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ON THE USE OF A-WEIGHTED LEVELS TO DESCRIBE LOW FREQUENCY NOISE

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0. Introduction

The most common descriptor of noise exposure is the A-weighted sound pressure level as described in IEC 651 [1]. Unfortunately, it seems that the A-weighted sound pressure level does not always reflect the annoyance perceived by the population. Therefore, corrections are sometimes added to the A-weighted level, such as for impulsive noise and for noise containing pure tones [2].

Another class of noise, for which the A-weighted level is considered insufficient, is noise with significant spectral components in the low frequency range. It seems to be a general understanding that A-weighted levels underestimate the annoyance in these cases. Examples are given for instance by Waye [3] and by Landström [4].

The lack of coherence between A-weighted levels and the perceived annoyance is reflected in the Danish rules for external industrial noise ([5], Clause 2.2.2, p. 17, author's translation): "*If the loudness of a noise is mainly determined by very low frequency noise (frequencies below 50 Hz), then caution should be exercised, if the nuisances from the noise are assessed only from the A-weighted level, since this level does not constitute a satisfactory measure of the nuisances from low frequency noise. If, nevertheless, the A-weighted level is used, then a too mild assessment of the nuisances will result. However, there is at present no generally approved method for assessment of nuisances from noise with pronounced low frequency character.*"

Corresponding rules in Norway suggest to use C-weighting in case of a high fraction of low frequency noise [6]. The wording of the document implies that in these cases the same limits should be used for the C-weighted level as would normally be used for the A-weighted levels.

Regulations of external noise in Sweden and Finland have no specific rules or comments on low frequency noise [7], [8]. Swedish regulation of indoor noise from sanitary and other technical appliances has a 50 dB limit for C-weighted levels in bedrooms along with a 30 dB limit for A-weighted levels [9].

In an attempt to explain the lack of coherence between A-weighted levels and perceived annoyance, it would be rather natural to start the other way round and try to explain why anyone has ever expected a coherence. The basic idea of this is that a given noise has a perceived magnitude, called loudness, and that the annoyance from the sound is determined entirely or mainly by its loudness. If the A-weighted level reflects the loudness, then it would also reflect the annoyance. Several more or less obvious misunderstandings are inherent in this justification, and the present paper will examine some of these. The paper will focus on the connection between loudness and A-weighted level and only briefly mention the connection between loudness and annoyance.

The use of A-weighting to describe the sensitivity of the ear is discussed in Section 1. This discussion assumes that the equal loudness contours described in ISO 226 [10] are correct. However, recent experiments seem to show that this may not be true, and Section 2 presents a literature review of data on equal loudness contours. Section 3 presents very briefly a study of the connection between loudness and annoyance at low frequencies.

The discussion in the present paper does not cover the infrasonic region, i. e. the frequencies below 20 Hz. These are considered well described by the G-weighted level [11]. The level should preferable be below the threshold of perception in most cases, which means that the G-weighted level should be below approximately 95 dB for the average person and probably below approximately 85 dB for the most sensitive individuals.

1. ISO 226 equal loudness contours and A-weighting

The pure tone free field sensitivity of the human ear is described in the international standard ISO 226 [10]. The standard presents contours of equal loudness levels (given in phon), see Figure 1.

If the equal loudness contours are inverted they describe "sensitivity curves" for the human hearing. A relevant weighting curve for loudness prediction should approximate the inverse equal loudness curves. Inverse equal loudness curves are shown in Figure 2 together with the A-weighting. It is seen that the inverse equal loudness curves vary substantially with loudness level. It is also seen that the A-weighting curve constitutes a relatively poor approximation to the inverse equal loudness curves at any level.

The problem can also be illustrated by plotting curves with fixed A-weighted level onto the equal loudness contours as shown in Figure 3. It is seen that the curves with fixed A-weighted level do not follow the loudness curves; in fact, most of them "cross" several loudness curves throughout the frequency range.

The curves with fixed A-weighted level can also be converted into loudness levels as seen in Figure 4. It is evident that the loudness level varies significantly with frequency, even when the A-weighted level is the same. The loudness level is only close to the A-weighted level in a narrow frequency range slightly above 1 kHz, and for very low levels in a wider range from below 100 Hz to several kilohertz.

A possible explanation for the A-weighting being inadequate in loudness prediction may be found in the history of the curve. Originally, also B- and C-weighting curves were described. The weightings were claimed to be simple approximations to inverse equal loudness contours at low, medium and high levels, respectively. When measured with the frequency weighting relevant for the level concerned, the weighted level would thus serve as an approximate indicator of loudness.

Figure 5 shows fixed values of A-, B- and C-weighted levels at low, medium and high levels together with the equal loudness curves. Like in Figure 3, where only A-weighted levels were used, the curves do not follow the loudness contours.

The problem is also illustrated in Figure 6, where fixed A-, B- and C-weighted levels have been converted into loudness level. These curves should ideally be horizontal lines at the loudness level corresponding to the weighted level, and this is clearly not the case. (The deviations from flat curves look even larger than in Figure 4, where only the A-weighting was used. This can partly be explained by the fact that the high level curve in Figure 4 had to be limited in frequency as it would otherwise go beyond the loudness range of ISO 226).

Earlier standardized versions of the weighting curves did mention the connection between the curves and the human hearing, while the present version questions this connection.

IEC 123:1961 [12] states in clause 4.3: "*Although these weightings approximate very roughly certain properties of the ear, they are to be considered merely as conventional*".

IEC 179:1973 [13] states in clause 4.3: "*Although the curves A, B and C take certain properties of the ear into account, they must be considered to be purely conventional*".

IEC 651:1979 [1] states in clause 2.3.3: "*In the past, frequency weighting and time weighting have been associated with certain characteristics of the ear. However, recent work has not substantiated these historical associations so that frequency and time weighting characteristics of sound level meters may be considered to be conventional. The A weighting characteristic is now frequently specified for rating sounds irrespective of level and is no longer restricted to low sound levels*".

Although the B- and C-weightings still exist in the present standard [1], they are not often used, and it is planned to delete the B-weighting in a current revision.

Provided that the contours of equal loudness given in ISO 226 are correct, then the above considerations have shown that quite large errors should be expected, if A-weighted levels are used in prediction of loudness of sound. The errors are especially large at low frequencies. Level dependent use of A-, B- and C-weighting curves does not seem to solve the problem.

It should be noted that there are alternative procedures to weighting curves for prediction of loudness, e. g. Stevens loudness (ISO 532 [14] method A) and Zwicker loudness (ISO 532 [14] method B, DIN 45 631 [15]).

2. Evaluation of ISO 226 equal loudness contours

The discussion in Section 1 is based on the assumption that the values given in ISO 226 are correct. However, this assumption has been questioned from time to time, and the responsible working group, ISO TC 43 WG 1, has decided to revise the standard.

As a part of the revision, a review of literature data on equal loudness contours has been carried out [16]. The data obtained from the literature are presented in Figure 7: Plots of loudness level versus sound pressure level (frequency by frequency at third-octave frequencies), and Figure 8: Plots of equal loudness contours. Data are presented as close to original data as possible.

The data included in Figure 7 and Figure 8 are given in the following, including their signature in the plots and comments about any processing of original data.

+ **Kingsbury 1927 [17]**

General: These data were obtained with monaural exposure with an earphone. No calibration was offered to the free field. The data include a hearing threshold for the group involved. Assuming they had normal hearing, the threshold data have been made equal to the free field hearing threshold of ISO 389-7 [18], however increased by 3 dB to account for the monaural exposure in the experiment.
Loudness level versus sound pressure level plots (frequency by frequency): Some minor interpolations were made to achieve values at the normal 1/3 octave frequencies.
Loudness contour plots: On loudness level versus sound pressure level plots at the original frequencies each original data point was interpolated to the nearest "nice" loudness level.

