Equal-loudness-level contours for pure tones[a)]

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Equal-loudness-level contours provide the foundation for theoretical and practical analyses of intensity-frequency characteristics of auditory systems. Since 1956 equal-loudness-level contours based on the free-field measurements of Robinson and Dadson [Br. J. Appl. Phys. **7**, 166–181 (1956)] have been widely accepted. However, in 1987 some questions about the general applicability of these contours were published [H. Fastl and E. Zwicker, Fortschritte der Akustik, DAGA '87, pp. 189–193 (1987)]. As a result, a new international effort to measure equal-loudness-level contours was undertaken. The present paper brings together the results of 12 studies starting in the mid-1980s to arrive at a new set of contours. The new contours estimated in this study are compared with four sets of classic contours taken from the available literature. The contours described by Fletcher and Munson [J. Acoust. Soc. Am. **5**, 82–108 (1933)] exhibit some overall similarity to our proposed estimated contours in the mid-frequency range up to 60 phons. The contours described by Robinson and Dadson exhibit clear differences from the new contours. These differences are most pronounced below 500 Hz and the discrepancy is often as large as 14 dB.
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I. INTRODUCTION

The loudness of a sound strongly depends on both the sound intensity and the frequency spectrum of a stimulus. For sounds such as a pure tone or a narrow-band noise, an equal-loudness-level contour can be defined. This contour represents the sound pressure levels of a sound that give rise to a sensation of equal-loudness magnitude as a function of sound frequency. The equal-loudness-level contours are so foundational that they are considered to reveal the frequency characteristics of the human auditory system.

Many attempts have been made to determine equal-loudness-level contours spanning the audible range of hearing. The earliest measurements of equal-loudness-level contours were reported by Kingsbury (1927). Those measurements were obtained under monaural listening conditions and were relatively limited. Although equal-loudness relations can be measured in a free field, in a diffuse field, and under earphone listening conditions, most of the published equal-loudness-level contours have been measured either under binaural listening conditions or under conditions relative to a free field. The first complete set of equal-loudness-level contours obtained under binaural listening conditions and given relative to free-field listening was made by Fletcher and Munson (1933). Their pioneering study was followed by studies measuring contours by Churcher and King (1937), Zwicker and Feldtkeller (1955), and Robinson and Dadson (1956). The contours measured by Robinson and Dadson (1956) were adopted as an international standard for pure tones heard under free-field listening conditions (ISO/R 226, 1961; ISO 226, 1987); they have been widely accepted.

In recent years there has been renewed interest in equal-loudness-level contours. This interest was triggered by a report from Fastl and Zwicker (1987) who noted marked departures from the contours specified by Robinson and Dadson (1956) in the region near 400 Hz. Subsequently, the deviations found by Fastl and Zwicker (1987) have been confirmed by many investigators (Betke and Mellert, 1989; Suzuki *et al.*, 1989; Fastl *et al.*, 1990; Watanabe and Møller, 1990; Poulsen and Thøgersen, 1994; Lydolf and Møller, 1997; Takeshima *et al.*, 1997; Bellmann *et al.*, 1999; Takeshima *et al.*, 2001, 2002). Specifically, all of the new data show that at frequencies below about 800 Hz equal-loudness levels are higher than the levels measured by Robinson and Dadson (1956); one example of this is the level differences of loudness levels of 40 phons which record differences from 12.7 to 20.6 dB at the frequency of 125 Hz. Figure 1 illustrates the extent of this discrepancy. Here the 40-phon contour measured by Robinson and Dadson (1956) is compared with data obtained from recent studies. Clearly, in the low-frequency region all the newer data deviate systematically from the equal-loudness-level contour based on Robinson and Dadson's data. Possible causes of the difference are discussed in Sec. IV. Such marked deviations are not only of theoretical importance, they also have practical implications. For example, the current A-weighting for sound level meters is based on the equal-loudness-level contour at 40 phons.

