilar membrane and then the more selective analysis is performed in the nervous system itself. Later measurements (Davis, Galambos, Stevens, Schouten) seem to confirm this hypothesis.

The shape and amplitude of the nerve pulses produced in the organ of Corti along the basilar membrane are independent of the excitation amplitude. Only the number of pulses depends upon the excitation. However, as soon as the nerve is excited it will be "blocked" for a certain time interval during which it is completely insensitive to further excitation, and a maximum of about 150 pulses per second has been observed for the strongest excitations.

To produce a single pulse a certain excitation level has to be exceeded, and in this way the "limits of hearing" may be explained—at least to a certain extent.

The complete hearing process seems to consist of a number of separate processes which, in themselves, are fairly complicated, so no simple and unique relationship exists between the physical measurement of a sound pressure level and the human perception of the sound. The loudness of a certain pure tone may, for example, be judged to sound different to that of another pure tone, and different again from a combination of tones, even if the sound pressure level is the same in all cases.

Loudness and Loudness Level.

Some of the earliest investigations of the human perception of sound were carried out by Helmholtz who, on the basis of thorough calculations, promoted the "resonance theory" of excitation along the basilar membrane. His calculations have later been reviewed and extended by Roaf and Fletcher, Kucharski, and Zwislocki-Moscicki.

In October 1933 H. Fletcher and W. A. Munson published their "Loudness Level Contours" for pure tones in the "Journal of the Acoustical Society of America". This set of curves is reproduced in Fig. 3 and shows the intensity levels (in db re. 2×10^{-4} μbar) which at various frequencies are judged by the "average" human to sound equally loud.

Of course, such a set of curves will be valid only when certain experimental conditions are fulfilled. For example, should the observer face the sound source, the source as well as the observer are to be placed in an acoustically free field. The observer should be in "normal" physiological and psychological

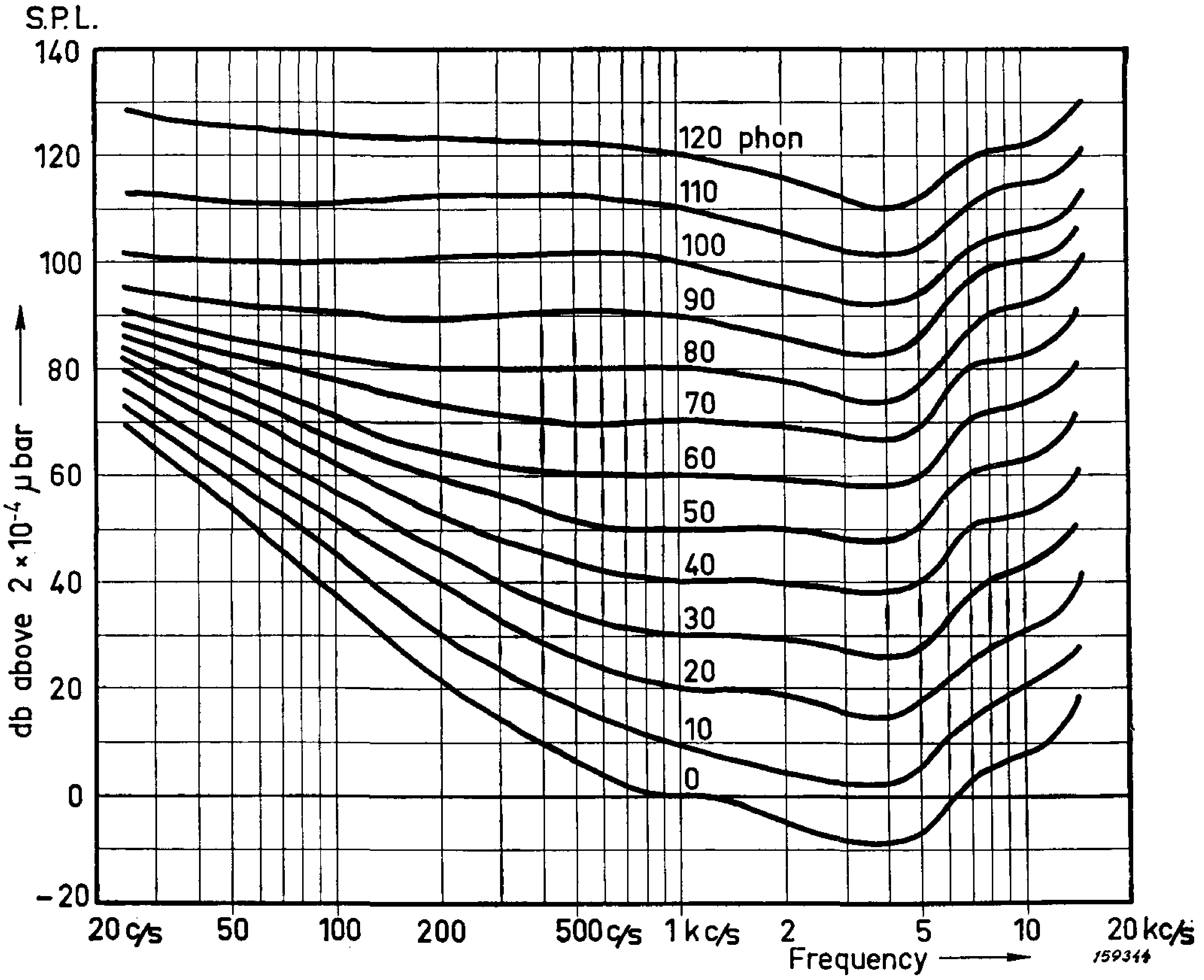

Fig. 3. The Fletcher-Munson equal loudness level curves.

condition and should be unable to "see what he is doing" and thereby try to influence the measured result, etc.

Other sets of equal loudness contours, which deviate from the Fletcher-Munson curves in certain respects, have been determined later by other investigators. However, the curves shown in Fig. 3 have for many years been used as common reference data and in 1949 were adopted as American Standard.

Fig. 3 shows how the loudness levels of pure tones with constant sound pressure level (SPL) vary with frequency. The decibel (db) scale used on the Y-axis (ordinate) of the figure is well known electronic engineers and is a logarithmic scale.*) It has been chosen, partly on the basis of Weber-Fechner's basic psychophysical law,**) and partly for convenience because the human perception of sound covers a dynamic range of 1 : 1000000.

On the other hand, if the physical intensity of a sound is increased so that the sound appears twice as loud to the observer, the increase is not equal to a factor of two on the decibel scale. Over most of the audible range the increase is approximately equal to 10 db. In an effort to obtain a subjective loudness scale a number of investigations were carried out by Fletcher a.o. and a curve was suggested which gave the relationship between the loudness level in db (at 1000 c/s) and the subjectively judged loudness.

Investigations have shown that with good approximation the relation between sound level (phon) and loudness (sone) can be taken as linear over the commonly experienced range of sound levels, (20—120 phons), see Fig. 4.

In this range a twofold change in loudness approximately equals a change in sound intensity level of 10 db (phon), so that it has been generally recommended (ISO Recommendations ISO/R131-1959(E)) to use this figure in estimates.

From the above discussion it is seen that the relationship between frequency and the human perception of pure tones can be given in the form of Fig. 3, while the relationship between the loudness level and the human perception of loudness can be found from Fig 4. By combining the two sets of information it is possible to construct a set of loudness curves for pure tones.

The Critical Band Concept.

Now, if a number of pure tones are combined into a complex sound, not only the loudness and pitch determine the human perception of the sound, but a third factor, the timbre enters the picture. The timbre depends upon the harmonic content of the sound and its transient behaviour (and thus also to

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*) The scale is used to express the SPL in relation to a ref. value.

SPL (db) = 20 log $\frac{p}{po}$, $p_0 = 2 \times 10^{-4}$ μbar = average threshold of hearing at 1000 c/s

**) The Weber-Fechner law states that the change in response to a certain change in excitation is inversely proportional to the absolute excitation before the change. Mathematically this can be written: $\frac{dR}{dE}$ = Const. $\frac{1}{E}$).

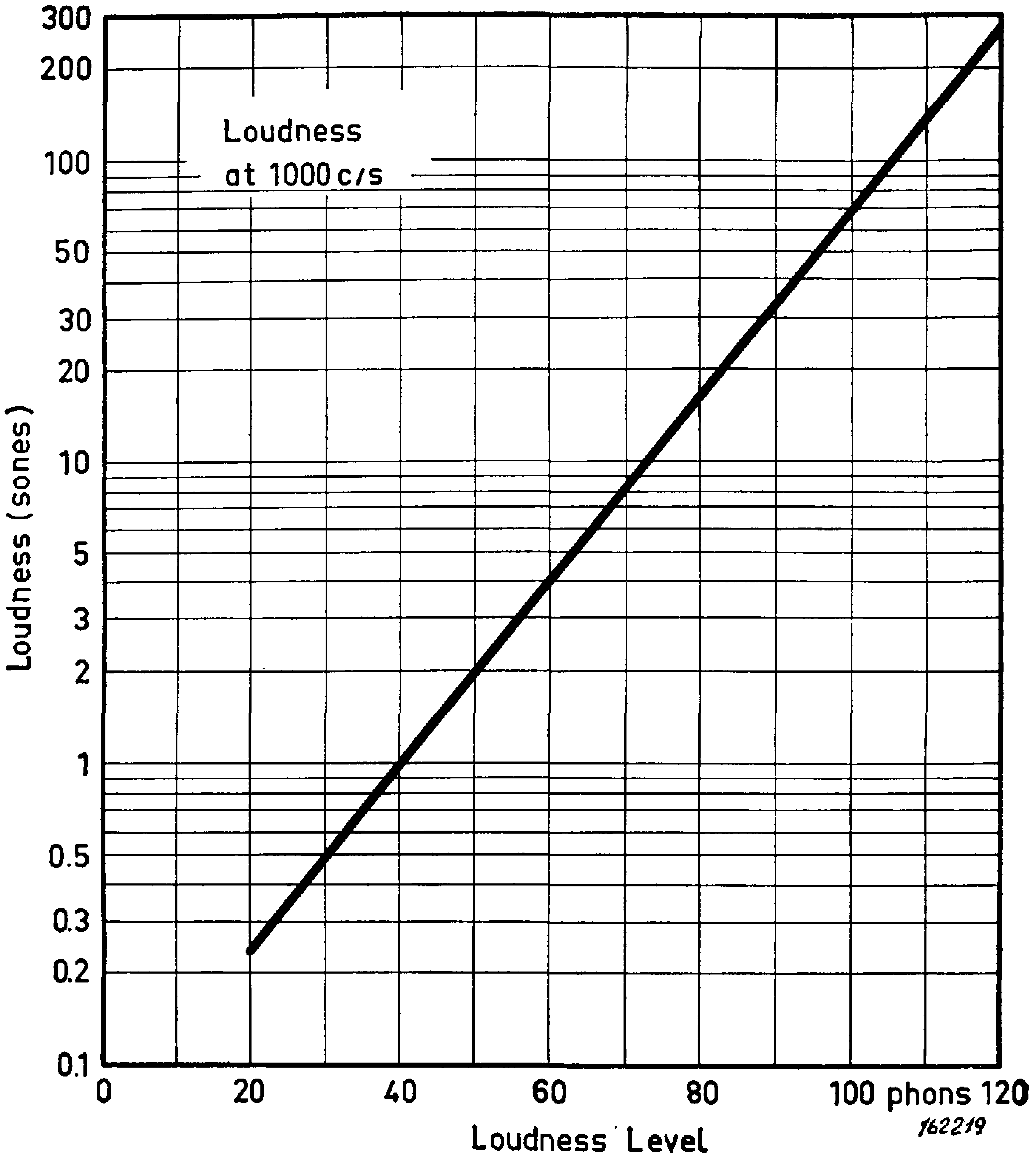

Fig. 4. The relationship between the loudness in sones and the loudness level in phon. According to the I.S.O. Recommendations ISO/R 131-1959 (E) the relationship may be written as $S = 2^{(P-40)/10}$ *for loudness levels between 20 phon and 120 phon.*

a certain extent upon the phase relationship between the various components of the sound). A great amount of research work has been done in trying to make possible the measurement and/or calculation of this effect so as to take it into account during noise measurements. Investigations made by Zwicker and Feldtkeller and Zwicker, Flottorp and Stevens have shown the existence of certain "critical" bands of frequencies (German: Frequenzgruppen), and that there is a definite relationship between these bands and the previously mentioned vibration maxima on the basilar membrane.

Based on these results they have divided the "main" audible frequency range into 24 critical bands, see Table 1.

Within one critical band the loudness of the sound is mainly proportional to the r.m.s. value of the sound pressure, while the loudness of the various

Table 1.

Critical Band (Bark)	1	2	3	4	5	6	7	8
Center Frequency (c/s)	50	150	250	350	450	570	700	840
Bandwidth f (c/s)	100	100	100	100	110	120	140	150
Critical Band (Bark)	9	10	11	12	13	14	15	16
Center Frequency (c/s)	1000	1170	1370	1600	1850	2150	2500	2900
Bandwidth f (c/s)	160	190	210	240	280	320	380	450
Critical Band (Bark)	17	18	19	20	21	22	23	24
Center Frequency (c/s)	3400	4000	4800	5800	7000	8500	10500	13500
Bandwidth f (c/s)	550	700	900	1100	1300	1800	2500	3500

bands add together according to a somewhat different scheme. A method of adding the loudness of the different bands together taking also a fourth factor, the masking effect, into account has been devised by Zwicker.

No commercially available frequency analyzer exists today which divides the spectrum into the critical bands described in Table 1, so a set of correction curves which relate the well-known 1/3 octave band frequency analyzer to the critical bands has been derived. By studying Table 1 and the correction curves, Fig. 5, it can be seen that the bandwidths of the 1/3 octave frequency analyzers very nearly conform with the critical bands at frequencies above some 250 c/s.

Even though in practice, at least for the time being, 1/3 and 1/1 octave analyses are used, Zwicker's theory is based on the critical bands.

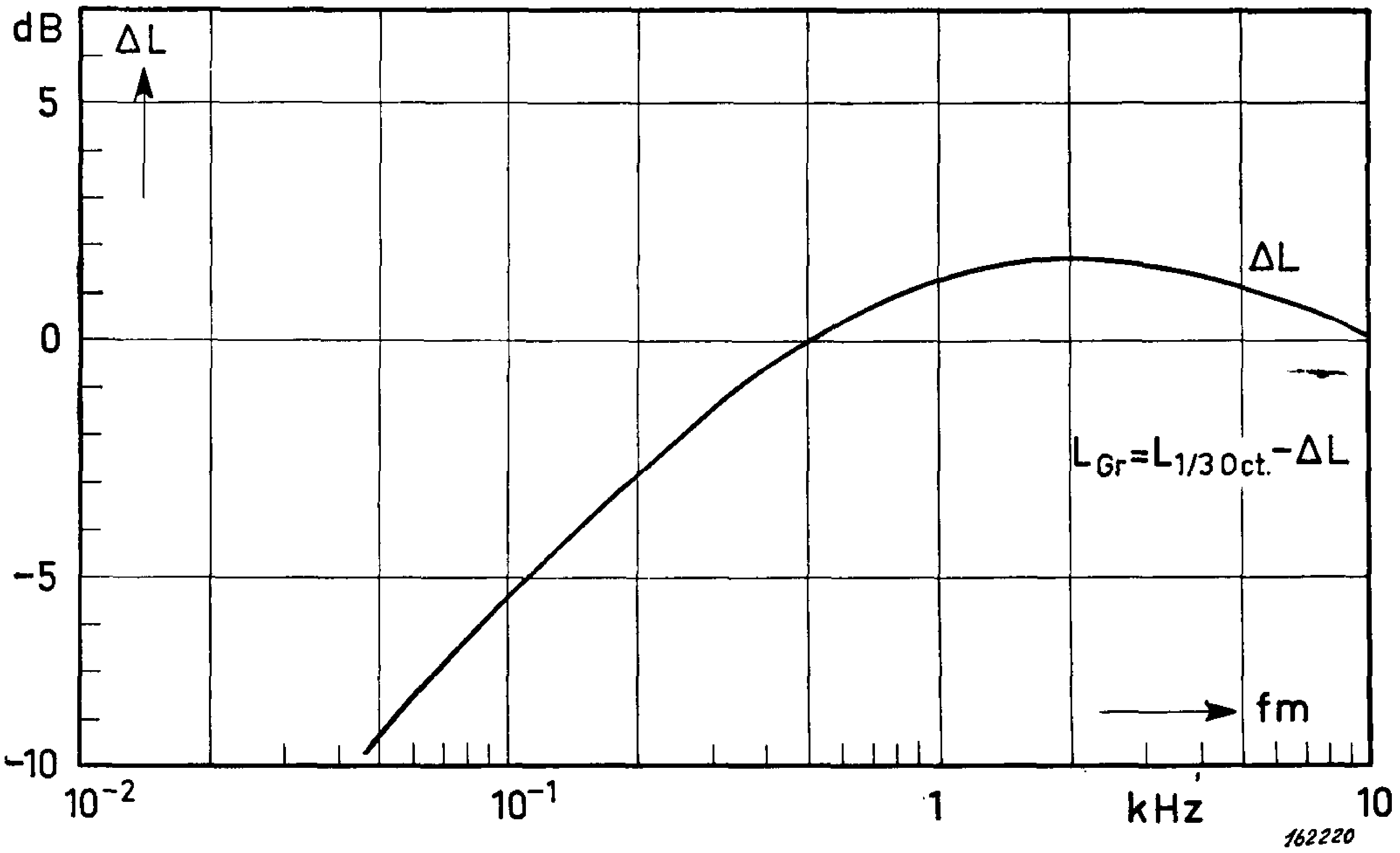

Fig. 5. Correction curves which relate 1/3 octave data to critical bands (Reichardt).