◊ **Fletcher and Munson 1933 [19]**

Loudness level versus sound pressure level plots (frequency by frequency): A few data were interpolated to the nearest 1/3 octave values.
Loudness contour plots: To obtain loudness curves at "nice" levels the loudness level versus sound pressure level curves were slightly interpolated.

♥ **Churcher and King 1937 [20]**

Loudness level versus sound pressure level plots (frequency by frequency): Some data were interpolated to the nearest 1/3 octave values.

- - - **Zwicker and Feldtkeller 1955 [21]**

General: The calibration to free field seems doubtful. The data include a hearing threshold for the group involved. Assuming they had normal hearing, the threshold data have been made equal to the free field hearing threshold of ISO 389-7. Although not reported, we assume they used binaural exposure, and no further correction is made.
Loudness level versus sound pressure level plots (frequency by frequency): The corrected curves were read at the third octave frequencies.
Loudness contour plots: The loudness level versus sound pressure level curves were read at selected loudness levels.
Note: The procedure used for these data result in smoother curves than from other authors, since the original data were not available - a considerable smoothing had already been made.

< **Fastl and Zwicker 1987 [22]**

Data were used directly.

♣ **Fastl et al. 1990 [23]**

Data were used directly.

• **Robinson and Dadson 1956 [24]**

General: Only data points determined with direct reference to 1 kHz are reported under this signature.
Loudness level versus sound pressure level plots (frequency by frequency): Some data were interpolated to the nearest 1/3 octave frequency.
Loudness contour plots: To obtain loudness curves at "nice" levels the loudness level versus sound pressure level curves were interpolated.

○ Robinson and Dadson 1956i [24]

General: Data points with indirect reference to 1 kHz are reported under this signature.
Loudness level versus sound pressure level plots (frequency by frequency): Some data were interpolated to the nearest 1/3 octave frequency. The loudness level of a point was found by interpolation between points determined with direct reference to 1 kHz.
Loudness contour plots: To obtain loudness curves at "nice" levels the loudness level versus sound pressure level curves were interpolated.

⊂ Robinson and Dadson 1956a [24]

General: Data points at 100 Hz obtained with the "average error" method (Table 5).
Loudness level versus sound pressure level plots (frequency by frequency): Data were used directly.
Loudness contour plots: To obtain loudness curves at "nice" levels the loudness level versus sound pressure level curves were interpolated.

⊃ Robinson and Dadson 1956b [24]

General: Data points at 50 Hz obtained with interchange of fixed and variable tones (Table 7).
Loudness level versus sound pressure level plots (frequency by frequency): Data used directly.
Loudness contour plots: To obtain loudness curves at "nice" levels the loudness level versus sound pressure level curves were interpolated.

∨ Whittle et al. 1972 [25]

Loudness level versus sound pressure level plot (frequency by frequency): These data have no connection to 1 kHz and cannot be plotted in a loudness level versus sound pressure level plot.
Loudness contour plot: Shown in these plots without reference to a specific loudness level (black line).

■ Møller and Andresen 1984 [26]

Data were used directly.

*** Watanabe and Møller 1990 [27]**

Data from the bracketing method used directly.

× Watanabe and Møller 1990a [27]

Data from the method of maximum likelihood used directly.

▿ Betke et al. 1987 [28]

Data were used directly.

△ **Betke 1991 [29]**
Data were used directly (mean).

∧ **Gabriel et al. 1994 [30]**
Data were used directly.

⊗ **Suzuki et al. 1989a [31]**
Data from Test 1 were used directly.

⊕ **Suzuki et al. 1989b [31]**
Data from Test 2 were used directly.

♦ **Suzuki and Sone 1993 [32]**
Data were used directly.

∞ **Poulsen and Thøgersen 1994 [33]**
Loudness level versus sound pressure level plot (frequency by frequency): Data used directly (however, some data were at 1/6 octave frequencies which were not included in our plot set).
Loudness contour plot: Data used directly.

— **ISO 226 1987 [10]**
Data were used directly.

Differences between investigations are clearly seen in Figure 7 and Figure 8, especially at low frequencies. ISO 226 is based on data from Robinson and Dadson [24], and as their sound pressure levels are in general to the "low" side for a given loudness level (to the left of most other data in Figure 7 and below most other data in Figure 8), this also applies to the ISO 226 values.

At present, the reason for the discrepancies is not fully understood. It is unlikely that deviations in the sound field or measurement errors can explain very much. Quite naturally, the experimental procedure should then be considered.

The method of constant stimuli, which has been used in most of the experiments, is normally believed to be rather precise and the results well defined. However, Gabriel et al. showed in a recent study [30] that the range of stimuli has a pronounced effect on the results. They used a stimulus range of 30 dB positioned at 8 different levels. Figure 9 shows their results for the determination of the 50 phon point at 500 Hz. It is seen clearly that the result depends very much on the stimulus range. Gabriel et al. also found (which is quite natural) that the bias from the stimulus range increases with increasing frequency distance between test tone and reference.

It might be expected that adaptive methods (e. g. the bracketing method) would avoid bias from the "stimulus range", since this range follows the point to be determined. However, it seems that bias is also introduced in these methods, especially when a small step-size is used. An example is given by Lydolf et al. [34] and reported here in Figure 10. It is seen that the result tends to be biased towards the starting level.

One of the investigations that show sound pressure levels to the "high" side for a given loudness level (i. e. values to the right of most other data in Figure 7 and above most other data for the same loudness level in Figure 8) is the study by Watanabe and Møller [27]. They used a starting point 15-20 dB above the ISO 226 levels and a step-size of 2 dB. In addition to this method, they examined six points with an alternative and faster adaptive procedure (the Method of Maximum Likelihood as used by Møller and Andresen [26]). The same subjects participated, and the results were on the average 4.1 dB lower.

The above discussion shows that still some details in the experimental method should be clarified, before a new set of equal loudness curves can be standardized.

3. Connection between loudness and annoyance

It has often been proposed that the lack of coherence between measured levels of low frequency noise and annoyance might be due to lack of coherence between loudness and annoyance at low frequencies.

Andresen and Møller [35] examined equal annoyance contours in the frequency range 4 Hz to 31.5 Hz using a reference at 1 kHz. In a previous investigation [26] they had obtained equal loudness contours in the frequency range 2 Hz to 63 Hz, also with a reference at 1 kHz. The results of the two investigations for the frequencies 16 Hz, 31.5 Hz and 1000 Hz are shown in Figure 11. The two sets of curves are very similar, and an analysis has shown that the differences are not statistically significant.

In a later experiment Møller [36] showed that the annoyance from third octave noise in the range 8 Hz to 31.5 Hz did not deviate from the annoyance from pure tones with the same sound pressure level.

The similarity reported here between points of equal loudness and points of equal annoyance at low frequencies was shown in laboratory experiments. Whether the result is valid also for annoyance as perceived in real life situations is not known at present.

4. Conclusion

It has been shown that the A-weighting comprises a rather poor approximation to the inverse equal loudness contours as given in ISO 226. Thus if the values in ISO 226 are correct, then the A-weighted level will be a rather poor predictor of loudness of pure tones. There is no reason to believe that it should be a better predictor of loudness of more complex noise. Level dependent use of the A-, B- and C-weighting curves - which was originally intended - does not seem to be a better solution.

These considerations were based on the assumption that the equal loudness contours in ISO 226 are correct. Unfortunately, this seems doubtful, and a revision of the standard is necessary (and ongoing). Before the revision can be accomplished a careful evaluation is needed of the psychometric methods used for determination of points of subjective equality, since the methods used for most of the literature data may introduce bias. There is a severe lack of concordance between investigations, especially at low frequencies. After revision of ISO 226 a re-assessment of the weighting curves will be appropriate.