[a)]Portions of this article were presented at InterNoise 2000 in Nice, France, August 2000 [Suzuki *et al.*, Proc. InterNoise 2000, pp. 3664–3669 (2000)] and the 143rd Meeting of the Acoustical Society of America in Pittsburgh, PA, June 2002 [Y. Suzuki and H. Takeshima, J. Acoust. Soc. Am. **111**(5) Pt. 2, 2468 (2002)].
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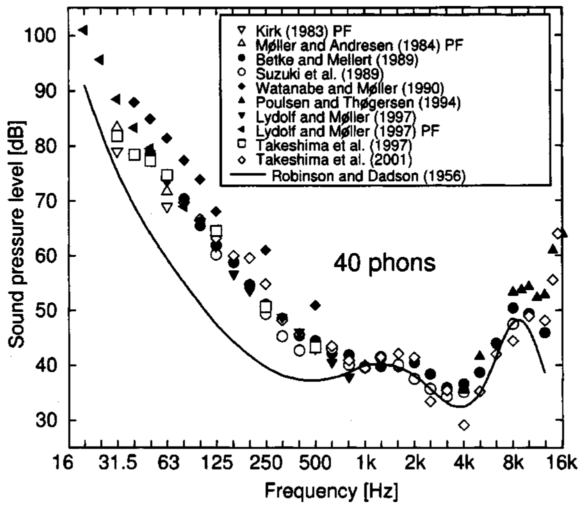

FIG. 1. Equal-loudness-level contour of 40 phons for pure tones. The solid lines represent the contour measured by Robinson and Dadson (1956), which were adapted as an international standard, ISO R/226 (1961) and ISO 226 (1987). Symbols show the experimental data collected since 1983.

Given the marked and consistent deviations obtained by the newer data, an attempt has been made to establish a new set of equal-loudness-level contours. Section II of this paper provides a brief review of equal-loudness relations measured for pure tones. Data from this overview are analyzed and evaluated to help establish new equal-loudness-level contours. The results are compared with those reported in four classic studies (Fletcher and Munson, 1933; Churcher and King, 1937; Zwicker and Feldtkeller, 1955; Robinson and Dadson, 1956). In Sec. III a new set of equal-loudness-level contours that span a wide range of frequencies and levels is introduced. A loudness function that provides a good account of the data (Takeshima *et al.*, 2003) is utilized. In this paper, we focus on contours for pure tones under free-field listening conditions that represent the average judgment of otologically normal persons.

II. A BRIEF REVIEW OF STUDIES OF EQUAL-LOUDNESS-LEVEL CONTOURS AND THRESHOLDS OF HEARING

A. Equal-loudness-level contours

This section gives an overview of all published studies of equal-loudness-level contours. Our analysis provides a basis for selecting basic data to use for constructing a new set of equal-loudness-level contours. Table I lists 19 studies in chronological order.

Although our aim is to establish new equal-loudness-level contours under free-field listening conditions, in several studies equal-loudness levels at low frequencies were measured in a pressure field obtained by using a small room installed with a number of loudspeakers on each of the walls and the ceiling. These loudspeakers are driven in phase so

TABLE I. Studies on the equal-loudness-level contours and their important experimental conditions. FF: free field, PF: pressure field, MA: method of adjustment, CS: method of constant stimuli, RMLSP: randomized maximum likelihood sequential procedure (Takeshima *et al.*, 2001), and CP: category partitioning procedure.

Year	Researchers	Listening condition	No. of subjects (age)	Method	Reference tone frequency (level)	Test tone frequency (Hz)
1927	Kingsbury	Earphone	22 (unspecified)	MA	700 Hz (fix)	60–4000
1933	Fletcher–Munson	Earphone with FF correction	11 (unspecified)	CS	1 kHz (variable)	62–16 000
1937	Churcher–King	FF	10 (unspedified)	CS	1 kHz (fix)	54–9000
1955	Zwicker–Feldtkeller	Earphone with FF equalizer	8 (unspecified)	Modified Békésy	1 kHz (fix)	50–16 000
1956	Robinson–Dadson	FF	90 (16–63)/ 30 (ave. 30)	CS	1 kHz (variable)	25–15 000
1972	Whittle *et al.*	PF	20 (ave. 20)	CS	higher freq. (fix)	3.15–50
1983	Kirk	PF	14 (18–25)	RMLSP	63 Hz (fix)	2–63
1984	Møller–Andresen	PF	20 (18–25)	RMLSP	63 Hz (fix)	2–63
1989	Betke–Mellert	FF	13–49 (17–25)	CS	1 kHz (fix)	50–12 500
1989	Suzuki *et al.*	FF	9–32 (19–25)	CS	1 kHz (fix)	31.5–16 000
1990	Fastl *et al.*	FF	12 (21–25)	CS	1 kHz (fix)	100–1000
1990	Watanabe–Møller	FF	10–12 (18–30)	Bracketing	1 kHz (fix)	25–1000
1994	Müller–Fichtl	Open headphones	8 (21–25)	CP	—	62.5–10 000
1994	Poulsen–Thøgersen	FF	29 (18–25)	Bracketing	1 kHz (fix)	1000–16 000
1997	Lydolf–Møller	FF	27 (19–25)	RMLSP	1 kHz (fix)	50–1000
		PF	27 (19–25)	RMLSP	100 Hz (fix)	20–100
1997	Takeshima *et al.*	FF	9–30 (19–25)	CS	1 kHz (fix)	31.5–12 500
1999	Bellmann *et al.*	FF	12 (unspecified)	Adaptive 1up–1down	1 kHz (fix)	100–1000
		PF	12 (unspecified)	Adaptive 1up–1down	100 Hz (fix)	16–160
2001	Takeshima *et al.*	FF	7–32 (18–25)	RMLSP	1 kHz (fix)	50–16 000
2002	Takeshima *et al.*	FF	21 (20–25)	RMLSP	1 kHz (fix)	1000–12 500