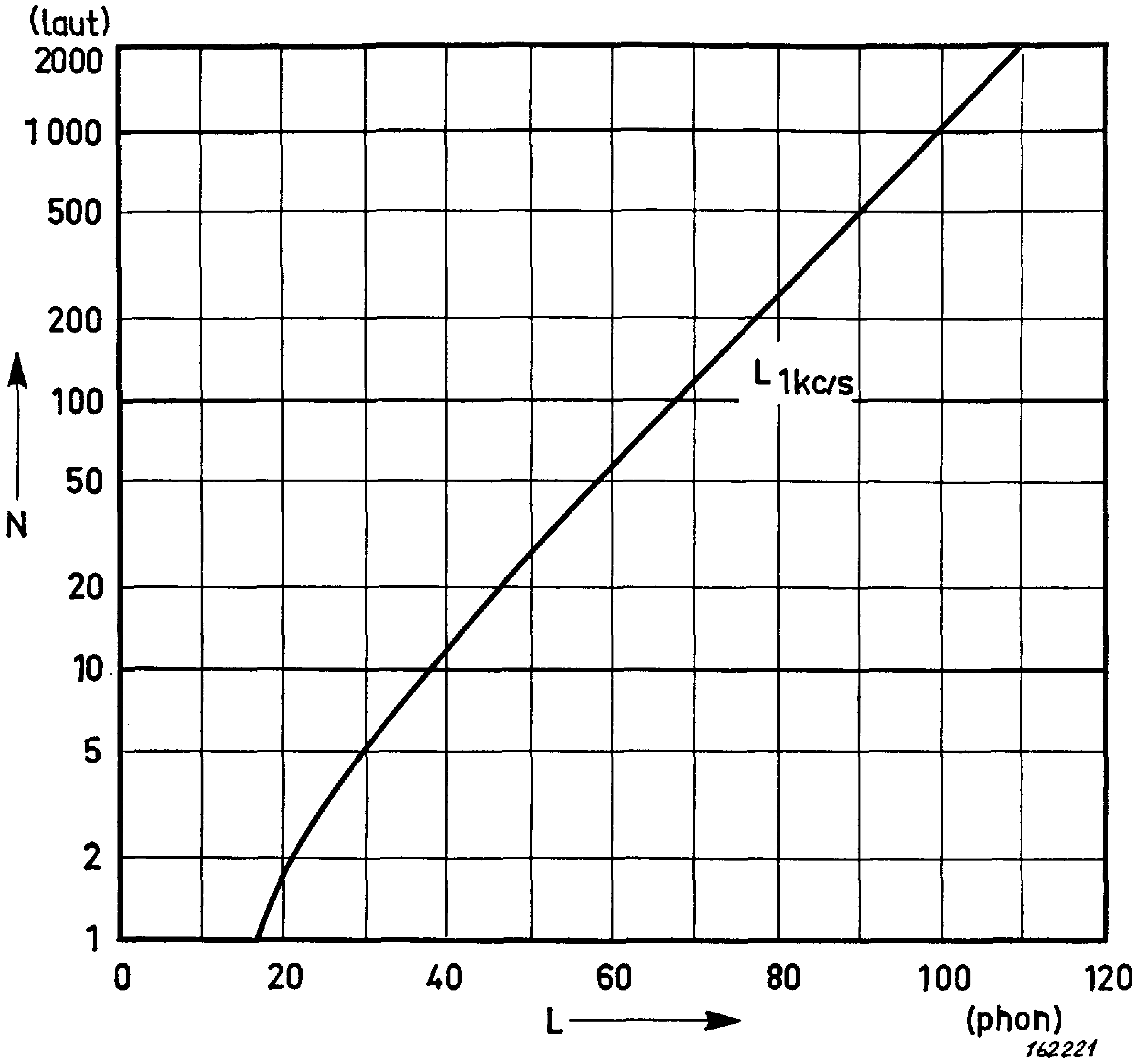

Fig. 6. The relationship between laut and phon (Zwicker).

Zwicker's Loudness Calculation Method.

One critical band corresponds to a distance of 1·3 mm along the basilar membrane and this is defined as 1 bark (in honour of Barkhausen). The loudness is measured in "laut", and the specific loudness is defined as laut/bark (a definition which is analogous to "power spectrum density" although in other scales). Based on a "modified" Weber-Fechner law,*) which takes the threshold of hearing for each frequency group into account Zwicker now draws up his loudness versus loudness level relationship. By plotting the laut/bark (which is a linear measure) versus bark for a certain sound excitation and integrating over the complete bark scale (basilar membrane), taking the frequency response of the ear and the masking effect into account, Zwicker obtains the total loudness in laut. Now, using his laut vs.db relationship for a 1ooo c/s tone, Fig. 6, the loudness level of an equally loud 1ooo c/s tone is found in phon, and the relationship between laut and sone can thus also be established.

*) See page 7.

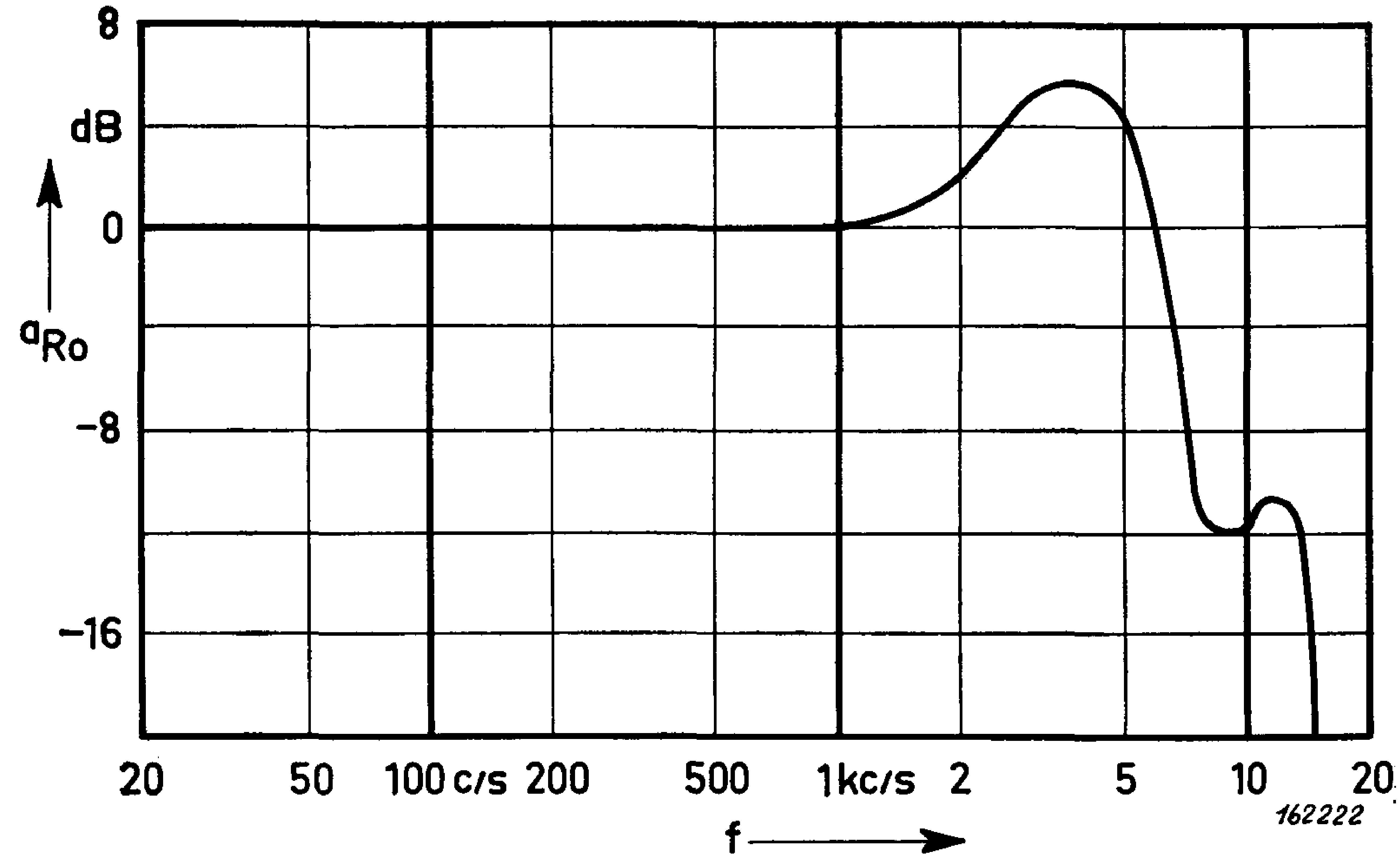

Fig. 7. Relative vibration amplitude of the oval window vs. frequency for constant sound pressure "input" (Zwicker).

To simplify the calculation process Zwicker has published certain diagrams which allow all the above mentioned effects to be taken into account directly from 1/3 octave data, the integration either being performed by means of a planimeter or by drawing a mean line according to "the best judgement". Before giving the diagrams originally devised by Zwicker the frequency response of the human ear and the masking effect should be described in a little more detail. Because Zwicker bases his calculations upon the integrated exicitation along the basilar membrane, it is necessary to know the relationship between the sound pressure in the sound field and the vibration amplitudes of the oval window. In his first papers Zwicker uses data obtained by Robinson for free, plane sound waves, Fig. 7. Later on data have been obtained for diffuse sound fields.

The masking effect causes the threshold of hearing of a testtone to be considerably changed if a tone of constant level (masking tone) is already being listened to. The change is greatest around the frequency of the masking tone. The masking effect is different for pure tones and for bands of noise of the same overall level—a difference which may, at least to a certain extent, be explained on the basis of beats between the tone being masked and the masking tone Zwicker uses in his method the measured and calculated masking effect of narrow bands of noise, Fig. 8, and approximates the masking as shown to a linear scale in Fig. 9, dashed.

His complete loudness calculation diagram for plane sound waves will thus be of the type shown in Fig. 10. If the diagram is changed to yield 1/3 octave

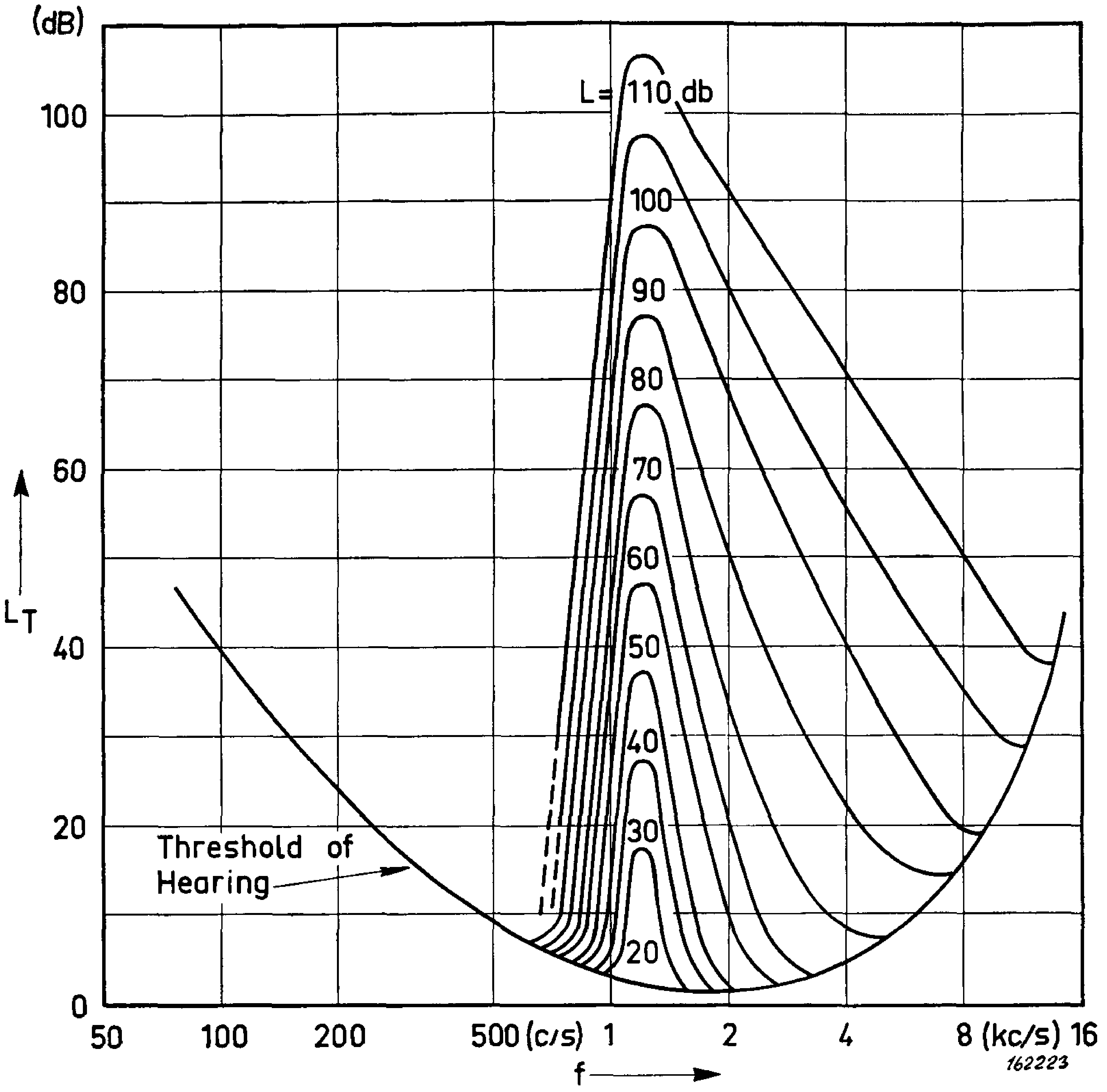

Fig. 8. Masking effect of narrow band noise with a center frequency of 1200 c/s. The parameter is the r.m.s. value of the noise band (Zwicker).

data for direct practical calculations the charts shown in Figs. 11 and 12 are obtained.

Similar charts valid for measurements in diffuse sound fields are shown in Figs. 13 and 14. An example of the use of the charts will be given later in this article (p. 24).

Zwickers method, which is based on graphical evaluation and, for the sake of convenience, requires a set of preprinted diagrams, may be a little laborious if the integration process is carried out with a planimeter. This is necessary if a high accuracy is desired. *However, the method is fairly simple to use if the integration and determination of the mean line is made from "the best judgement", which allows fully enough accuracy in most practical cases.*

Stevens' Loudness Calculation Method.