A single investigation has shown a good agreement between the two perceptions loudness and annoyance at low frequencies (even extending into the infrasonic frequency range). This result was obtained in laboratory experiments, and it is not known, whether it is valid also for real life exposure.

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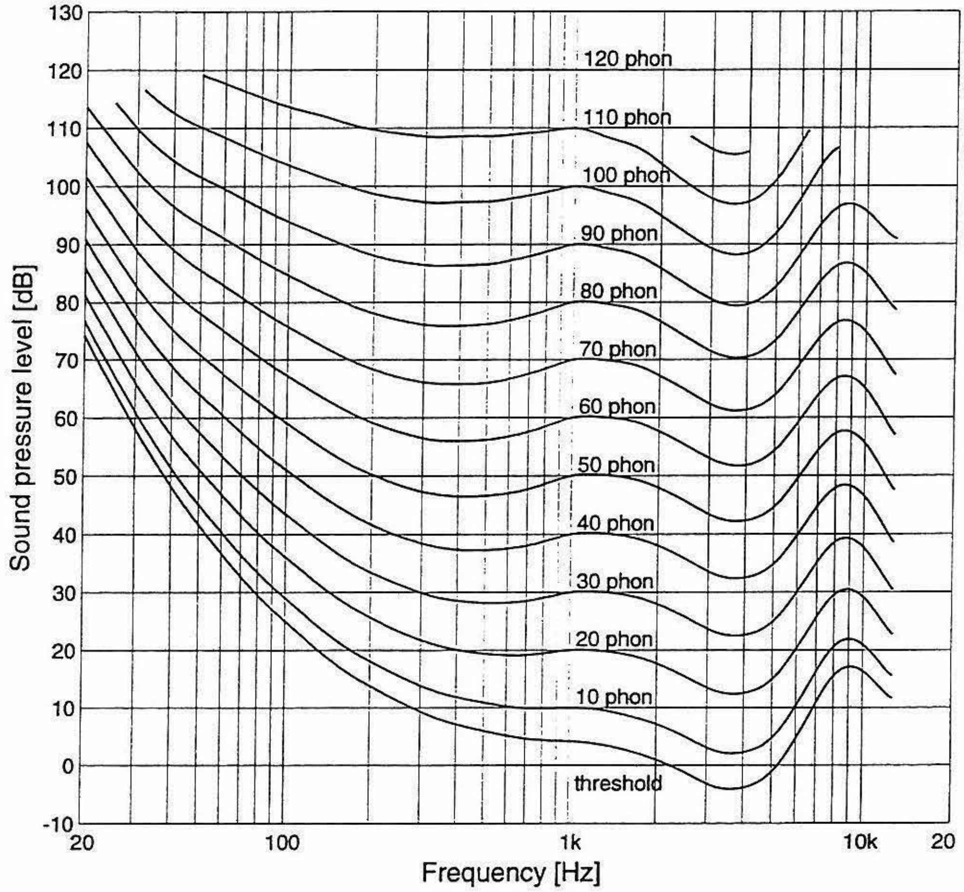


Figure 1

Equal loudness contours as given by ISO 226 [10].

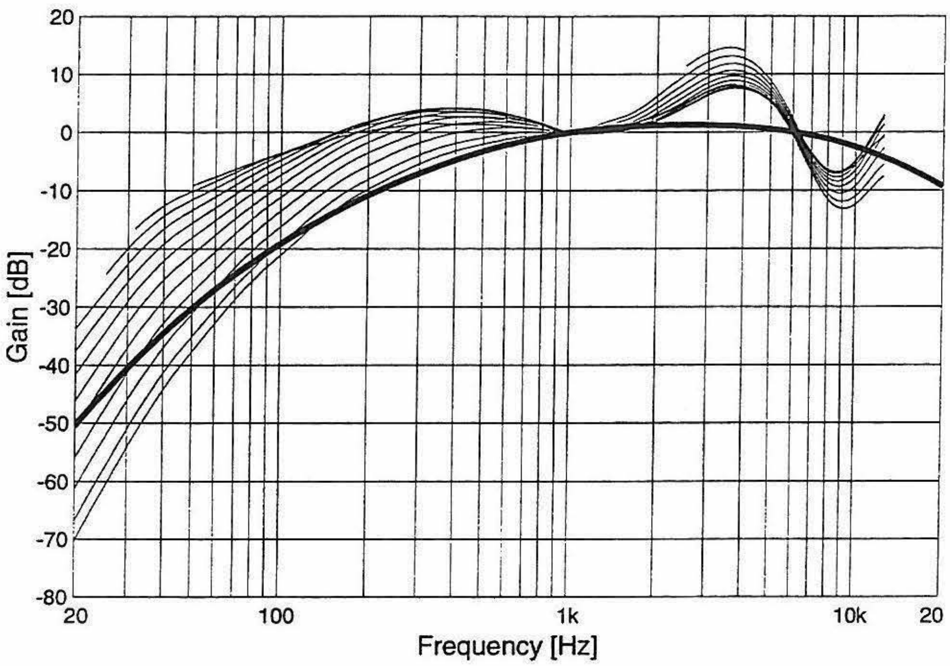


Figure 2

Inverse equal loudness contours for the range 10-110 phon (thin lines) and A-weighting (thick line).

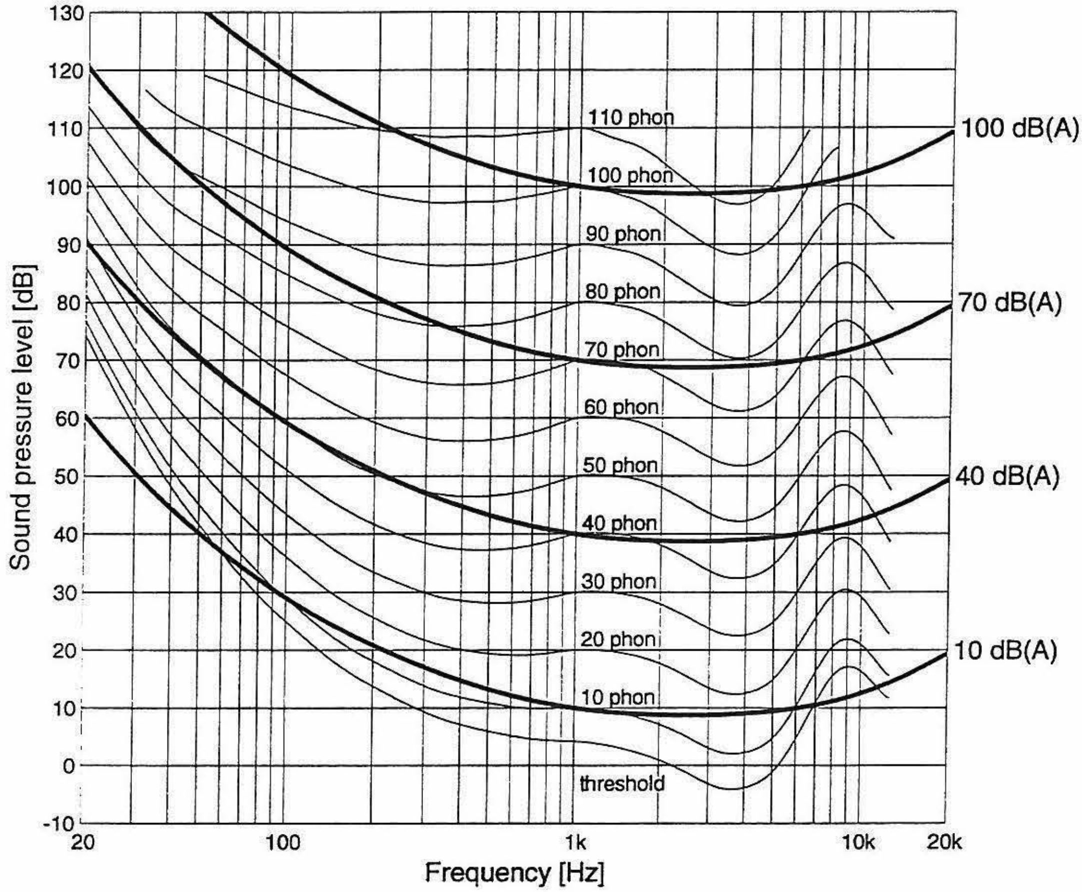


Figure 3

Equal loudness curves (according to ISO 226) shown together with curves of fixed A-weighted level.