that no energy could flow in the room. They are Whittle *et al.* (1972), Kirk (1983), Møller and Andresen (1984), Lydolf and Møller (1997), and Bellmann *et al.* (1999). These studies are also included in Table I because at frequencies lower than a few hundred Hertz equal-loudness levels of pure tones measured in a free field are consistent with those measured in a pressure field (Lydolf and Møller, 1997).

Of the 19 studies listed in Table I, we suggest that three studies (Kingsbury, 1927; Whittle *et al.*, 1972; Müller and Fichtl, 1994) be excluded as candidates for the basic data. Kingsbury (1927) measured equal-loudness levels under monaural listening conditions with a telephone receiver. However, the levels measured were not calibrated relative to the levels in a free field. Although Whittle *et al.* (1972) made their measurements in a pressure field, equal-loudness levels at 3.15, 6.3, 12.5, and 25 Hz were obtained with reference tones set at 6.3, 12.5, 25, and 50 Hz. No comparison was made to a 1-kHz reference tone. As a result of this shortcoming, the equal-loudness levels they measured cannot be expressed directly in phons. Finally, in Müller and Fichtl (1994) the loudness of the pure tones was based on the category partitioning procedure. In this procedure, loudness was judged by two successive scalings. First, subjects judge loudness by choosing from seven categories ranging from ''nothing heard'' to ''painfully loud.'' Then when a subject chose one of the six categories other than ''nothing heard,'' the same stimulus was presented once more and the subject was asked to judge the loudness on a more finely subdivided scaling which consisted of five steps for the ''painfully loud'' category and ten steps for the other five ''middle'' categories from ranging ''very soft'' to ''very loud.'' Using this technique, the loudness of a pure tone is recorded as an integer ranging from 0 (nothing heard) to 55 (painfully loud). Equal-loudness-level contours are based on these categorized loudness-related values. Unfortunately, category-scaling procedures are easily influenced by context effects such as stimulus spacing, frequency of stimulus presentation, stimulus range, and stimulus distribution (Gescheider, 1997). The degree of these context effects cannot be assessed because no paired-comparison data were obtained.

Figure 2 shows the equal-loudness-level data from the studies listed in Table I excluding the results of Kingsbury (1927), Whittle *et al.* (1972), and Müller and Fichtl (1994). Four studies, Fletcher and Munson (1933), Churcher and King (1937), Zwicker and Feldtkeller (1955), and Robinson and Dadson (1956), proposed a complete set of equal-loudness-level contours whereas the remaining studies reported only measured equal-loudness levels. Results from the individual studies are given by the symbols; the curves represent the four sets of equal-loudness-level contours. Owing to their importance, these four sets of contours are referred to as *classic* equal-loudness-level contours, whereas the studies published since 1983 are referred to as *recent* experimental data.

In spite of some differences among the results of the various studies, Fig. 2 makes it clear that most of the *recent* data sets exhibit similar trends. By comparison, none of the four sets of *classic* contours coincide acceptably over the whole range of frequencies and levels with the recent data. The four sets of *classic* contours show both similarity and dissimilarity to these data sets. Thus the *recent* data are compared with the *classic* contours more in detail. It is notable that the three sets of *classic* contours apart from that of Robinson and Dadson (1956) agree remarkably well with the *recent* data at 20 phons. Moreover, the agreement between the *recent* data and the *classic* contours of Fletcher and Munson (1933) is quite good at 60 phons and below; at higher loudness levels the contours of Fletcher and Munson (1933) become progressively flatter than the *recent* data value. At the 100-phon level the difference at 25 Hz amounts to 30 dB. Between 60 and 90 phons the *classic* contours of Churcher and King (1937) and Zwicker and Feldtkeller (1955) also tend to be flatter in the low-frequency region than the *recent* data values. Another conflict between the *recent* data and the *classic* contours of Zwicker and Feldtkeller (1955) is evident at 4 kHz. In this frequency region, the contours of Zwicker and Feldtkeller (1955) are inconsistent with both the *recent* data and the other three *classic* contours. Unlike all the other studies, the contours reported by Zwicker and Feldtkeller (1955) do not exhibit a dip in the 4-kHz region. Finally, in the low-frequency region below 1 kHz almost all of the *recent* data are located well above the contours proposed by Robinson and Dadson (1956). Moreover, between 20 and 80 phons the differences are often greater than 14 dB. Based on these observations, it is clear that the discrepancies both among the *classic* contours and between the *classic* contours and the *recent* data can be considered non-negligible and systematic. Consequently, we decided to use the *recent* data to estimate a new set of equal-loudness-level contours. We would then be able to critically compare the classic and new equal-loudness levels as contours.