A second method of loudness evaluation in use to-day is due to Stevens. Historically, the "starting point" of Stevens is somewhat different from that

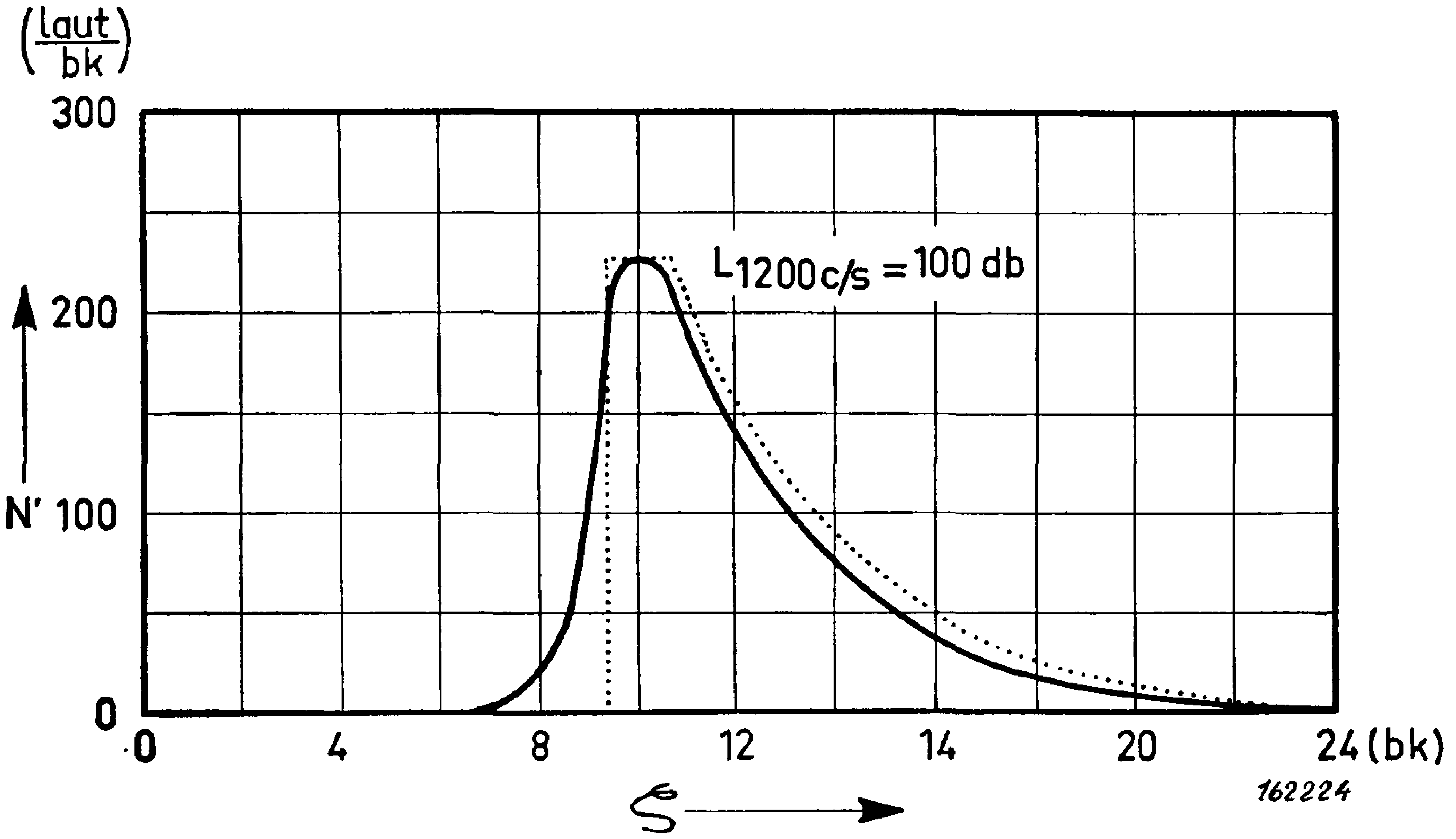

Fig. 9. ***Calculated*** *specific loudness (Spezifische Lautheit) of a 1200 c/s tone with a sound pressure level of 100 db. The dashed curve shows the "idealized" case (Zwicker).*

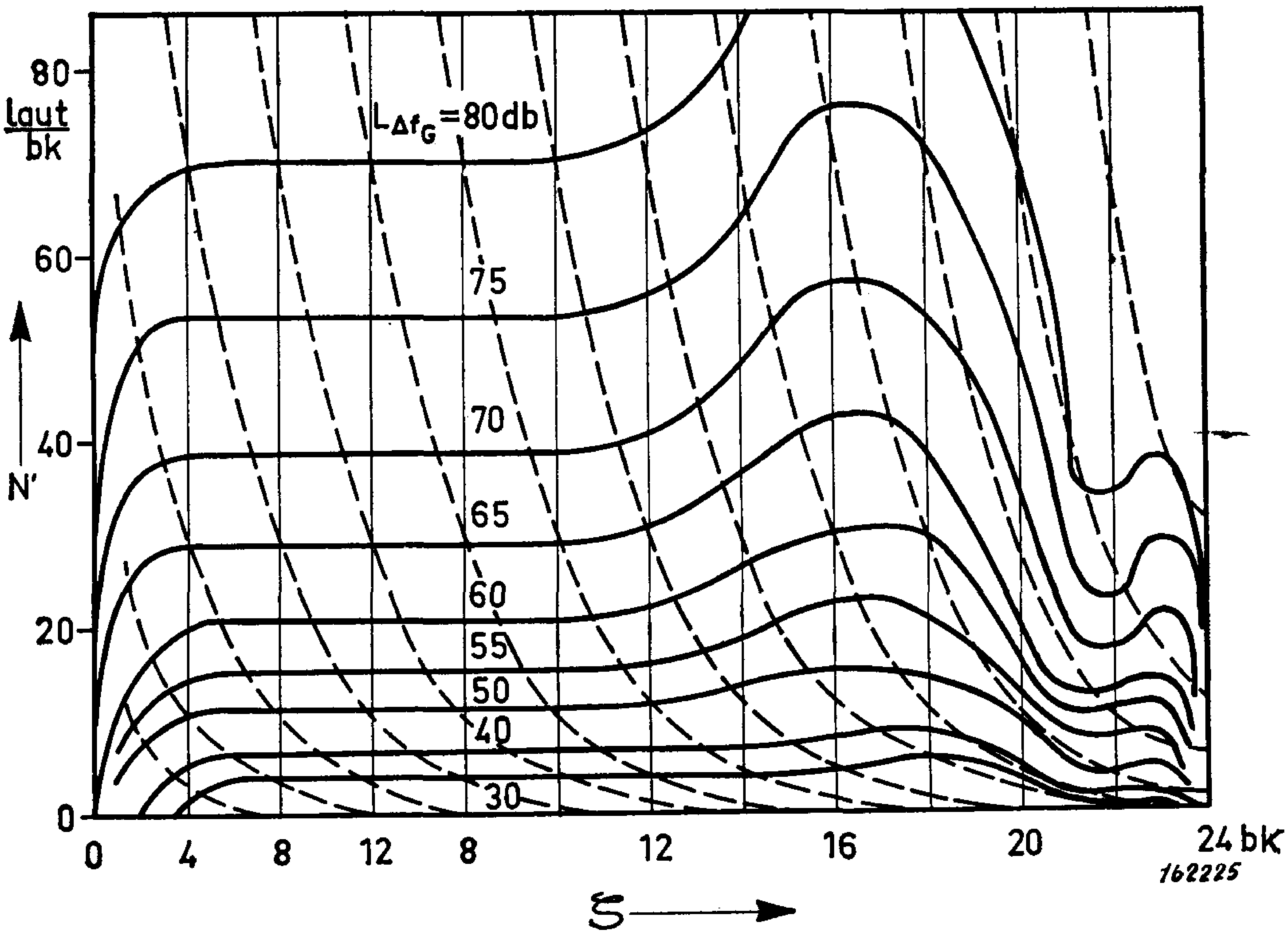

Fig. 10. Zwicker's original calculation diagram for plane sound waves.

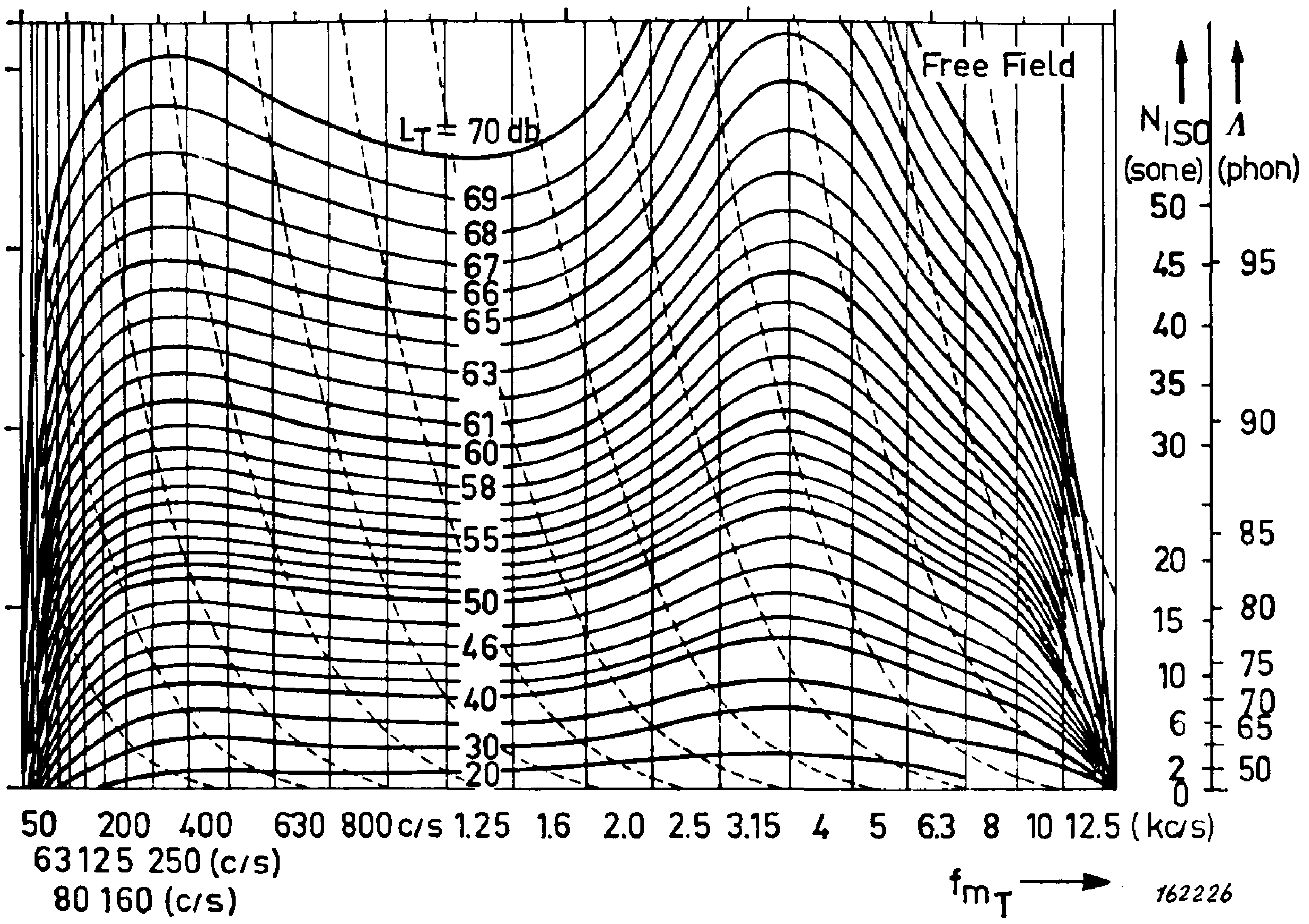

Fig. 11. Calculation diagram for 1/3 octave data and band pressure levels up to 70 db. Valid for plane sound waves (Zwicker).

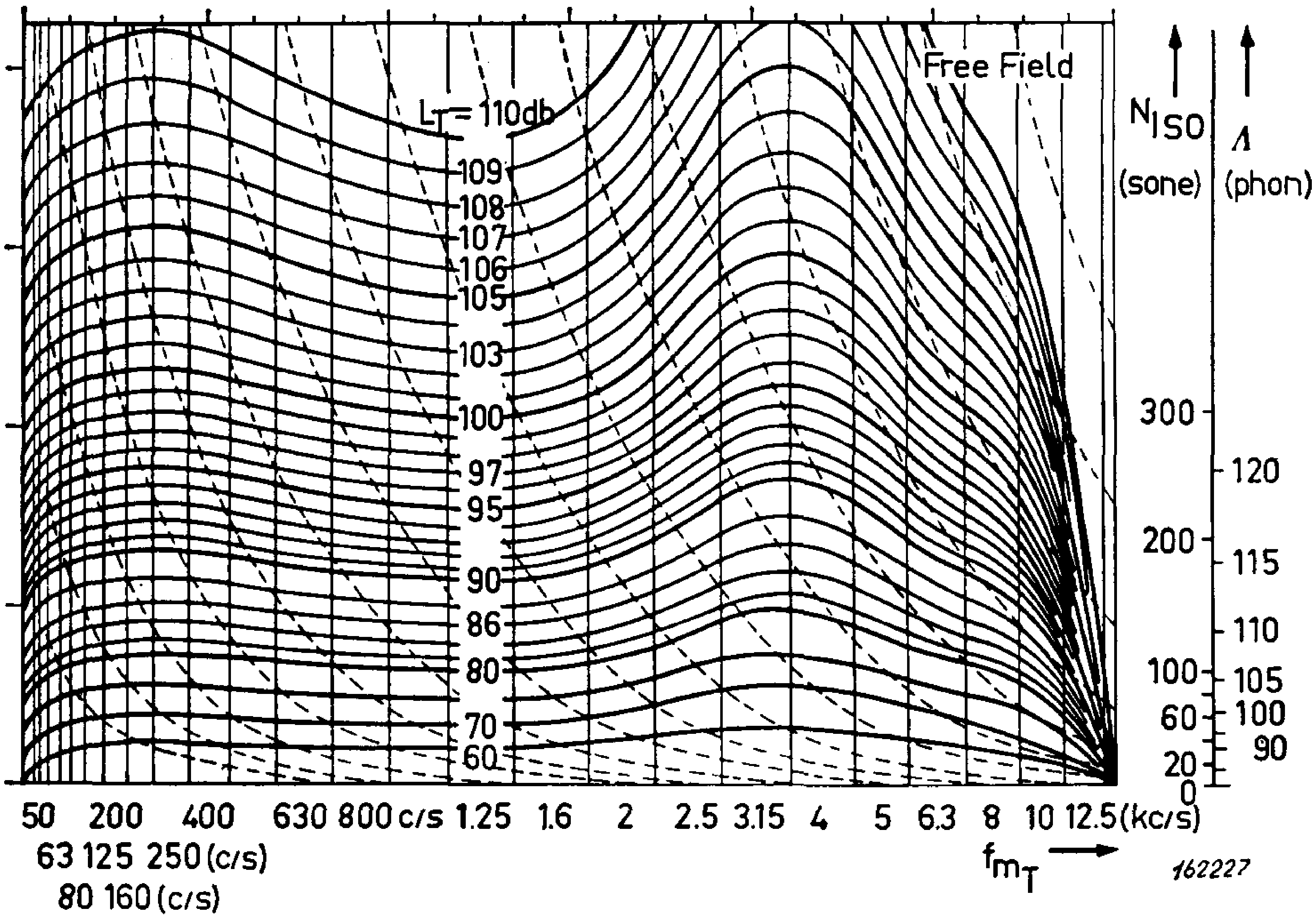

Fig. 12. Similar to Fig. 11 but valid for band pressure levels up to 110 db. (Zwicker).