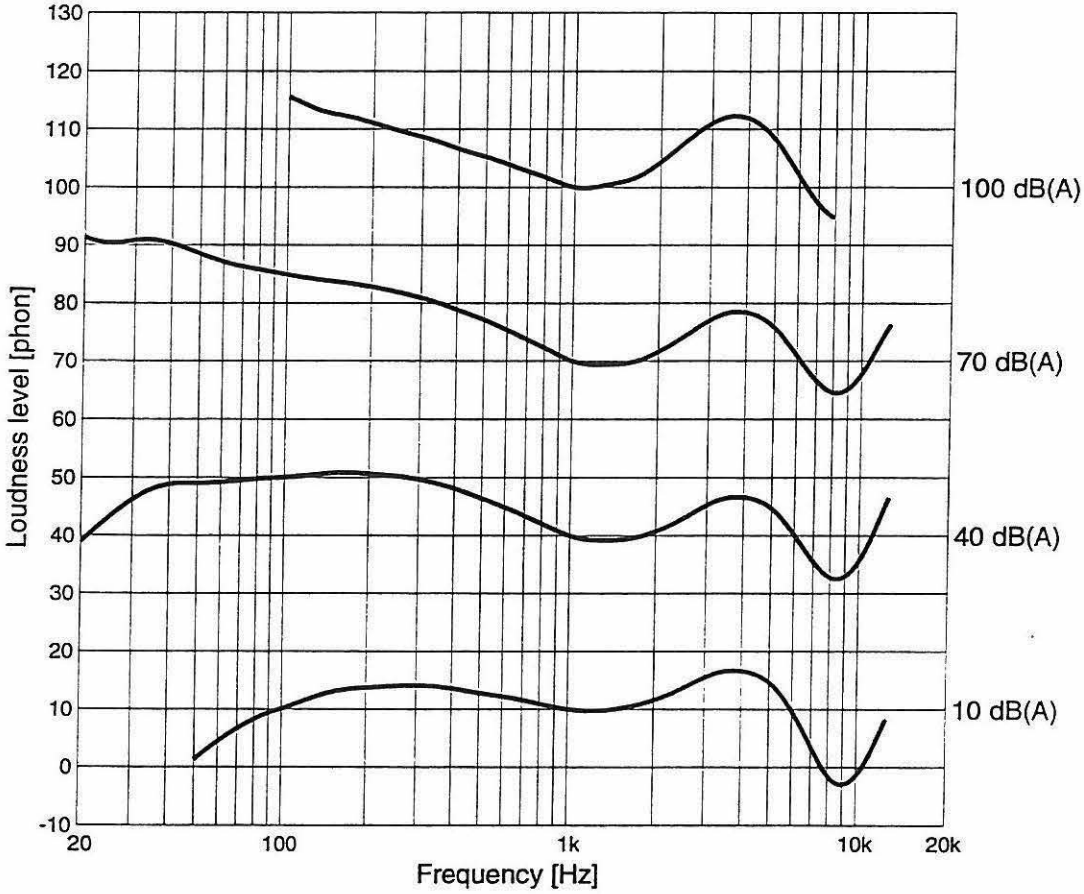


Figure 4

Loudness level versus frequency for fixed values of A-weighted sound pressure level (calculated from ISO 226).

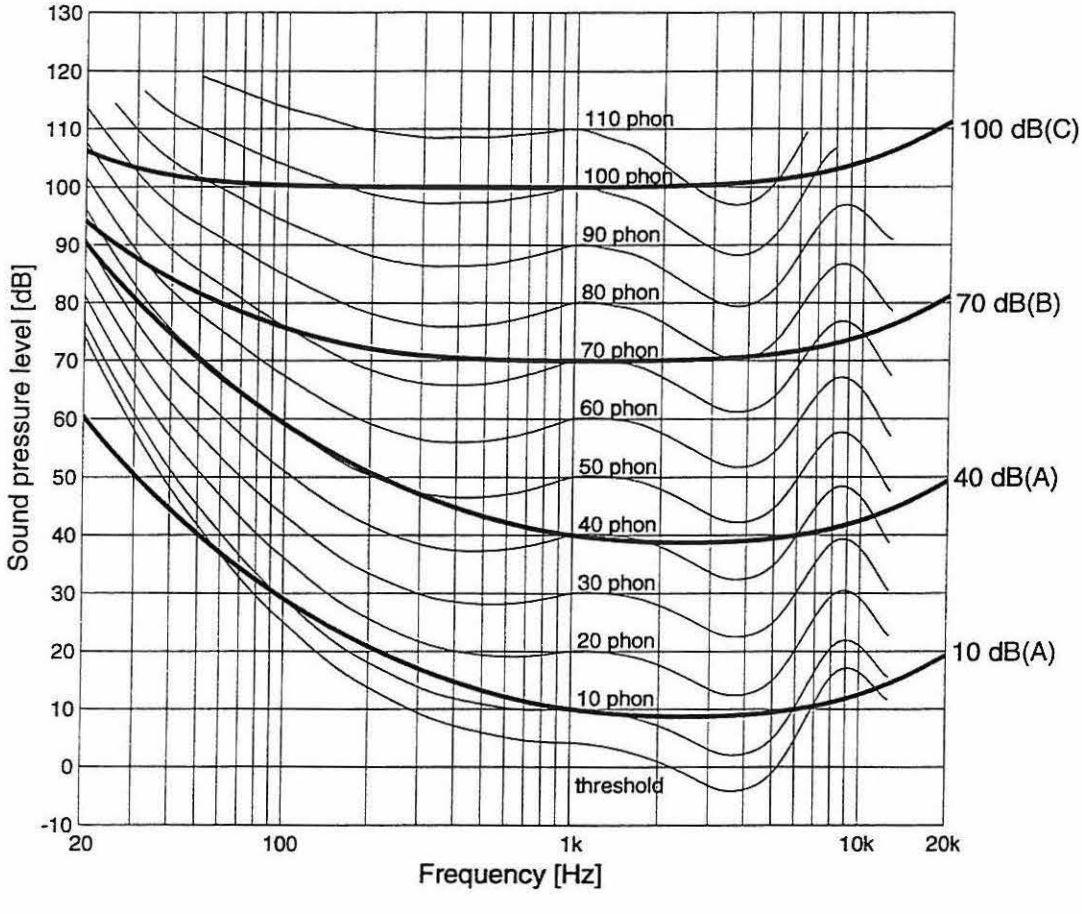


Figure 5

Equal loudness curves (according to ISO 226) shown together with curves of fixed A-, B- and C-weighted levels at low, medium and high levels, respectively.