The *recent* data show certain variance among the studies. The most marked discrepancies can be seen in the data by Fastl *et al.* (1990). The deviations are most pronounced at the 30- and 50-phon levels (filled squares). A possible explanation for the deviation between these results and our estimated contours can be found in the results of Gabriel *et al.* (1997) and Takeshima *et al.* (2001). These latter studies showed that when the method of constant stimuli is used a strong range effect may bias the results toward the central level of the variable stimuli. In the study by Fastl *et al.* (1990) the central levels were set to the equal-loudness-level contours calculated by Zwicker (1958): At 125 Hz the central levels applied by Fastl *et al.* (1990) were 40.2 dB at 30 phons, 57.6 dB at 50 phons, and 76.5 dB at 70 phons. These levels are considerably lower than the loudness levels in the other *recent* studies. Another data set that requires closer scrutiny is the one obtained from the results of Watanabe and Møller (1990). According to Møller and Lydolf (1996) this data (filled diamonds) may have been biased towards higher sound pressure levels because, in the bracketing procedure used, the initial level was invariably set at 15 to 20 dB above the expected equal-loudness levels reported by Robinson and Dadson (1956). Despite these caveats, the data from the two studies do not show extreme variation from the other *recent* data. We therefore decided to include all of the *recent* data in the determination of a new set of equal-loudness-level contours.