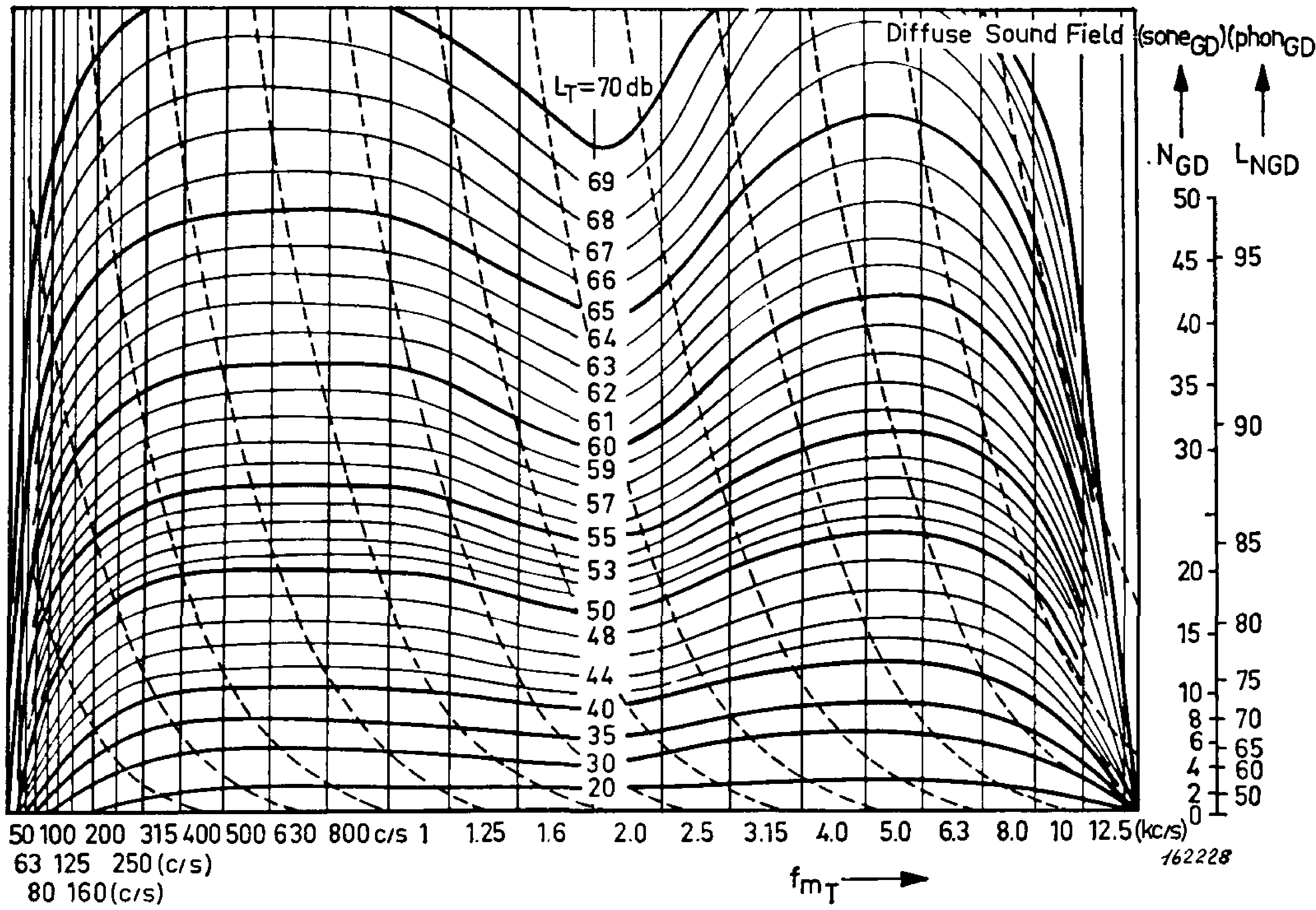

Fig. 13. Calculation diagram for 1/3 octave data and band pressure levels up to 70 db. Valid for measurement data obtained in a diffuse sound field (Zwicker).

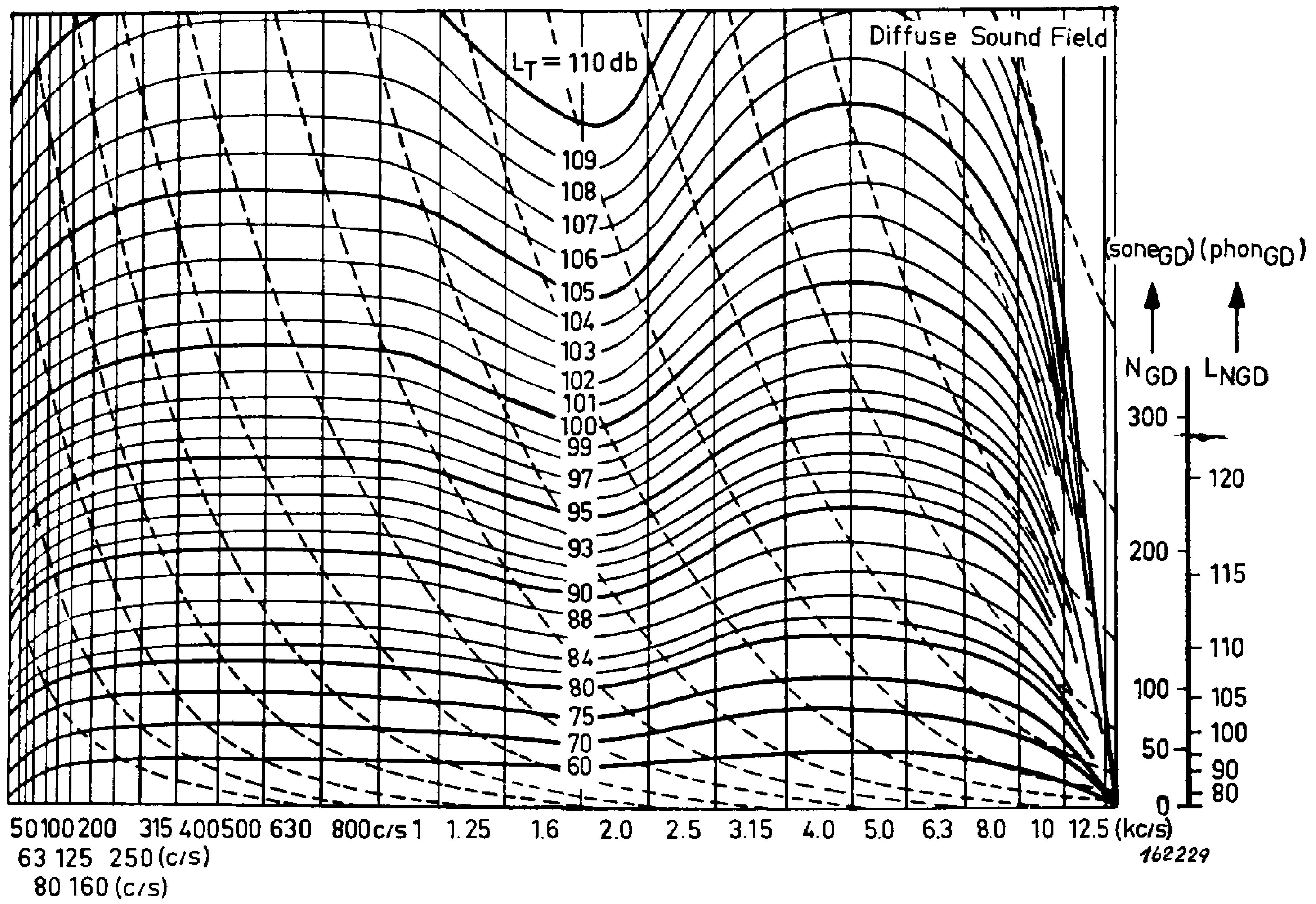

Fig. 14. Similar to Fig. 13 but valid for band pressure levels up to 110 db (Zwicker).

of Zwicker. Zwicker started out in studying the human ear and devised a loudness calculation method based upon the hearing mechanism. He then tried to relate the results to commercially available measuring equipment. Stevens, on the other hand, started out from the fact that certain types of measuring equipment were commercially available. By comparing measured results with subjective judgement and taking the known facts about hearing, such as the masking effect, into account, he arrived at a very simple, easy-to-use method of loudness calculation. His original measurements were carried out by means of a 1/1 octave frequency analyzer, and he found that the loudness summation of octave data should follow the rule:

$$S_t = S_m + 0.3\ (\Sigma S - S_m)$$

Here S_t is the total loudness in sones, S_m is the loudness (in sones) of the loudest octave band, and ΣS is the sum of the loudness (in sones) of all the

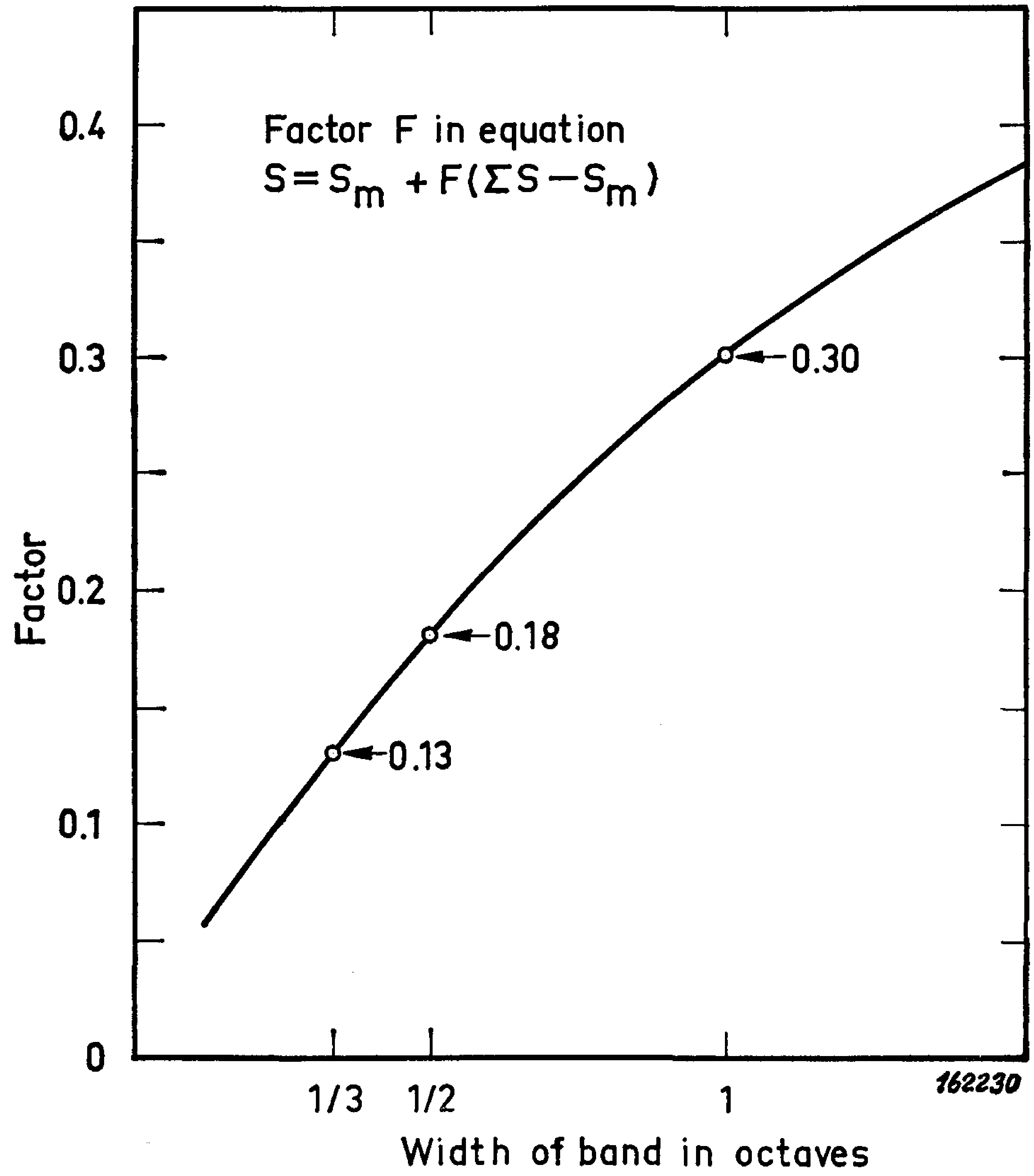

Fig. 15. Values of F for bands of various widths (Stevens).

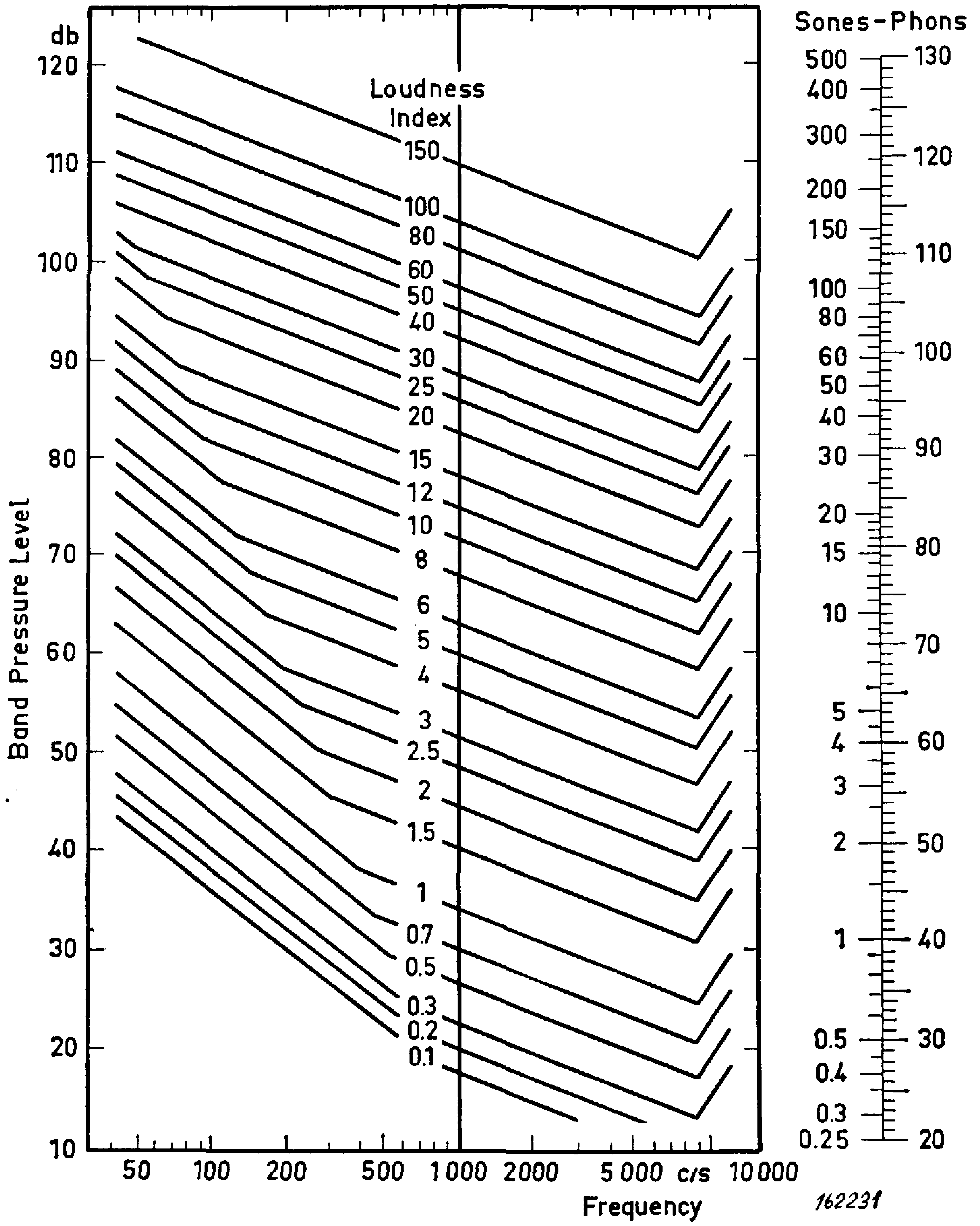

Fig. 16. Contours of equal loudness index (Stevens).

octave bands. The factor o.3 is arrived at by taking the bandwidth and the masking effect into account.

Originally his formula was given in the form:

$$S_t = S_m + F\,(\Sigma S - S_m)$$

By determining F for 1/1 octave band frequency analysis and introducing some basic, plausible assumptions with regard to masking, he could theoretically calculate the factor F for any constant percentage bandwidth type of frequency analysis, Fig. 15. For 1/3 octave type of analysis, for example, the factor, F, should be about o.13.