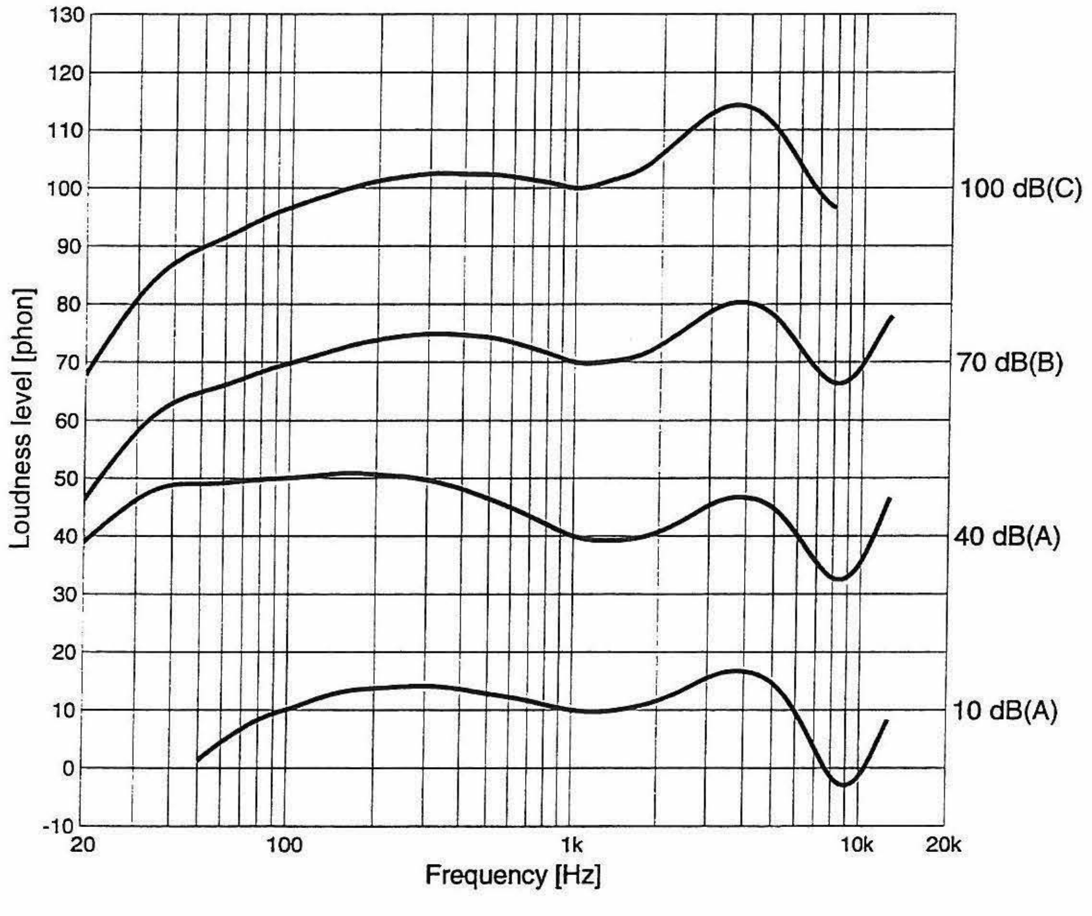
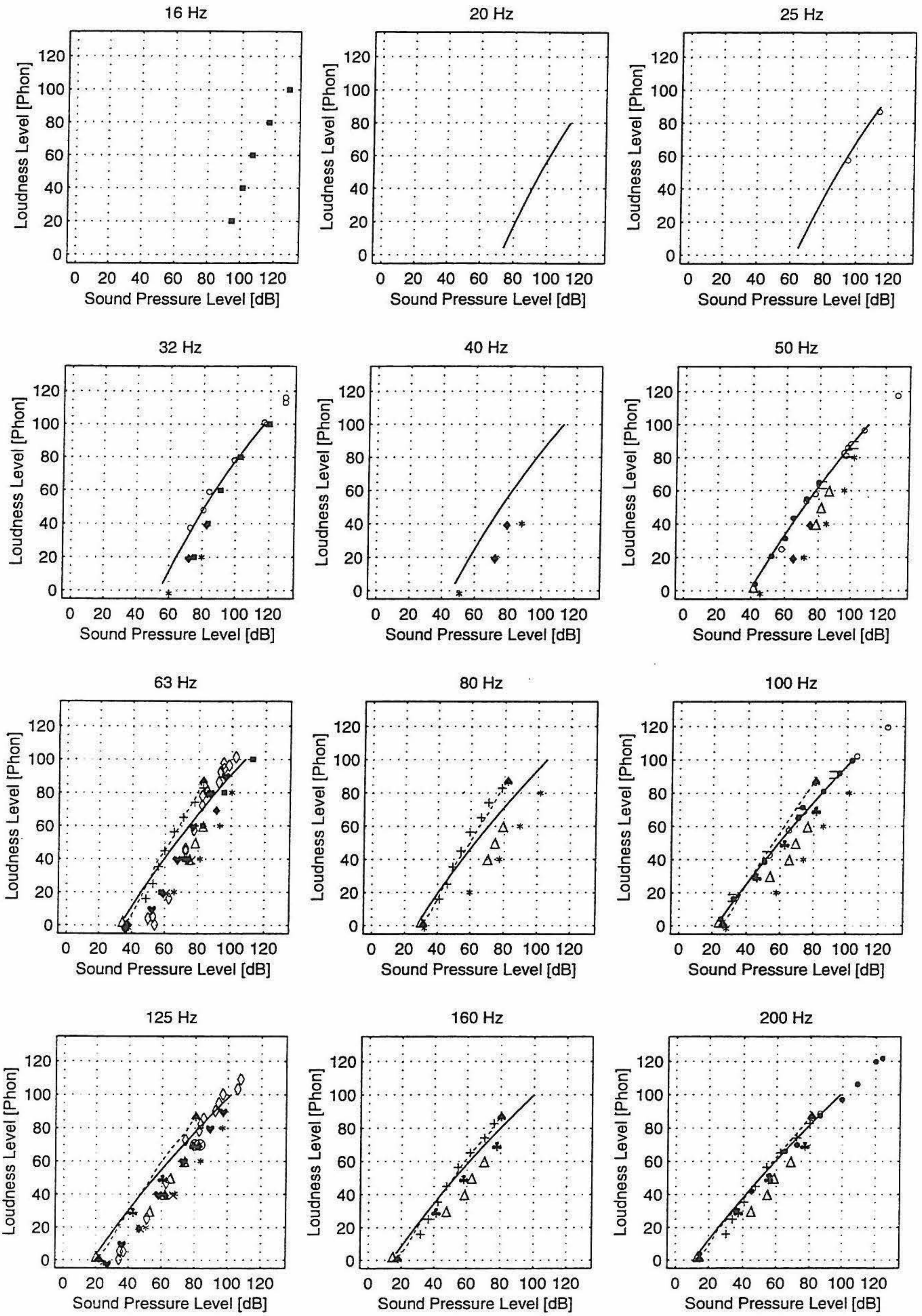