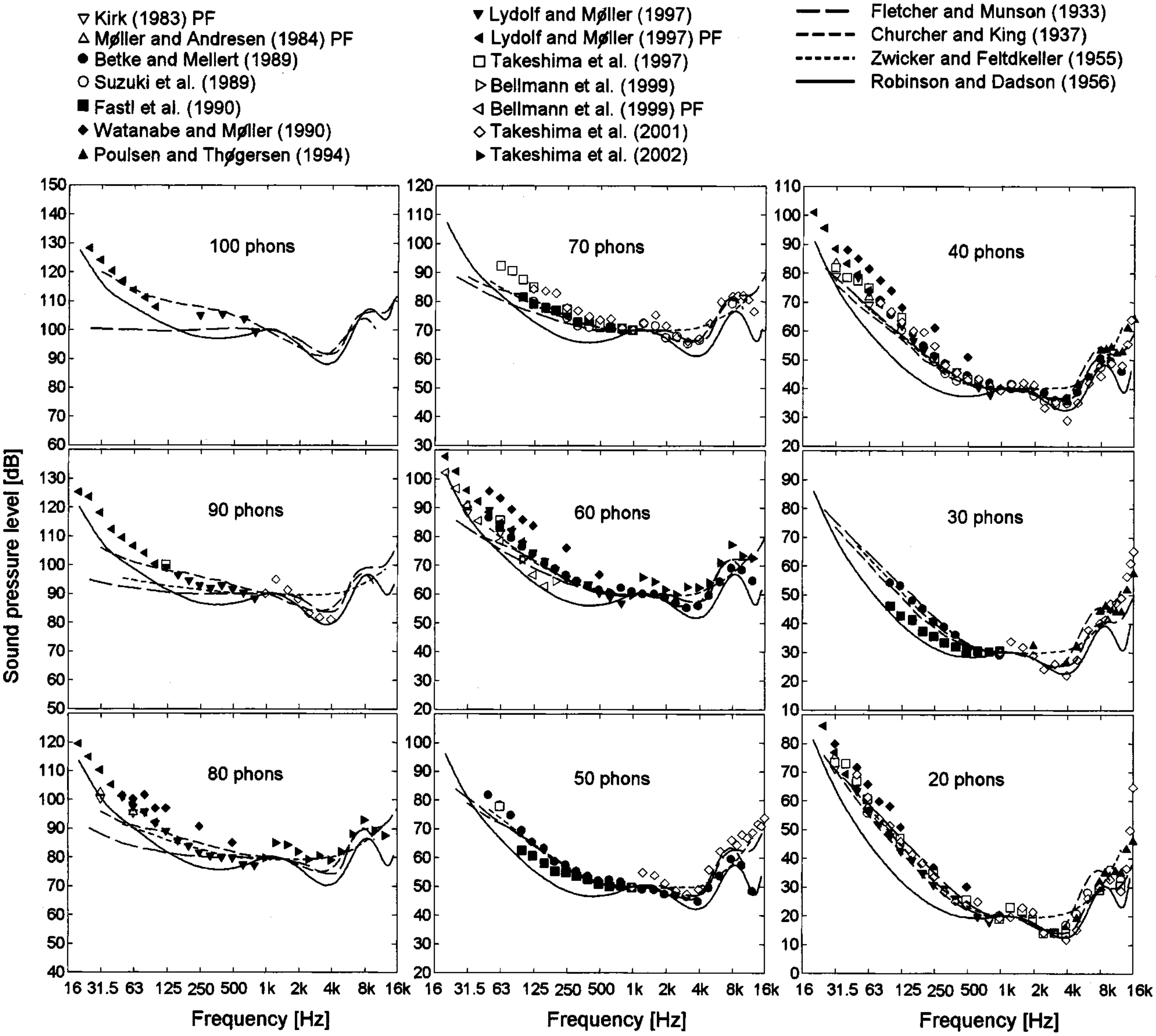

FIG. 2. Equal-loudness-level contours for pure tones. The four lines in each panel represent the contour reported by Fletcher and Munson (1933), by Churcher and King (1937), by Zwicker and Feldtkeller (1955), and by Robinson and Dadson (1956). The symbols are the experimental data of the *recent* studies reported since 1983. In the legend, PF means that the study was carried out under pressure-field listening condition.

B. Threshold of hearing

It is natural to draw a hearing threshold curve as a lower limit of audibility on a figure of equal-loudness-level contours; the threshold of hearing is also useful in estimating the new equal-loudness-level contours described in the following sections. Table II lists studies of the threshold of hearing for pure tones in chronological order. In most of the studies listed in Table II, equal-loudness relations were measured at the same time and are thus also listed in Table I. Studies other than those listed in Table I are Teranishi (1965), Brinkmann (1973), Vorländer (1991), Betke (1991), Takeshima *et al.* (1994), and Poulsen and Han (2000). The data concerning the threshold of hearing from all of the studies listed in Table II are shown in Fig. 3. In the figure, threshold curves reported with the four sets of *classic* equal-loudness-level contours are also drawn. It should be noted, however, that the curve of the threshold of hearing is not always regarded as an equal-loudness-level contour (Fletcher and Munson, 1933; Hellman and Zwislocki, 1968; Buus *et al.*, 1998).

As seen from Fig. 3, the data concerning the threshold of hearing are similar across the recent studies and fit well with the threshold curve of Robinson and Dadson (1956) while the other three curves, Fletcher and Munson (1933), Churcher and King (1937), and Zwicker and Feldtkeller (1955), deviate from the recent threshold data and the curve by Robinson and Dadson (1956) under 1 kHz.

III. DERIVATION OF A NEW SET OF EQUAL-LOUDNESS-LEVEL CONTOURS

The review carried out in Sec. II clearly indicates that a new set of equal-loudness-level contours needs to be drawn. The experimental measures of the equal-loudness relation reported in the 12 *recent* studies are given in Fig. 2 as discrete points along the frequency and sound pressure level axes. If the equal-loudness-level contours are drawn simply, by using a smoothing function across frequency at each loudness level, then the contours do not exhibit an acceptable pattern of parallel displacement. To achieve that goal, the smoothing

TABLE II. Studies on the threshold of hearing for pure tones under free-field listening condition and their important experimental conditions. (FF: free field, PF: pressure field)