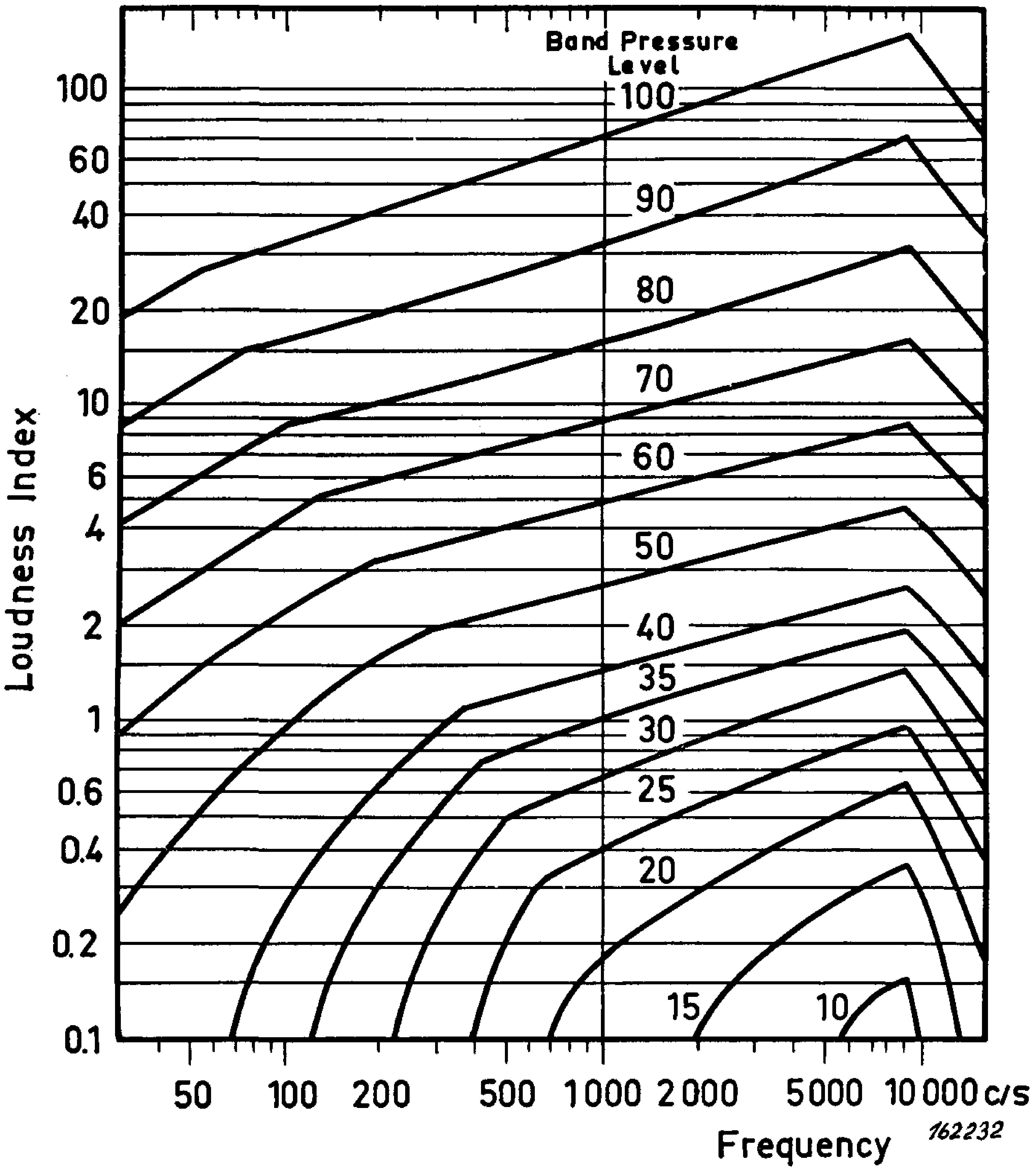

Fig. 17. Representation of the loudness index with band-pressure level as the parameter (Stevens).

In his original paper Stevens also gave a number of loudness curves which relates the loudness in sones to measured 1/1 octave as well as 1/2 and 1/3 octave sound pressure levels. A revision of his original data has lately been made in connection with a Secretarial Proposal in the Technical Committee 43 on Acoustics of the International Standards Organization.

In the revised version, Mark VI, Stevens gives the following relationship between the analysis bandwidth and the factor F:

Bandwidth	F
Third-octave	0.15
Half-octave	0.2
Octave	0.3

Also a new concept the loudness index is introduced.

The loudness indices, S, can be found from the equal loudness index contours

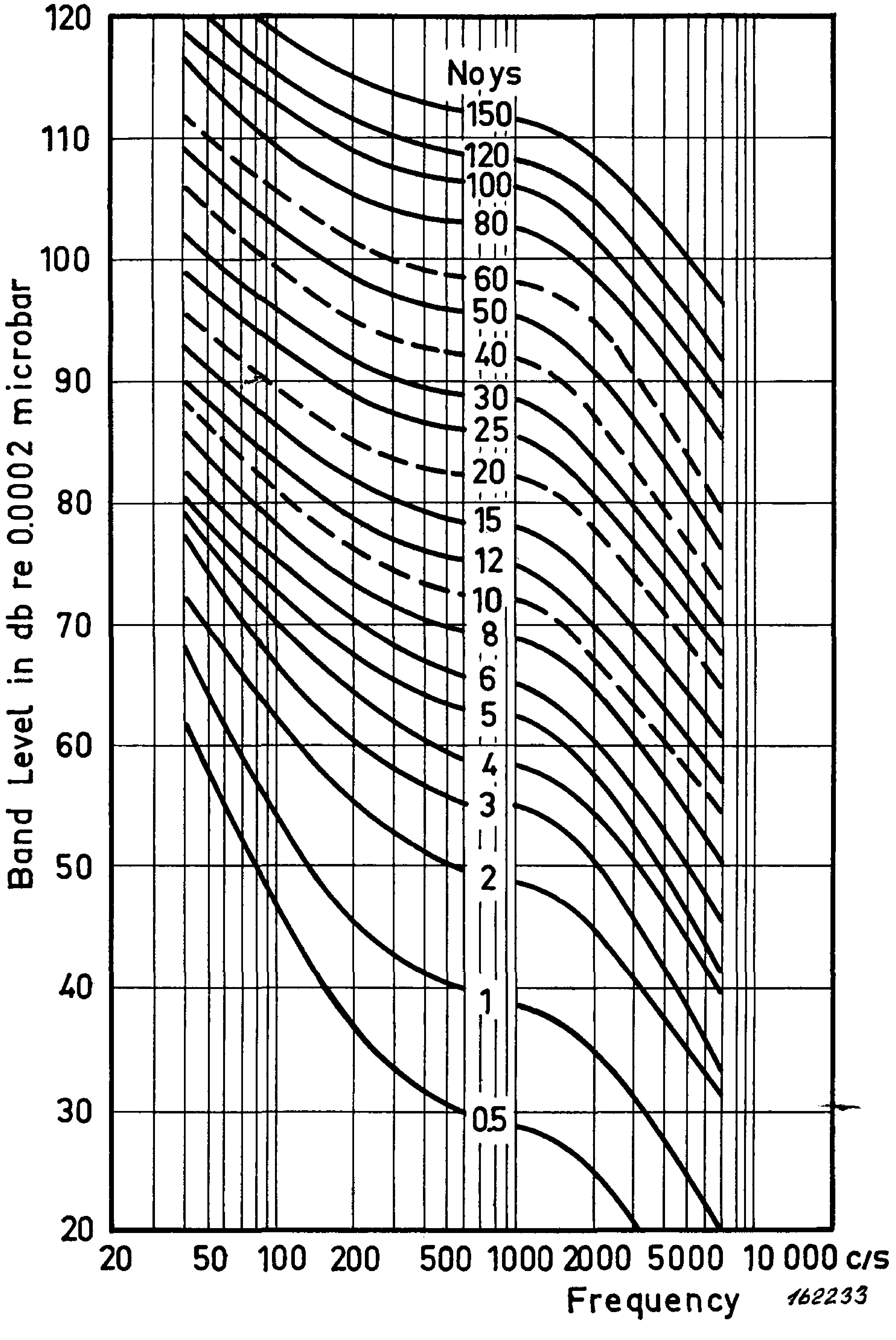

Fig. 18. The noisiness of bands of sound as a function of sound pressure level; the noisiness in noys is given as the parameter of the contours. To determine the noisiness of a band of sound one enters the chart on the center frequency and sound pressure level of the band. The bands must be no wider than one octave (Kryter).

shown in Fig. 16. As mentioned earlier in this article such a set of curves is only valid for certain specified conditions, and the curves shown in Fig. 16 relate to measurements in a diffuse sound field and of sounds which exhibit more or less continous frequency spectra. Also included in Fig. 16 is a nomogram which makes it possible to convert the total loudness, S_t, from sones into phons. The set of curves may, of course, also be presented in other ways, such as the curves shown in Fig. 17 or in the form of tables. It might be worth mentioning at this point, *that the curves shown in Figs. 16 and 17 are not valid only for a specific bandwidth but can actually be used for various types of practical constant percentage sound analyzers.* The geometric mean frequency of the band should be entered along the X-axis (abscissa) and the loudness index is read off either the parametric curves (Fig. 16) or the Y-axis (ordinate) in Fig. 17 at the measured band pressure level in db.

Measurement of Annoyance. The PN-db Concept.

The methods of Zwicker and Stevens both refer to the calculation of loudness. Beranek, Kryter and Miller have, on the other hand, tried to find a method by means of which is was possible to calculate the "annoyance" of, for instance, aircraft noise.

A great number of subjective tests were carried out, indoors as well as out of doors in trying to relate the subjective "annoyance" of the noise from a commercial jet airliner to that of a propeller aircraft. These investigations lead to the introduction of the terms "percieved noisiness" and "percieved noise level". The noisiness was measured in "Noys" which is an additive quantity and corresponds to sones (or laut) in loudness summation. Percieved noise level was measured in PN db (corresponding to phon). The calculation of the percieved noise level follows Steven's rule of loudness summation. However, the equal loudness index contours shown in Fig. 16 should in this case be substituted by the set of "equal noisiness" curves shown in Fig. 18.

Which of the three described methods of calculating the "subjective" effect of a sound will furnish the "best" result, depends to a certain extent upon the nature of the sound itself.

It seems, however, that the latest revisions of Stevens' equal loudness index contours (Fig. 16) and Kryter's equal "noisiness" contours*) bring the calculated result in phon according to Stevens', and Kryter's PN db fairly close to each other. From data given by D. W. Robinson at the "Control of Noise" conference at the N.P.L. in England, June 1961, it seems, furthermore, that the loudness level of a specific sound, when calculated according to Zwicker's method have a tendency to give a greater number of phon than when calculated according to Stevens' method.

Two Examples.

To demonstrate the use of the described methods two types of spectrograms

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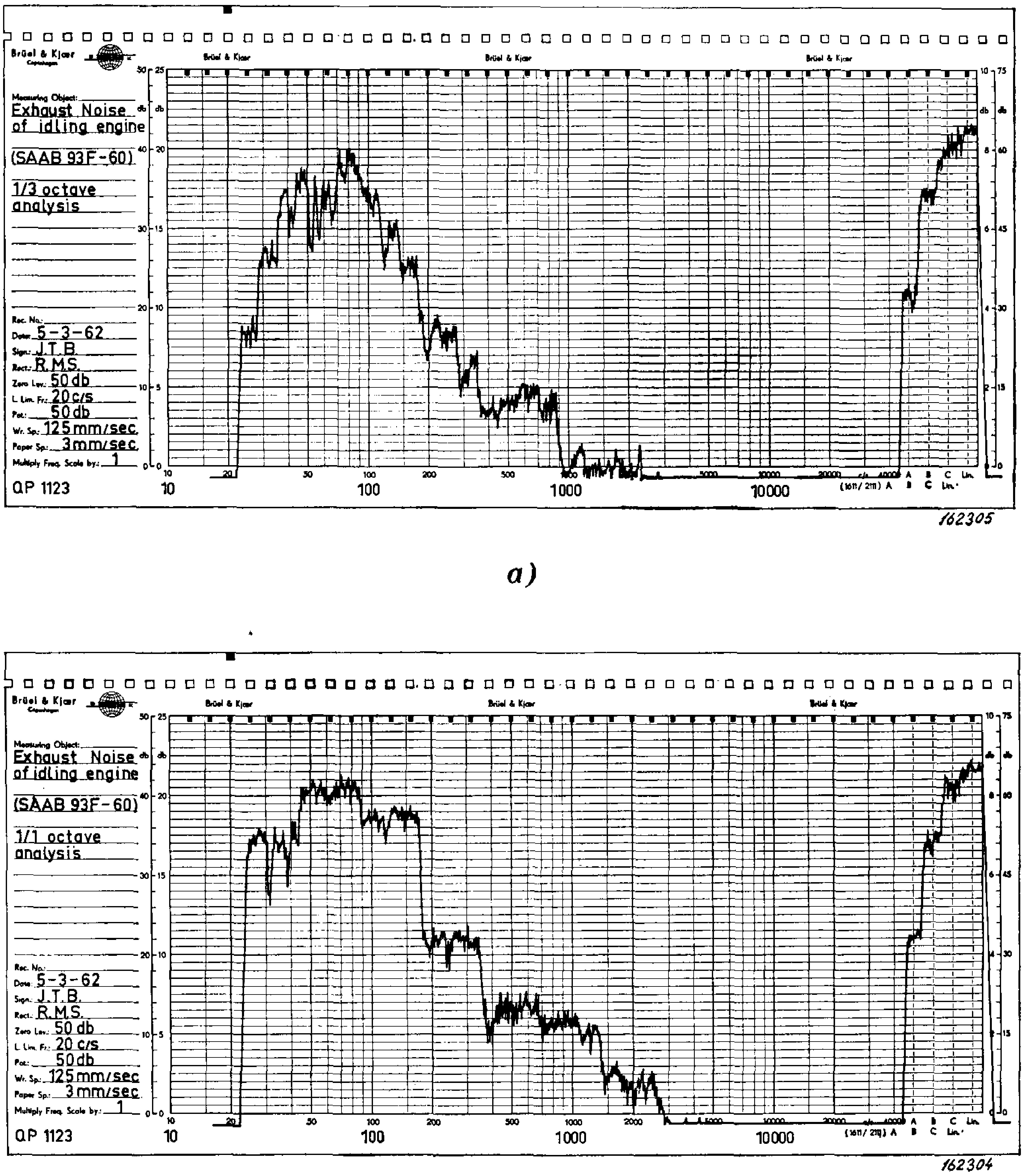
*) See Appendix p. 34.