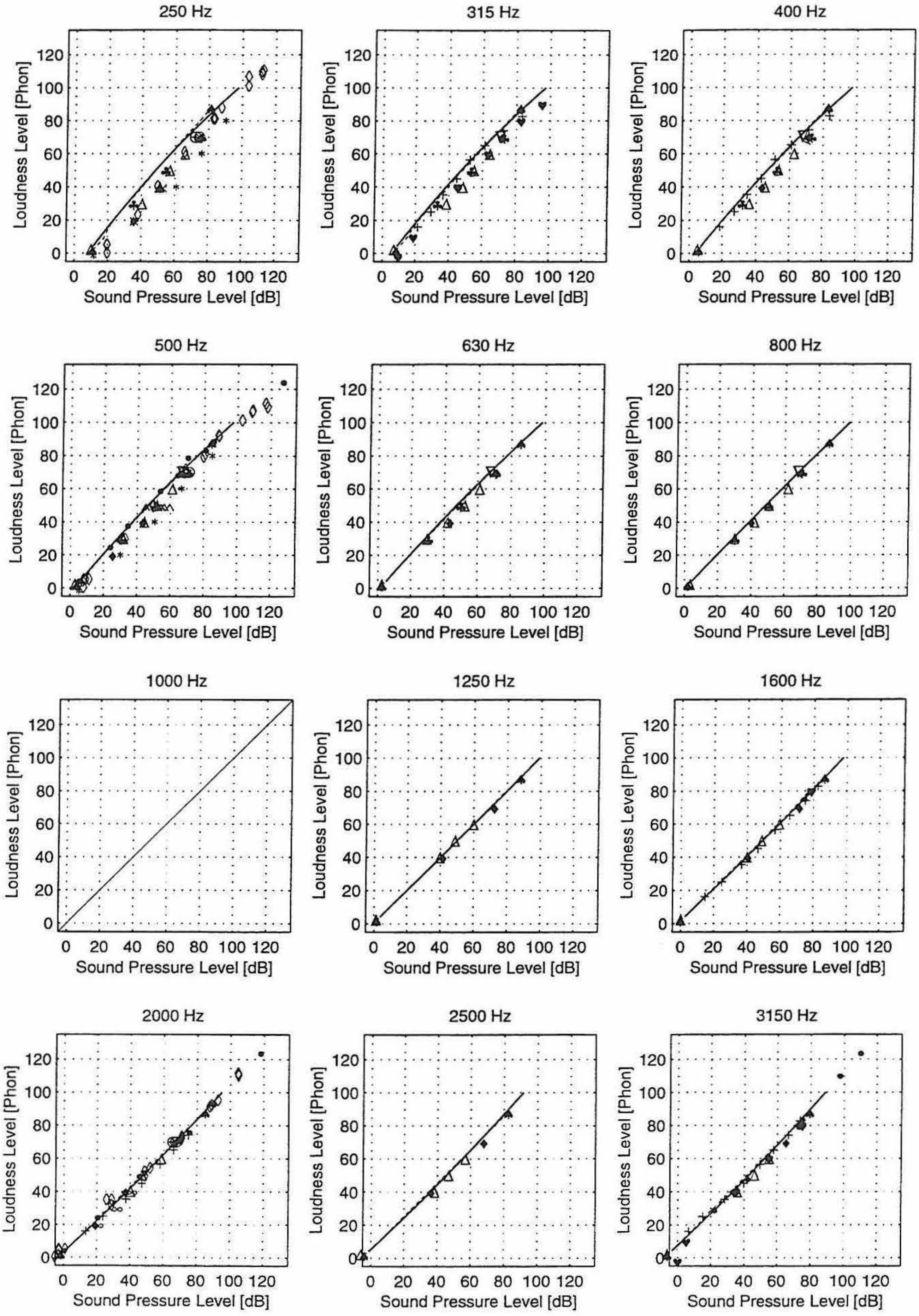
Figure 6

Loudness level versus frequency for fixed values of A-, B- and C-weighted sound pressure level at low, medium and high levels, respectively (calculated from ISO 226).

Figure 7 (following 3 pages)

Plot of literature data of loudness level versus sound pressure level (frequency by frequency). See text for data included.


16 Hz
20 Hz
25 Hz
32 Hz
40 Hz
50 Hz
63 Hz
80 Hz
100 Hz
125 Hz
160 Hz
200 Hz
Loudness Level [Phon]
Sound Pressure Level [dB]


250 Hz
315 Hz
400 Hz
500 Hz
630 Hz
800 Hz
1000 Hz
1250 Hz
1600 Hz
2000 Hz
2500 Hz
3150 Hz
Loudness Level [Phon]
Sound Pressure Level [dB]
0 20 40 60 80 100 120