Year	Researchers	Listening condition	No. of subjects (age)	Method	Frequency range (Hz)
1927	Kingsbury	Earphone	22 (unspecified)	unspecified	60–4000
1933	Fletcher–Munson	Earphone with FF correction	11 (unspecified)	Bracketing method	62–16 000
1937	Churcher–King	FF	10 (unspecified)	unspecified	54–6400
1955	Zwicker–Feldtkeller	Earphone with FF equalizer	8 (unspecified)	Békésy tracking	50–16 000
1956	Robinson–Dadson	FF	51 (ave. 20)[a]	Bracketing method	25–15 000
1965	Teranishi	FF	11 (18–24)[b]	Bracketing method	63–10 000
1973	Brinkmann	FF	9–56 (18–30)	Bracketing method	63–8000
1989	Suzuki *et al.*	FF	31 (19–25)	Bracketing method	63–12 500
1990	Fastl *et al.*	FF	12 (21–25)	Ascending method	100–1000
1990	Watanabe–Møller	FF	12 (18–30)	Bracketing method	25–1000
1991	Betke	FF	16–49 (18–25)	Bracketing method	40–15 000
1991	Vorländer	FF	31 (18–25)	Bracketing method	1000–16 000
1994	Poulsen–Thøgersen	FF	29 (18–25)	Bracketing method	1000–16 000
1994	Takeshima *et al.*	FF	10–30 (19–25)[c]	Bracketing method	31.5–16 000
1997	Lydolf–Møller	FF	27 (19–25)	Ascending method	50–8000
		PF	27 (19–25)	Ascending method	20–100
2000	Poulsen–Han	FF	31 (18–25)	Bracketing method	125–16 000
2001	Takeshima *et al.*	FF	7–32 (18–25)	Bracketing method	31.5–16 000
2002	Takeshima *et al.*	FF	21 (20–25)	Bracketing method	1000–12 500

[a]120 subjects below 2000 Hz.
[b]51 subjects with wide range of age (18–64 years old) participated in his experiments.
[c]Excluding the results of the experiments (EX1 and EX2) which have been reported in Suzuki *et al.* (1989).

process must be performed in a two-dimensional plane that takes into account both the frequency and sound pressure level axes. Fletcher and Munson (1933) produced functions for their discrete data values by first plotting the measured relation between loudness level and sound pressure level at each of their ten test frequencies and then fitting a smooth curve to each of the measured data sets. The ten data sets enabled a family of equal-loudness-level contours to be drawn. Based on the presumption that the equal-loudness-level contours were related to the underlying hearing mechanism, Fletcher and Munson (1933) hypothesized that these contours should be smooth and parallel. Robinson and Dadson (1956) applied a similar approach to the analysis of their data values. They used a second-order polynomial fit to obtain the relations between loudness level and sound pressure level at each of their 13 test frequencies.

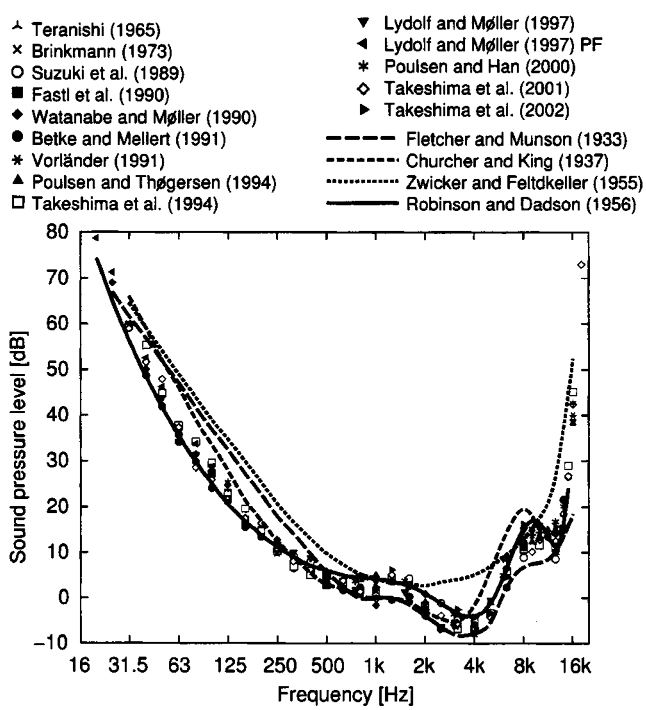

FIG. 3. Thresholds of hearing for pure tones. The four lines represent the threshold curve reported by Fletcher and Munson (1933), by Churcher and King (1937), by Zwicker and Feldtkeller (1955), and by Robinson and Dadson (1956). In the legend, PF means that the study was carried out under pressure-field listening condition.

In the present study, equal-loudness-level contours are obtained by making use of the established loudness-intensity relation, a compressive relation shown to be approximately compatible with recent measures of the nonlinear input–output response of the basilar membrane (Schlauch *et al.*, 1998; Yates, 1990; Florentine *et al.*, 1996; Buus and Florentine, 2001a,b). Our procedure makes it possible to parametrically derive a set of equal-loudness-level contours over the measured range of loudness levels from 20 to 100 phons.