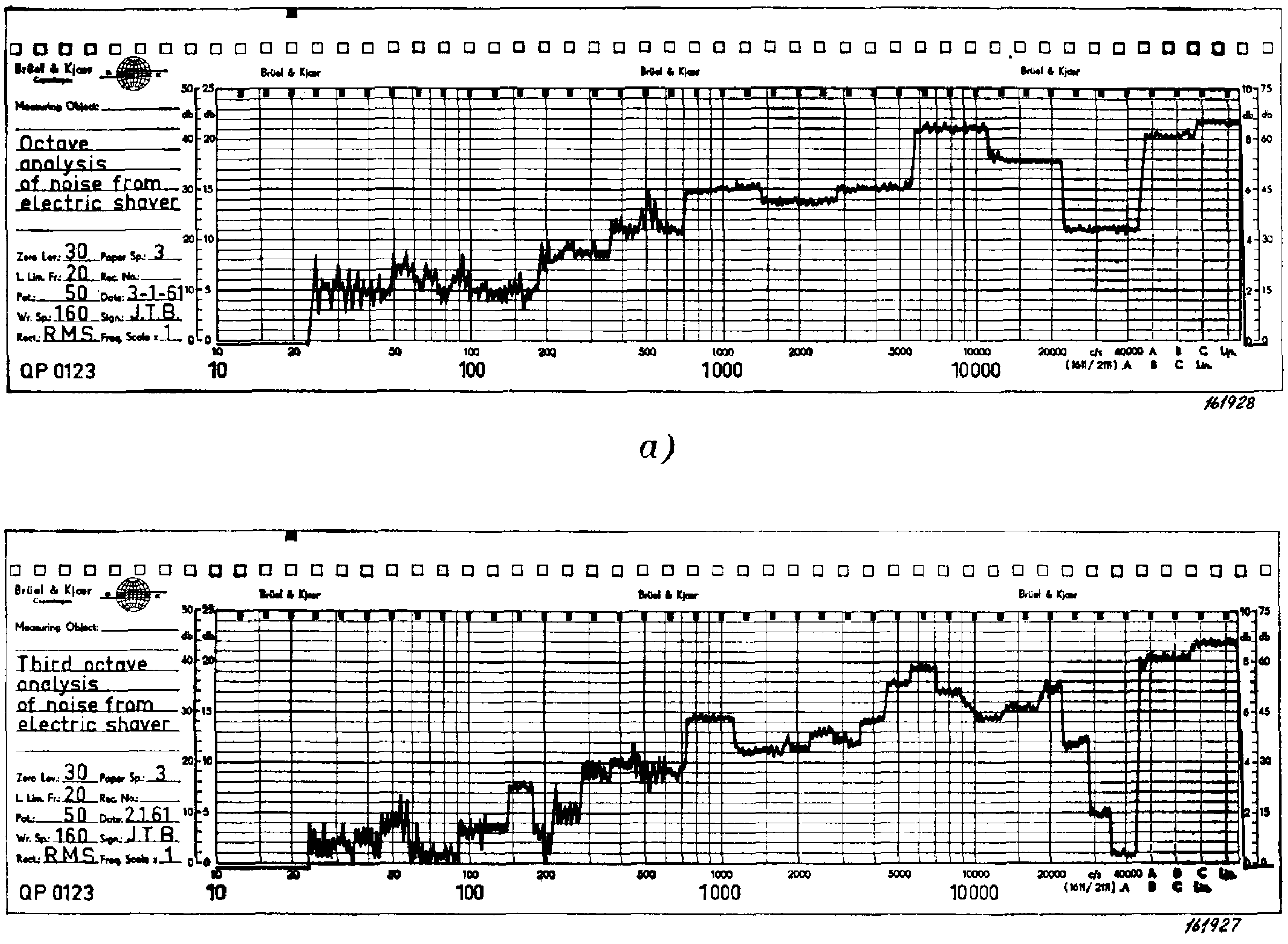


a)

b)

Fig. 19 Measurement of the exhaust noise from an automobile.
a) 1/3 octave analysis — b) 1/1 octave analysis.

will be considered in the following, Figs. 19 and 20. One of the spectrograms have been measured at about 50 cm distance away from the exhaust output of a two-stroke engine and the other depicts the spectrum of the noise radiated from an electric shaver. In both cases the spectra were recorded automatically on a Brüel & Kjær Type 3313 Audio Frequency Spectrum Recorder, first in the form of a 1/3 octave analysis and then with the Spectrum Recorder switched for 1/1 octave analysis. In Fig. 21 the 1/3 octave band pressure levels have been transferred to Zwicker's diagrams and the mean lines drawn in dashed. The mean line in the exhaust noise spectrogram



a)

b)

Fig. 20. Analysis of the noise from an electric shaver.
a) 1/3 octave analysis — b) 1/1 octave analysis.

corresponds to a loudness of 25 sones, which when converted to phons by means of the sone/phon scale to the right in the figure, corresponds to a loudness level of 86 phon. In the shaver noise spectrogram the mean line corresponds to a loudness of 28 sones or 87,5 phon.

Table 2.

Measurements of Exhaust Noise.

Band center frequency c/s	31.5	63	125	250	500	1000	2000
Band pressure level (db)	84	90	87	71.5	63	61	54
Loudness index	5.7	13.7	14.4	6.8	4.9	5.2	4.1

$$S_t = S_m + F\,(\Sigma S - S_m) = 14.4 + 0.3 \times 40.4 = 26.52$$

26.52 sones → 87.5 phons

Table 3.
Measurements on Electric Shaver.

Band center frequency c/s	31.5	63	125	250	500	1000	2000	4000	8000
Band pressure level (db)	40	42	40	47	54	60	58	60	72
Loudness index	0	0.16	0.37	1.44	2.84	4.8	5.2	7.0	17.5

$$S_t = S_m + F\,(\Sigma\,S - S_m) = 17.5 + 0.3 \times 21.8 = 24 \text{ sones}$$

24 sones → 86 phons

In table 2 and 3 the conversion of the 1/1 octave band pressure levels to loudness indices can be seen, together with the calculation of the overall loudness according to Stevens' methods.

Table 4.
Measurements of Exhaust Noise.

Band center frequency c/s	31.5	63	125	250	500	1000	2000
Band pressure level (db)	84	90	87	71.5	63	61	54
Noys	8.0	14.0	18.0	7.5	5.5	4.5	4.5

$$N_t = N_m + F\,(\Sigma\,N - N) = 18 + 0.3 \times 44 = 31.2 \text{ Noys}$$

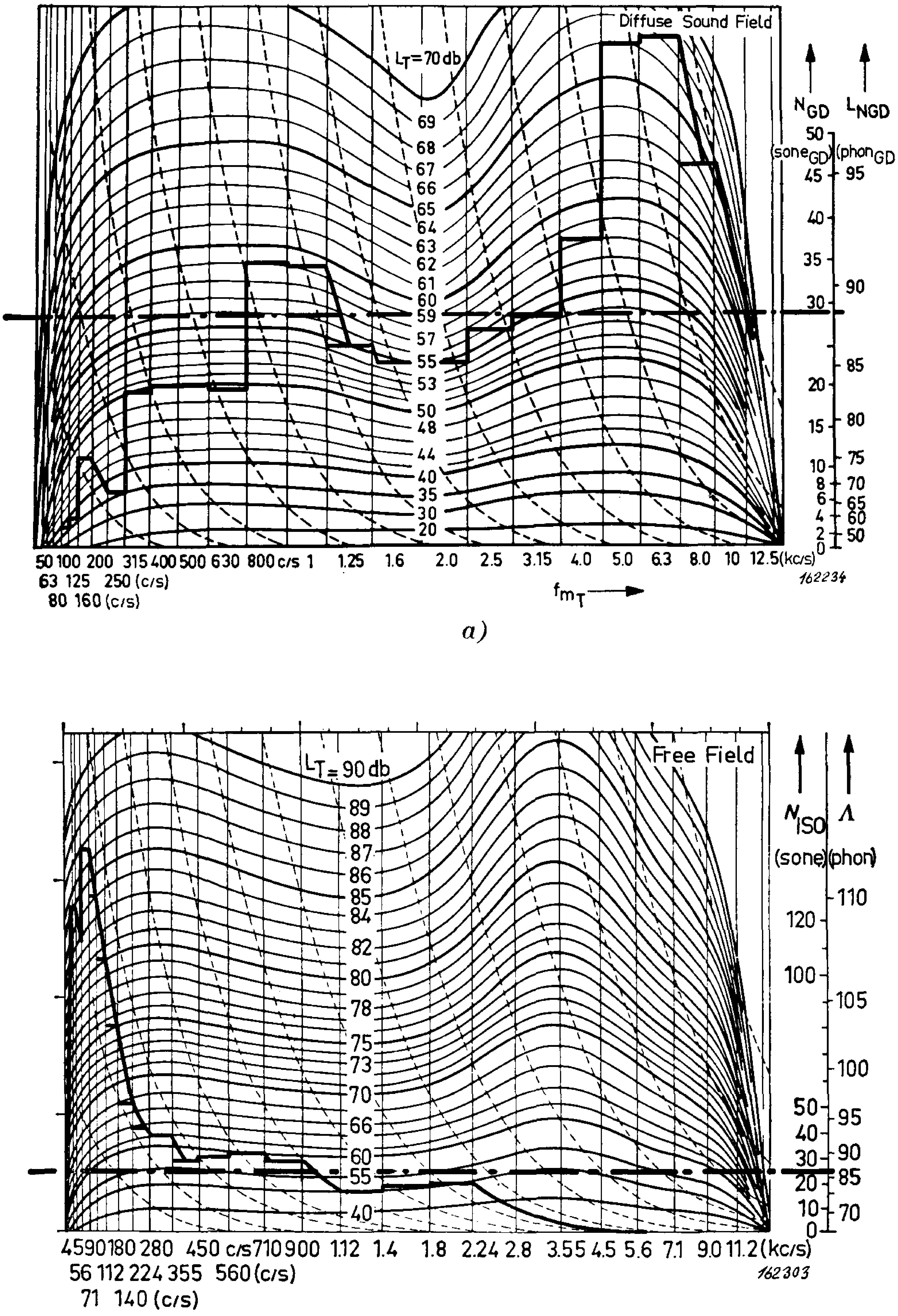
31.2 Noys → 89.5 PN db

Table 5.
Measurements on Electric Shaver.

Band center frequency c/s	31.5	63	125	250	500	1000	2000	4000	8000
Band pressure level (db)	40	42	40	47	54	60	58	60	72
Noys	0	0	0	1.0	3.0	4.0	5.5	10.0	35.0

$$N_t = N_m + F\,(\Sigma\,N - N_m) = 35 + 0.3 \times 23.5 = 42 \text{ Noys}$$

42 Noys → 93.5 PN db



a)

b)

Fig. 21. Calculation of loudness level according to Zwicker's method. The 1/3 octave data from Figs. 19a and 20a have here been transferred to Zwicker's diagrams. The mean lines have been drawn out to the right indicating the sone (and corresponding phon) values resulting from the calculation.
a) Exhaust noise — b) Shaver noise.

Finally the number of Noys corresponding to the 1/1 octave band pressure levels are given in table 4 and 5 together with the calculated PN db values. It can be seen that in both cases there are relatively little differences between the loudness values calculated according to Zwicker and the loudness values calculated according to Stevens, while in the case of the shaver noise spectrum a difference of approximately 8 db exists between the loudness value and the PN db values. This discrepancy may be explained on the basis of the shape of the noise spectrum radiated from the shaver, as the PN db gives greater "weight" to the high frequency region than to the low- and mid-frequency part.

Use of Weighting Networks.

The methods outlined above greatly help the noise abatement engineer to predetermine the "subjective" results of his efforts, and make possible a fairly accurate comparison of measuring results. On the other hand, it requires a certain amount of measurement data and calculation and it might thus be an "ideal" situation if the loudness calculation could be substituted by a single meter reading.

This has been the aim of many investigators. However, because of the complexity of the hearing mechanism no instrument has yet been designed which can measure the loudness "subjectively" by means of a meter reading. A very elaborate apparatus has been suggested by Niese, who has later modified the original version into a special sound level meter. One of the objectives of Niese's apparatus is that it should also be capable of measuring pulse type

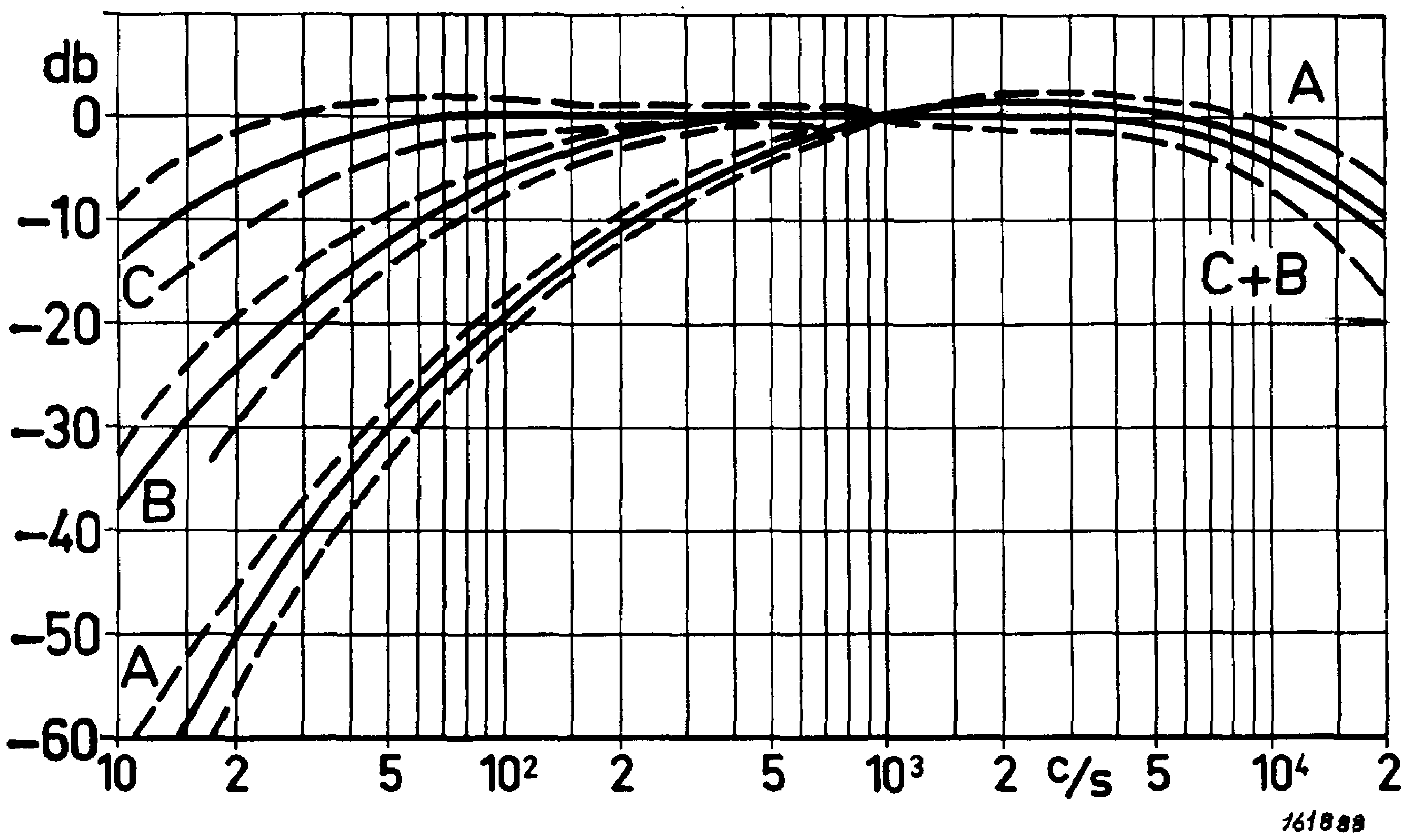


Fig. 22. The internationally proposed weighting curves for sound level meters. The tolerances allowed for "precision sound level meters" are also shown.

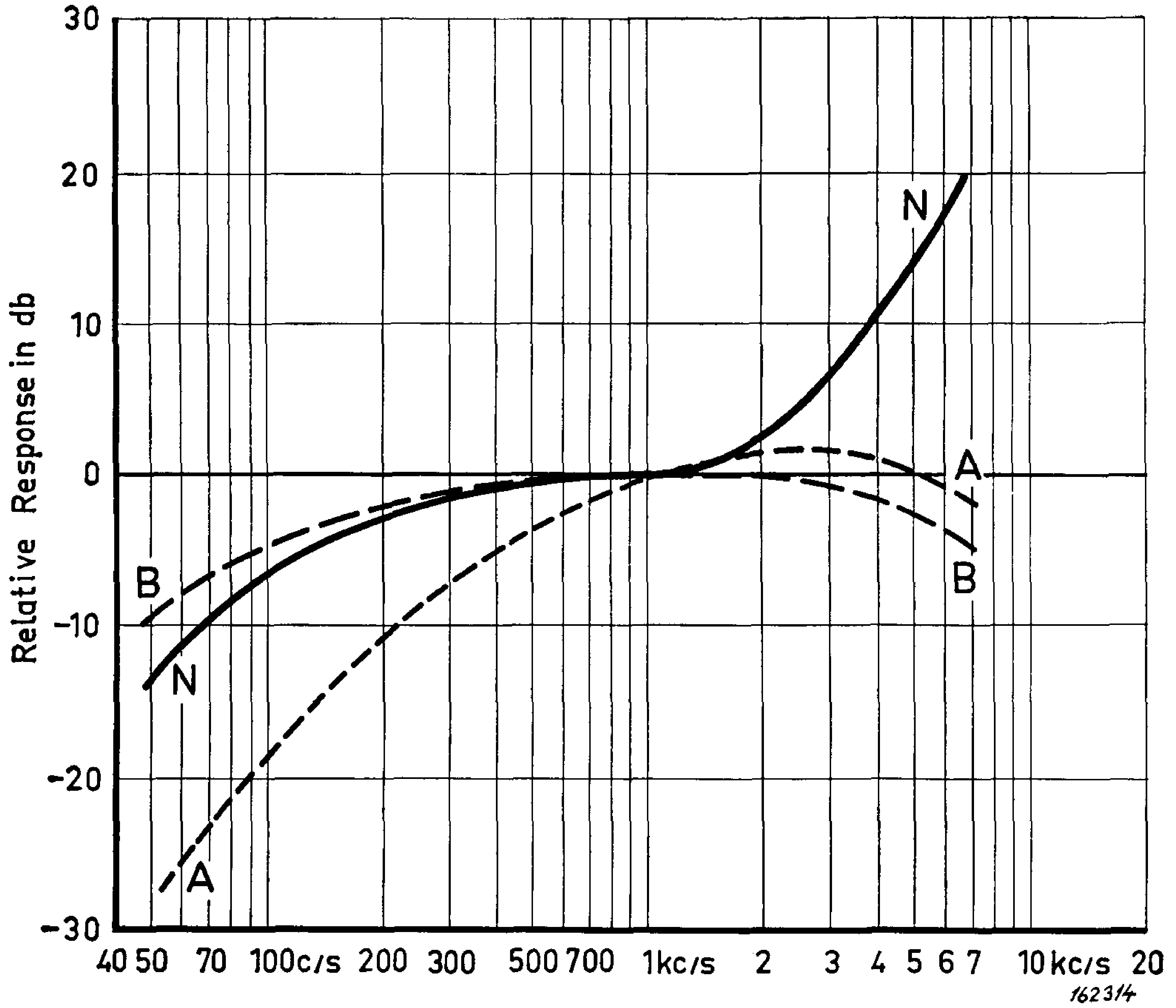


Fig. 23. Suggested N-weighting curve for the measurement of PN db (Kryter).

sounds "subjectively". For this purpose he introduces a "peak-r.m.s." rectifier circuit with a time constant of approximately 23 m sec. for the r.m.s. circuit and 2 sec. (or more) for the peak circuit. This arrangement should, according to Niese, simulate the ear-response to these types of sounds.