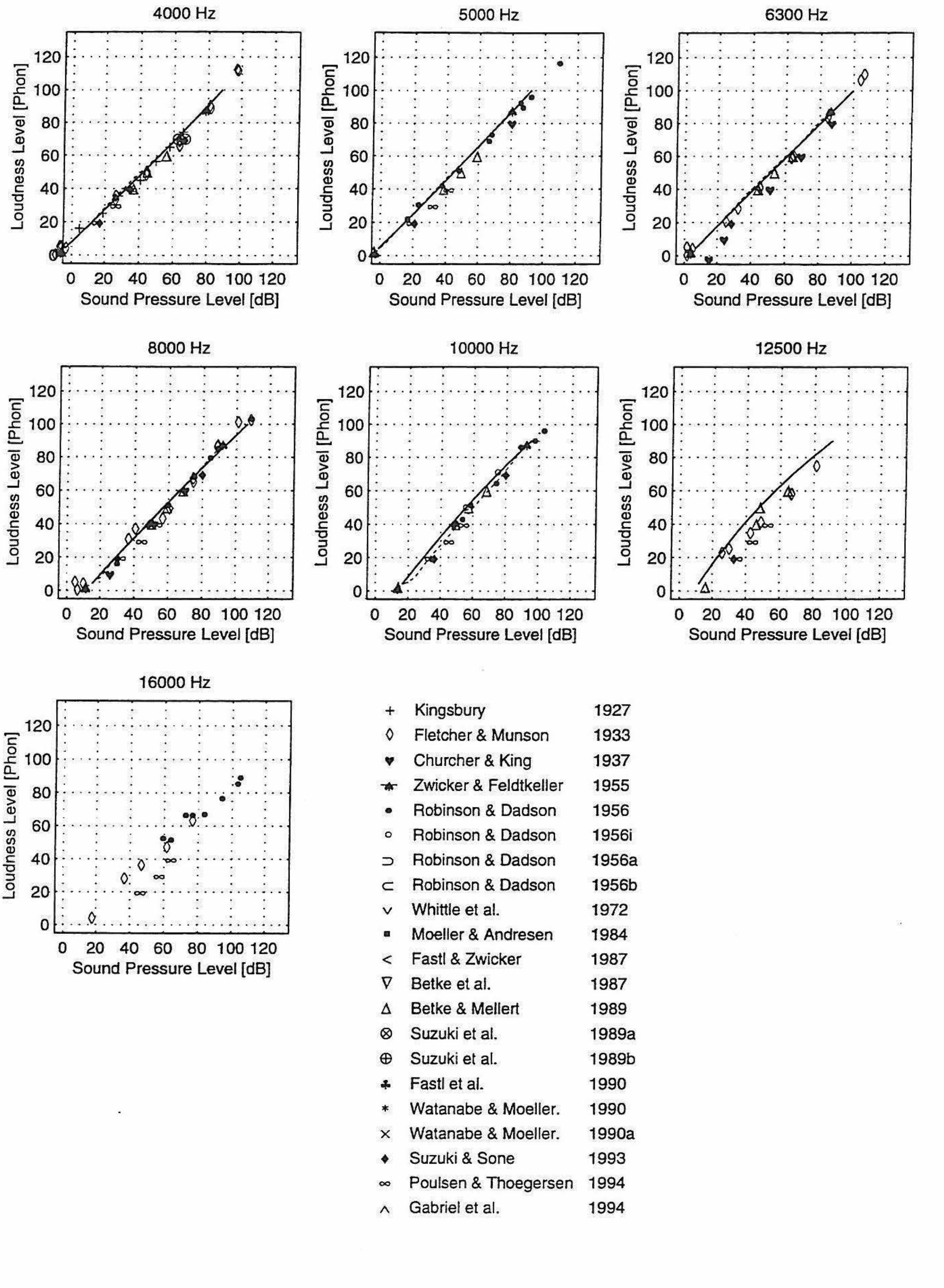
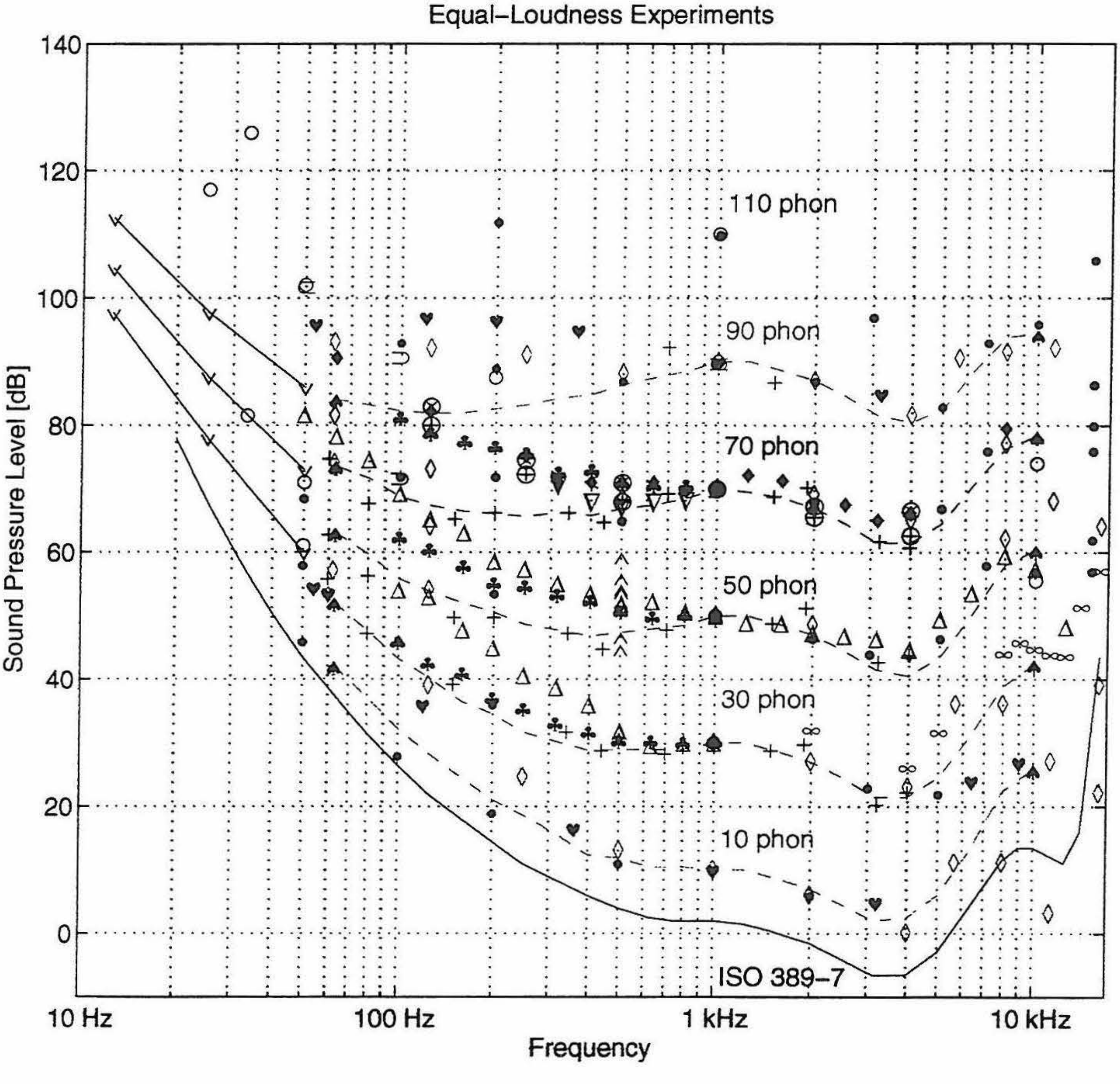
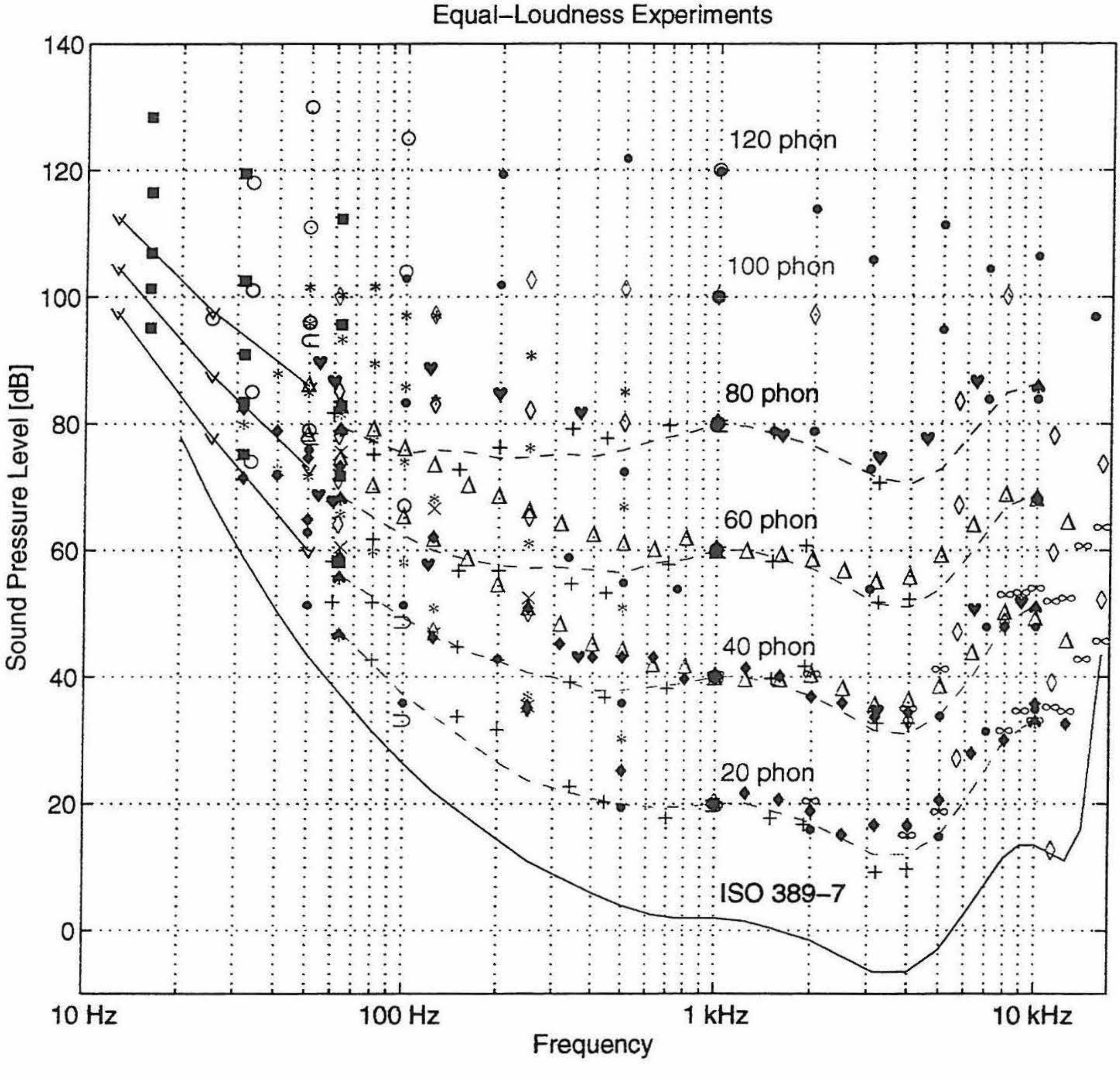

4000 Hz
5000 Hz
6300 Hz
8000 Hz
10000 Hz
12500 Hz
16000 Hz
Loudness Level [Phon]
Sound Pressure Level [dB]
0 20 40 60 80 100 120
+ Kingsbury 1927
◊ Fletcher & Munson 1933
♥ Churcher & King 1937
Zwicker & Feldtkeller 1955
• Robinson & Dadson 1956
o Robinson & Dadson 1956i
⊃ Robinson & Dadson 1956a
⊂ Robinson & Dadson 1956b
v Whittle et al. 1972
▪ Moeller & Andresen 1984
< Fastl & Zwicker 1987
∇ Betke et al. 1987
Δ Betke & Mellert 1989
⊗ Suzuki et al. 1989a
⊕ Suzuki et al. 1989b
♣ Fastl et al. 1990
* Watanabe & Moeller. 1990
× Watanabe & Moeller. 1990a
♦ Suzuki & Sone 1993
∞ Poulsen & Thoegersen 1994
∧ Gabriel et al. 1994

Figure 8 (following 2 pages)

Plot of literature data of equal loudness contours. See text for data included.