A. Loudness functions suitable for representing the equal-loudness relation

At moderate to high sound pressure levels, the growth of loudness is well approximated by Stevens's (1953, 1957) power law in the form

$$S = ap^{2\alpha}, \tag{1}$$

where p is the sound pressure of a pure tone, a is a dimensional constant, α is the exponent, and S is the perceived loudness. However, Stevens's power law cannot describe the deviation of the loudness function from power-law behavior below about 30 dB HL (see, e.g., Hellman and Zwislocki, 1961; Scharf and Stevens, 1961). As a result, several modifications of Stevens's power law have been proposed. In the late 1950s a number of authors (Ekman, 1959; Luce, 1959; Stevens, 1959) suggested that the power law could be rewritten in the form

$$S=a(p^2-p_t^2)^{\alpha}, \tag{2}$$

where p_t is the threshold of hearing in terms of sound pressure. Later on, Zwislocki and Hellman (1960) and Lochner and Burger (1961) also proposed modifications. In these latter modifications, the relation between loudness and sound pressure is given by the equation

$$S=a(p^{2\alpha}-p_t^{2\alpha}). \tag{3}$$

The difference between Eqs. (2) and (3) lies in the domain where the subtraction is executed. In Eq. (2) a constant corresponding to the threshold is subtracted in the stimulus domain, whereas in Eq. (3) a constant corresponding to the threshold loudness is subtracted in loudness domain (Hellman, 1997). When $p=p_t$, both Eqs. (2) and (3) yield a threshold loudness of zero.

Zwicker (1958) considered that a power law stands between the sum of the excitation evoked by a sound and the internal noise and the sum of the specific loudness of the sound and the internal noise. By solving this equation, he derived the following specific loudness function:

$$S=a\{(p^2+Cp_t^2)^{\alpha}-(Cp_t^2)^{\alpha}\}, \tag{4}$$

where C is the noise-to-tone energy ratio required for a just detectable tone embedded in the internal masking noise. In 1965 Zwislocki introduced the internal noise into Eq. (3), resulting in a function that predicts the total loudness of a pure tone in quiet and in noise. The form of Zwislocki's (1965) equation for loudness functions is similar to the one obtained for the specific loudness function in Eq. (4). Unlike Eqs. (2) and (3), the threshold loudness given by Eq. (4) is greater than zero.

Zwicker and Fastl (1990) further modified Eq. (4) to set the loudness at threshold to be zero, resulting in the following equation for specific loudness function:

$$S=a[\{p^2+(C-1)p_t^2\}^{\alpha}-(Cp_t^2)^{\alpha}]. \tag{5}$$

Above 30 dB HL, the modifications in Eqs. (2)–(5) asymptotically approach Stevens's power law in Eq. (1). However, none of the equations describe the mid-level flattening claimed in recent studies of loudness growth (Allen and Neely, 1997; Neely and Allen, 1997; Buus and Florentine, 2001a,b), but they are probably sufficiently precise for present purposes and have the advantage of having few free parameters to fit.

Takeshima *et al.* (2003) examined which loudness function is the most appropriate to describe the equal-loudness relation between two pure tones with different frequencies. First, they measured equal-loudness levels of 125-Hz pure tone from 70 phons down to 5 phons. Then fitted the experimental data to the above-mentioned five loudness functions. Figure 4 shows the results (Takeshima *et al.*, 2003). Equations (1) and (2) clearly showed poorer performances. The