The "original" Barkhausen sound level meter actually gives a subjective measure of the sound by using a 1000 c/s comparison tone. However, the result of the measurements will depend, to a great extent, upon the physiological and psychological conditions of the user.

Certain standard sound level meters have therefore been internationally proposed for simple measurement of sound levels. These include some weighting characteristics which were originally presumed to "weight" the frequency spectrum of a sound in a way similar to the hearing mechanism,— and a different weighting network should be used for different sound levels (see also Fig. 3). The curves should be valid for binaural listening in a diffuse sound field.

It has later been found that the discrepancy between sound level meter read-

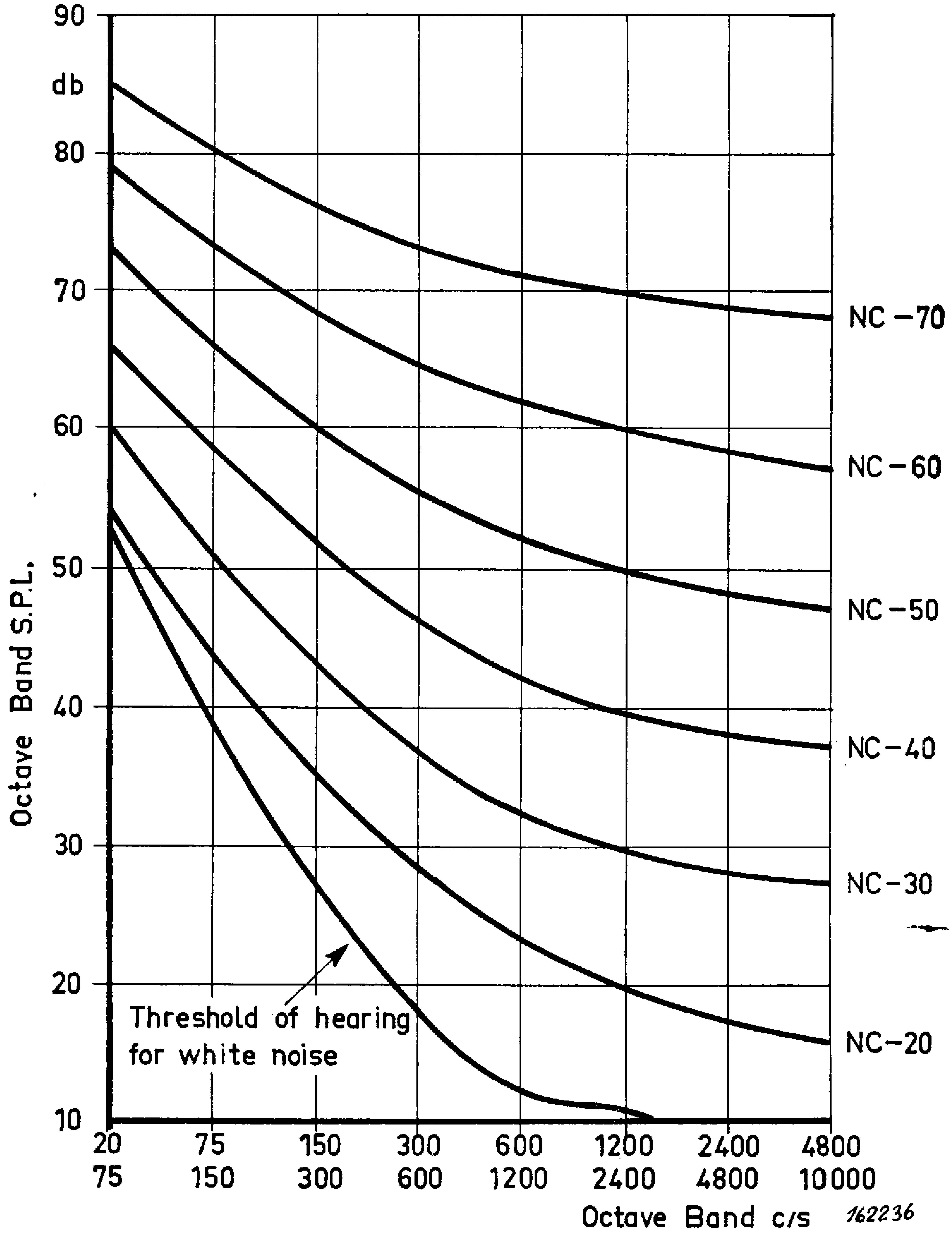


Fig. 24. Noise criterion curves (NC-curves) for determination of the permissible (or desirable) sound pressure levels in eight octave bands Each NC-curve has a loudness level (LL) in phons which is 22 units greater than the speech interference level (SIL) expressed by the NC-number of the curve (Beranek).

ings and the subjectively judged sound level were in many cases so great that the sound level meter must be regarded as an instrument making an almost purely physical measurement, with only little relation to subjective judgement. (See also Fig. 20 where measurements with A or B networks gave a value of 70 db while the "subjective" sound level was calculated to about 87 db). Nevertheless, sound level meter measurements are very useful for comparison purposes on an international basis.

A weighting curve for the measurement of PN db has been suggested by Kryter and follows the reciprocal of the 40 noys contour of Fig. 18. At high frequencies it has been found sufficiently accurate to chose a cut-off frequency of around 8 kc/s.

In Fig. 22 the weighting curves A, B and C of the internationally proposed standard Sound Level Meter are shown, and in Fig. 23 the suggested N (PN db) curve is reproduced. For the sake of convenience also the A and B curves are drawn in dashed in Fig. 23.

Because measurements with a sound level meter will never give "subjective" data *the result of the measurements should always be accompanied by a term which identifies the response characteristic of the instrument used.* In sound level measurements this is achieved by stating the db-value measured, followed by the letter A, B or C. If, for example, a sound level of 70 db has been measured with the weighting network corresponding to the B-curve (Fig. 22) switched in, the result should be termed 70 db (B).

When measuring noise with an N weighting curve the measured level is normally termed PN db.

Some Noise Criteria.

In the foregoing, various methods of measuring and evaluating the loudness level of a sound have been described. It might be useful also to summarize some important psycho-acoustic criteria for "tolerable" noise levels and speech interference, as well as hearing damage, because the value of a sound measurement and calculation only really achieves its objective when the result can be evaluated with respect to such a "damage" criterion.

As "tolerable noise levels" and speech interference are rather closely connected certain noise criteria curves have been worked out by L. L. Beranek, which take both effects into account. The curves are shown in Fig. 24 in the form of octave band data.

The number marked on each curve is the S.I.L. value (Speech Interference Level) and different NC curves should be used for different types of rooms. In very quiet conference rooms, hotel rooms, hospitals etc. a value between NC-25 and NC-30 is recommended as satisfactory. In small office rooms NC-40 may be considered as a satisfactory criterion, and in noisy rooms with a number of working typewriters a convenient value will be NC-50. In the latter case telephone conversation may, however, be somewhat difficult.

In the book "Noise Reduction" Beranek gives a table for recommended use of the NC-curves, see Table 6.

Table 6.

Recommended Noise Criteria for Rooms.

Type of Space	Recommended NC Curve of Fig. 23 NC units
Broadcast studios	15—20
Concert halls	16—20
Legitimate theaters (500 seats, no amplification)	20—25
Musicrooms	25
Schoolrooms (no amplification)	25
Television studios	25
Apartments and hotels	25—30
Assembly halls (amplification)	25—35
Homes (sleeping areas)+	25—35+
Motion-picture theaters	30
Hospitals	30
Churches (no amplification)	25
Courtrooms (no amplification)	25
Libraries	30
Restaurants	45
Coliseums for sports only (amplification)	50

+) Room air conditioners manufactured prior to 1957 commonly produce levels of 40 to 55 db (A) in sleeping areas.

Note: Noise levels are to be measured in unoccupied rooms. Each noise criterion curve is a code for specifying permissible sound-pressure levels in eight octave bands. It is intended that in no one frequency band should the specified level be exceeded. Ventilating systems should be operating, and outside noise sources, traffic conditions, etc., should be normal when measurements are made (Beranek).

The noise criteria as outlined in the table would, if they could always be followed, ensure a desirable sound environment. However, in some cases the costs involved in producing such environments may be so high that a compromise between the "ideal" situation and the situation which causes hearing damage must be made. A number of investigators have developed so-called hearing damage criteria and a few of these are given in the following.

In the U.S.S.R. certain "Tentative Standards and Regulations for Restricting Noise in Industry" have been compiled by I. I. Slawin and their derivation and background are described in his book "Industrielärm und seine Bekämpfung".*) Fig. 25a shows the tolerable sound pressure levels vs. frequency at the place of the observer as laid down in this standard. The curves are based on the fact that in 95 to 98 % of all cases investigated, no hearing loss

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*Also described in the journal "Noise Control", September 1959.

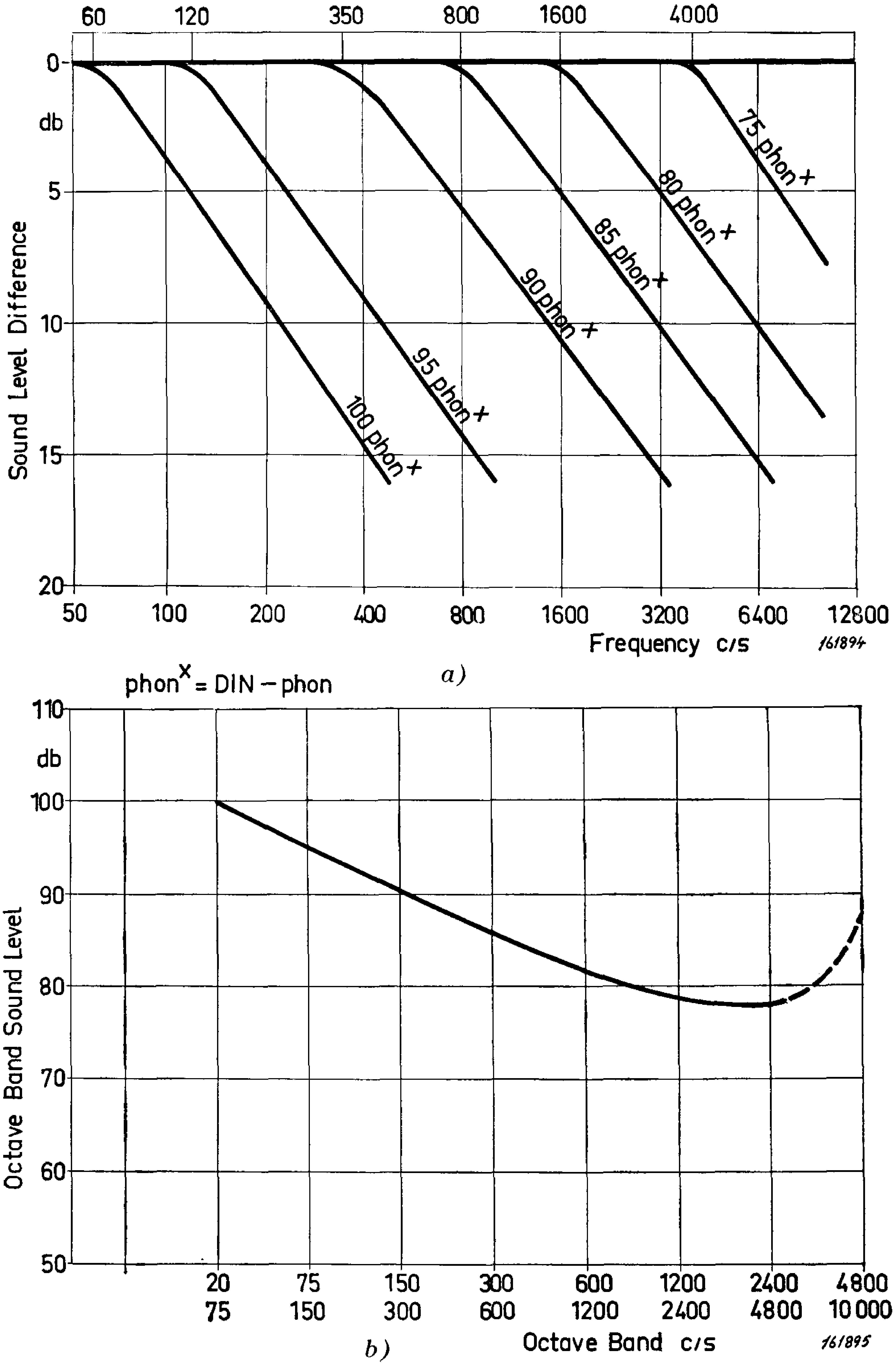

Fig. 25. Curves showing the tolerable noise level as a function of the spectral distribution of the noise according to data compiled by I. I. Slawin.

a) The data as laid down in the "Tentative Standards and Regulations for Restricting Noise in Industry" in the U.S.S.R.

b) Slawin's "translation" of the curves into allowable octave bands of noise.

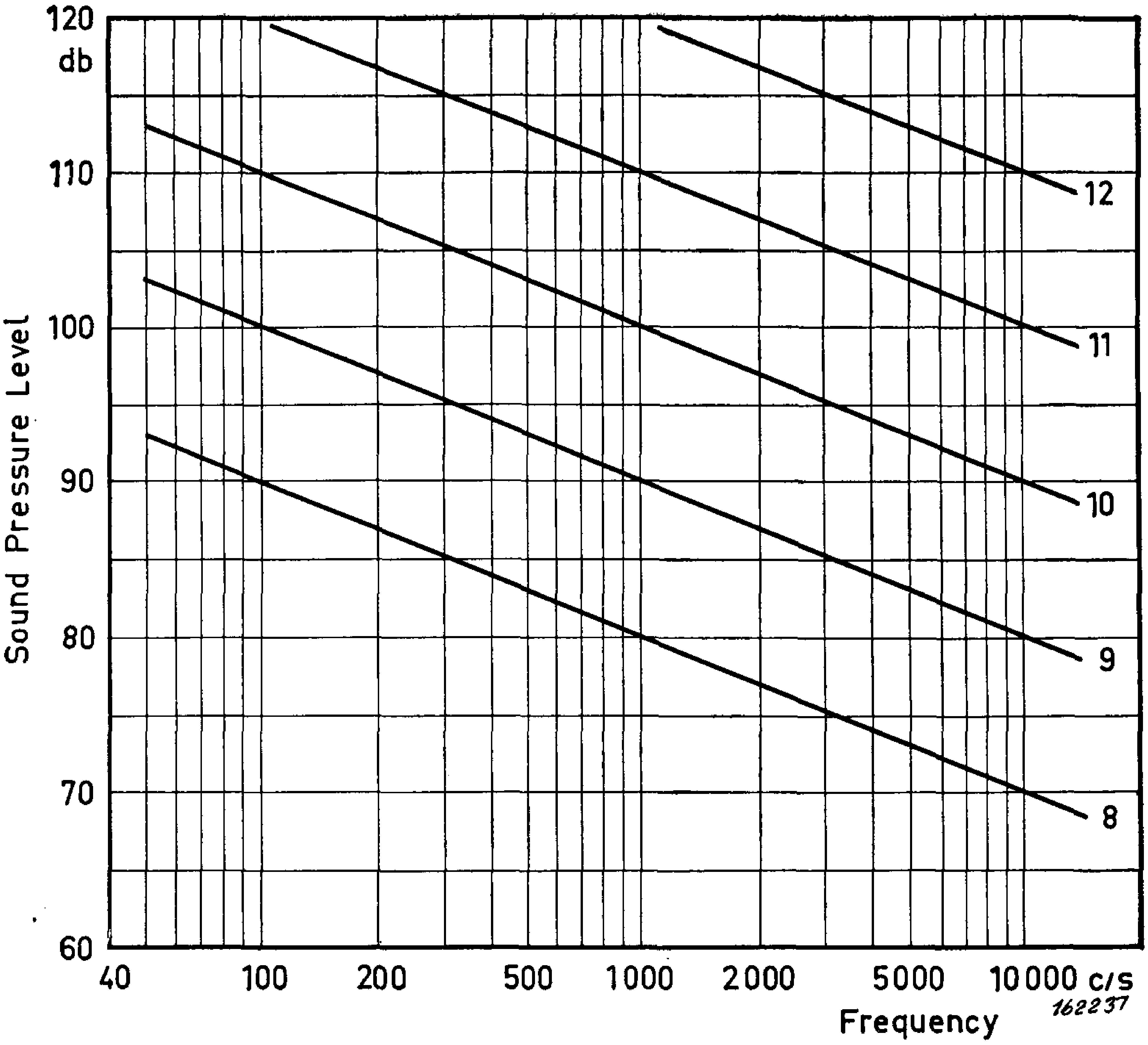

Fig. 26. Damage risk criteria as suggested by Cremer and Lübcke. The figure should be used in connection with table 7 of the text.

was caused as long as the sound level and spectral distribution of the sound were as shown. Furthermore, the speech intelligibility is good at distances of up to 1.5 m when these criteria are employed. The curves here are reprinted in the way they are given originally and might need a little further explanation. The curves marked "100 phon", "95 phon", "90 phon" etc. relate to the overall sound level (approximated by a sound level meter reading according to the German DIN 5045 standard). Regarding the spectral distribution of the sound it can thus be seen that if the overall sound level is 100 DIN-phon the sound pressure level at 100 c/s must not be greater than (100 — 3.5) = 97.5 db, at 200 c/s 100 — 9.5 = 90.5 db etc.