Equal-Loudness Experiments
Sound Pressure Level [dB]
140
120
100
80
60
40
20
0
110 phon
90 phon
70 phon
50 phon
30 phon
10 phon
ISO 389-7
10 Hz
100 Hz
1 kHz
10 kHz
Frequency


Equal–Loudness Experiments
140
120
100
80
60
40
20
0
Sound Pressure Level [dB]
120 phon
100 phon
80 phon
60 phon
40 phon
20 phon
ISO 389–7
10 Hz
100 Hz
1 kHz
10 kHz
Frequency

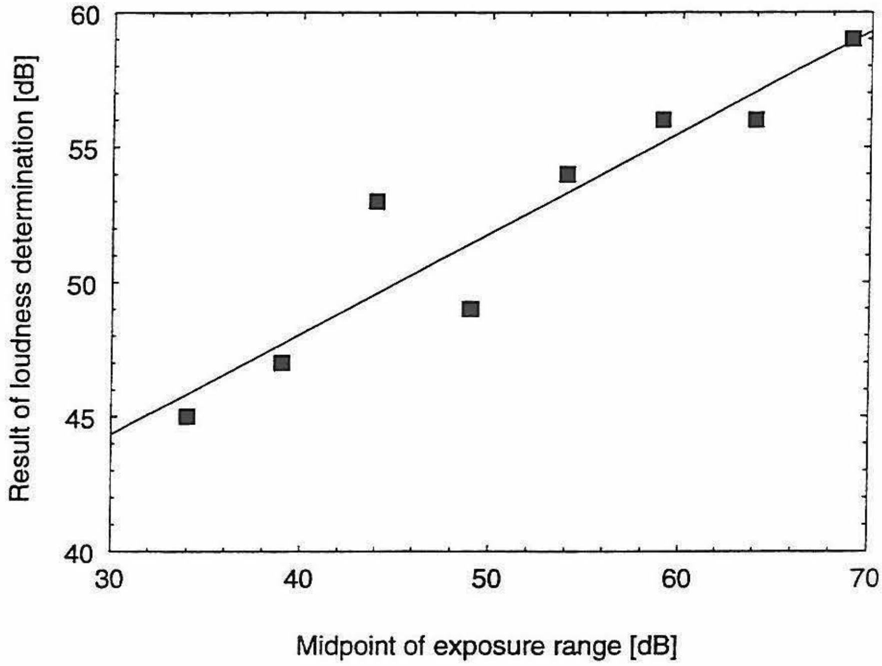


Figure 9

Loudness determination using the method of constant stimuli. The stimulus range is 30 dB for each of the points. The midpoint of the stimulus range is given as the abscissa, and the resulting point of equal loudness as the ordinate. Points indicate original observations, the line is a regression line. (Determination of 50 phon point at 500 Hz, data from Gabriel et al. [30]).

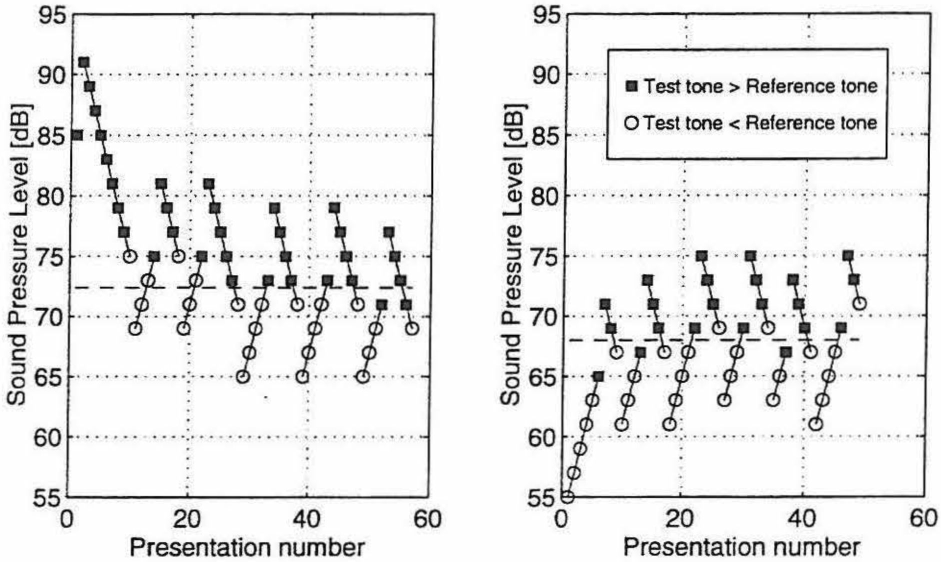


Figure 10

Example of two determinations of an equal loudness point using the bracketing method with a step-size of 2 dB. The starting point is much above the point of subjective equality in the left frame, whereas it is much below in the right frame. (Determination of a 50 phon point at 100 Hz, data from Lydolf et al. [34]).

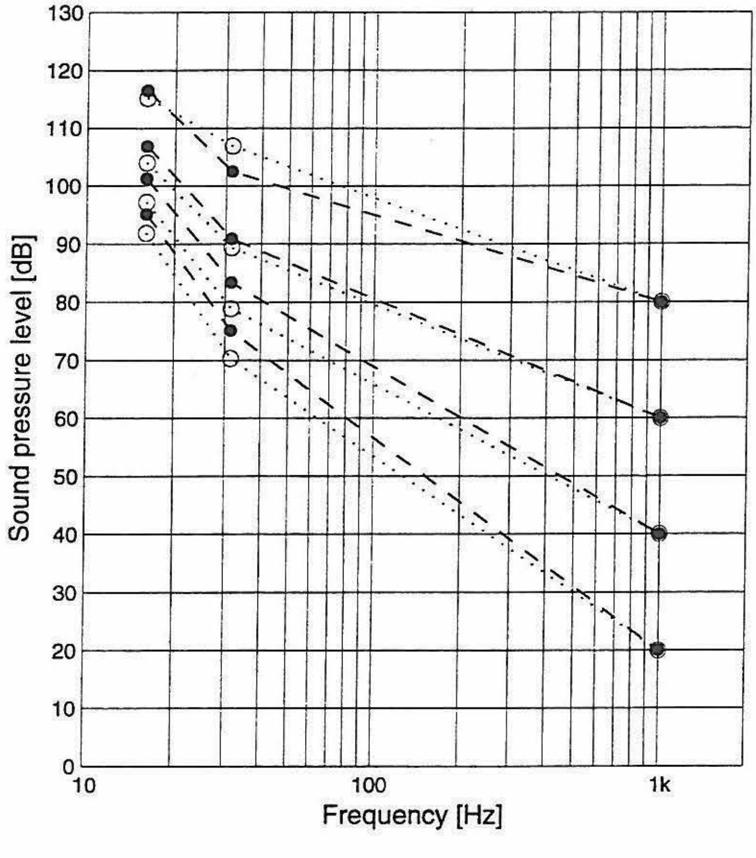


Figure 11

Equal loudness curves (filled circles, dashed line) and equal annoyance curves (unfilled circles, dotted line) as reported by Møller and Andresen [26] and Andresen and Møller [35], respectively.