As it has been common practice to employ octave bands in sound analysis, Slawin has also interpreted the curves when the sound levels are measured in this manner, Fig. 25b.

In Germany Cremer and Lübcke have suggested certain "limit lines" (Grenzlinien) with a slope of — 3 db/octave, as shown in Fig. 26. The number marked on the lines here refers to the Bel-value (1 Bel = 10 db) at 1000 c/s. and the following table may be used as guidance for the application of the curves:

Table 7.

By exceeding the "limit-line"	Degree of damage after given duration
8.	By lasting influence some hearing damage.
9.	By lasting influence hearing damage in numerous cases.
10.	By lasting influence health damage prevalent.
11.	Health damage possible after only a few hours.
12.	Health damage unavoidable.

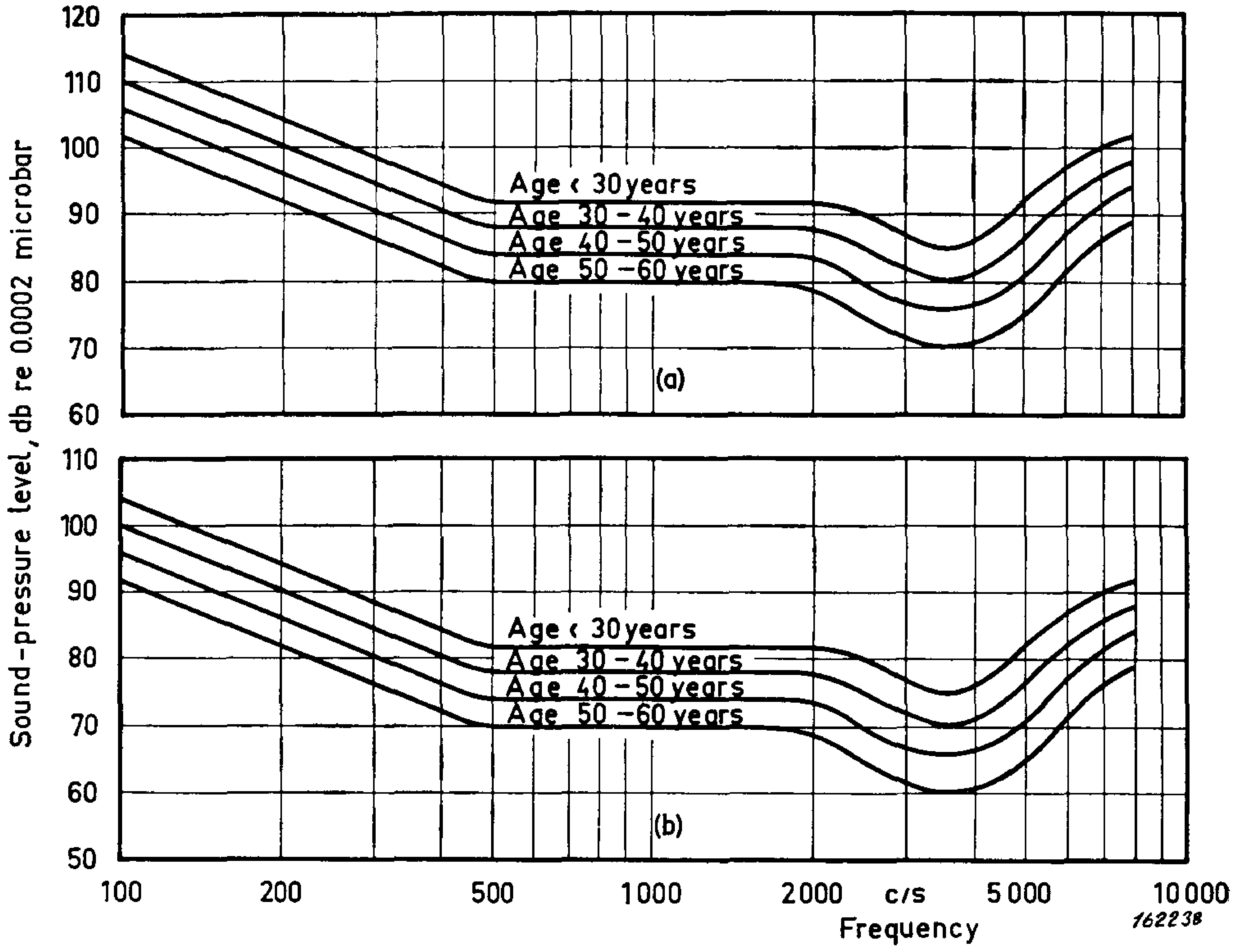

Fig. 27. Proposed damage-risk criteria (Kryter).
a) Damage risk criteria for wide band noise measured by octave, 8 hr continuous exposure.
b) Damage risk criteria for pure tones or critical bands of noise.

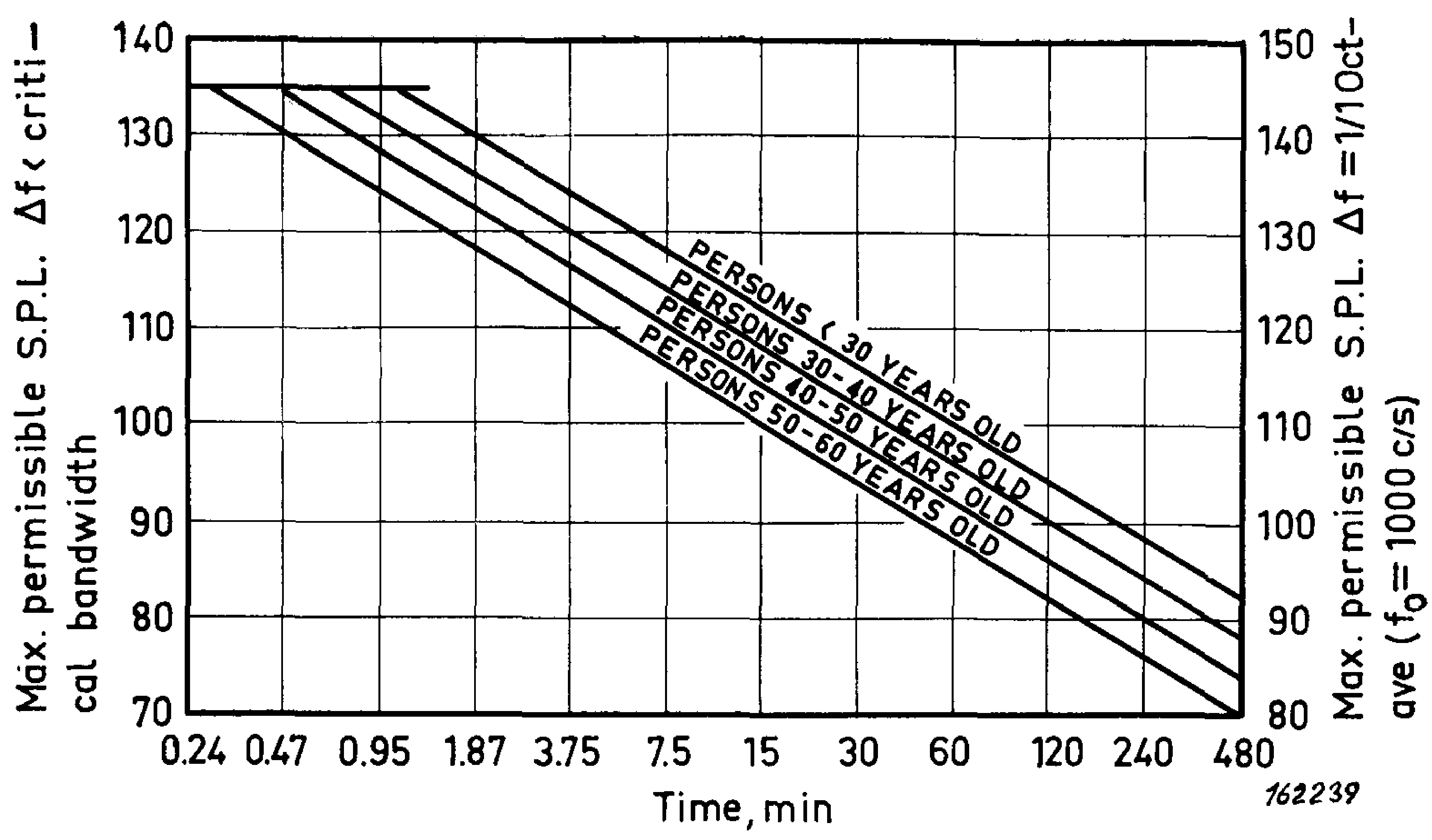

Fig. 28. Curves showing proposed damage-risk criteria for brief exposures (8 hr or less). The right-hand ordinate applies to sounds that have a bandwidth greater than a critical band. The lower curves apply to sound exposure. The left-hand ordinate applies to sounds that are less wide than one critical band. The parameter is age. Sound-pressure level should not exceed 135 db for any exposure to pure tones or critical bands of noise, or 145 db for octave bands of noise (Kryter).

In the U.S.A K. D. Kryter has proposed certain damage risk criteria which also take the presbycusis*) into account. His proposal is based upon the findings of the Sub-committee ZS4-X-2 of the American Standards Association and the assumption that a certain relationship exists between the damage risk and the auditory threshold as a function of frequency. The criteria can be summarized in the form of the curves shown in Figs. 27 and 28. Fig. 27 shows the maximum allowable sound pressure level vs. frequency relationship, both of octave band spectra and of pure tones (or critical bands of noise), for noise exposure over a long time. In Fig. 28 criteria for brief noise exposure are given. Both in Fig 27 and Fig. 28 the age has been plotted as parameter. Kryter concludes, however, that even if these criteria might prove useful in various ways, they involve a number of assumptions and hypothesis which need further study and testing.

Appendix

During the printing of this article the author has received the latest revision of the "equal noisiness" curves from Dr. Kryter. These curves are shown in

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*) Presbycusis is the gradual decrease in sensitivity of the ear which occurs as a person grows older and is attributed to the normal process of aging.

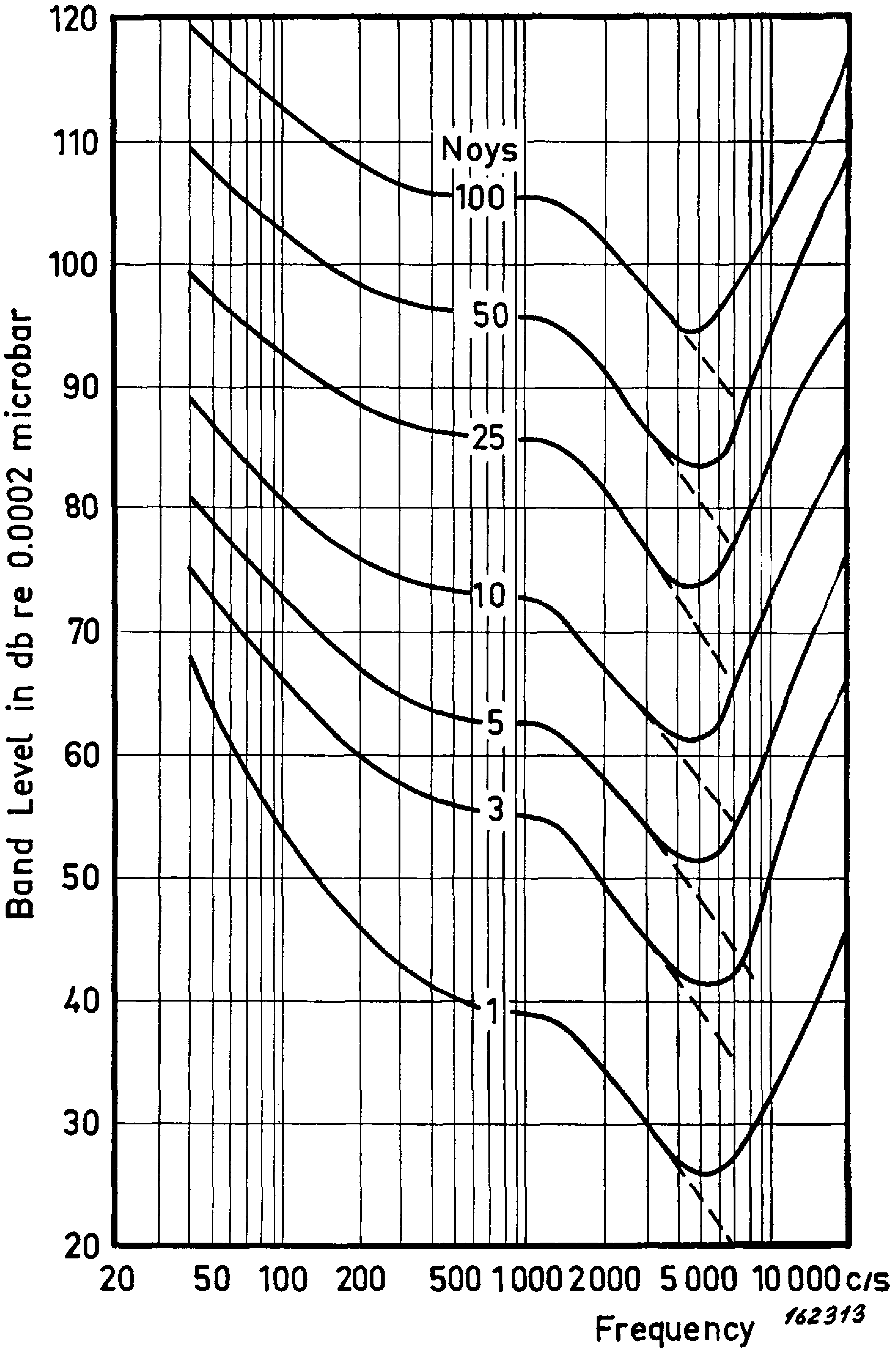

Fig. A.1. Revised equal "noisiness" contours (Kryter).

Fig. A.1 and indicate a considerable change in the high frequency weighting as compared with the curves proposed in Fig. 18. When the new curves are applied to the spectrogram shown in Figs. 19 and 20 PN db values of 90 PN db and 86.5 PN db are obtained instead of 89.5 PN db and 93.5 PN db.

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