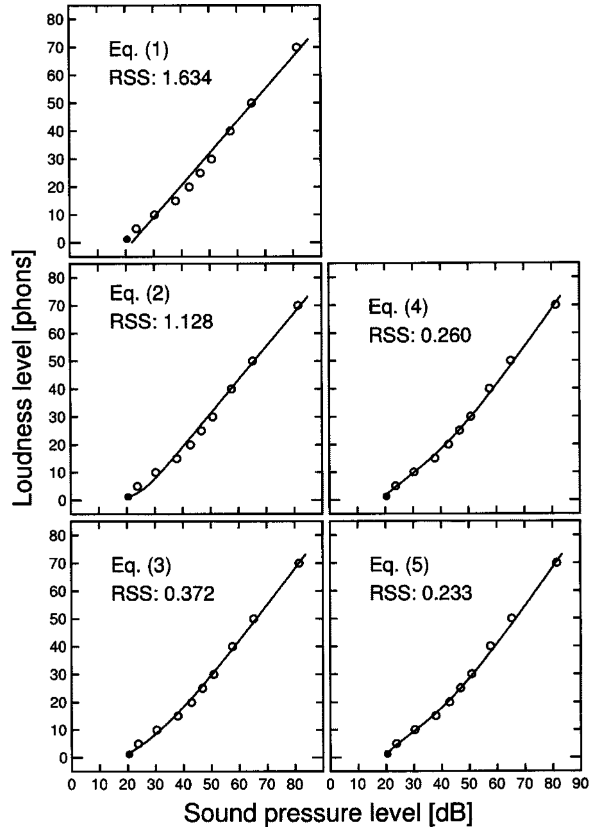

FIG. 4. Equal-loudness-relation curves derived from Eqs. (1) and (5), respectively. Open circles in each panel show equal-loudness levels of 125-Hz pure tones measured by the randomized maximum likelihood sequential procedure. The solid lines in each panel are the best fitting curves of each loudness function to the experimental data. RSS means the residual sum of squares in the fitting process of the nonlinear least squares method. This figure is a reprinting of Fig. 2 in Takeshima *et al.* (2003).

other three were well able to explain the equal-loudness relation down to 5 phons. The goodness of fit for these three functions did not differ significantly. Takeshima *et al.* (2003) further concluded that the number of parameters of Eq. (3) is less than the other two and free from the estimation of the parameter C, which represents the level of the intrinsic noise which suggests Eq. (3) is the most appropriate for present purposes. Since estimation of C is often unstable in the fitting of the three parameters with the available data, estimation of equal-loudness contours with Eq. (4) or (5) would be extremely problematic.

When loudness growth is expressed by use of Eq. (3), the following limitation should be noted. Equation (3) assumes the loudness at threshold of hearing to be zero. This is inconsistent with experimental data where the loudness at threshold of hearing is not zero (e.g., Hellman and Zwislocki, 1961, 1964; Hellman and Meiselman, 1990; Hellman, 1997; Buus *et al.*, 1998). Moreover, loudness at threshold is not zero but dependent on frequency as shown in the data of Hellman and Zwislocki (1968), Hellman (1994), and Buus and Florentine (2001a). Equation (4), and among the five only this equation, can account for these experimental results. However, as mentioned above, the fitting of this equation in our preliminary examination often resulted in unstable estimation. As seen from Fig. 4, Eqs. (3) and (4) resemble each other and acceptably coincide at and above 10 phons and we are encouraged that the fitting to Eq. (3) was quite stable. Furthermore, experimental data for the equal-loudness levels are available only at and above 20 phons. Therefore, in the present study, we adopt Eq. (3) for further consideration.

B. Derivation of equations describing the equal-loudness relation

As noted above in Sec. III A, Eq. (3) is used for the loudness function. Here, the authors assume that a and α are dependent on frequency since this makes the residual sum of squares in the fitting process much less than with a constant a and α. Thus, over the loudness ranges of interest the terms a and α in Eq. (3) at frequency f are denoted as a_f and α_f. When the loudness of an f-Hz comparison tone is equal to the loudness of a reference tone at 1 kHz with a sound pressure of p_r, then the sound pressure of p_f at the frequency of f Hz is given by the following function:

$$p_f^2=\frac{1}{U_f^2}\{(p_r^{2\alpha_r}-p_{rt}^{2\alpha_r})+(U_f p_{ft})^{2\alpha_f}\}^{1/\alpha_f}, \tag{6}$$

where suffixes r and f indicate that the parameters denote the sound pressure for the 1-kHz reference tone and the f-Hz comparison tone, respectively. Moreover, $U_f=(a_f/a_r)^{1/2\alpha_f}$. Obviously, U_f is unity at the reference frequency (1 kHz).

An equal-loudness-level contour for a specific p_r can be drawn by connecting p_f as a function of frequency, if the frequency-dependent parameters, α_f and U_f, are given. To do this, the value of α_r, the exponent of the loudness function at 1 kHz, is a prerequisite. Many investigators have reported that for a 1-kHz tone the exponent in Stevens's power law has a value of about 0.3 for sound intensity (e.g., Fletcher and Munson, 1933; Stevens, 1957, 1959; Robinson, 1957; Feldtkeller *et al.*, 1959; Hellman and Zwislocki, 1961, 1963; Hellman, 1976; Humes and Jesteadt, 1991; Lochner and Burger, 1961; Rowley and Studebaker, 1969; Scharf and Stevens, 1961; Zwislocki, 1965). Fletcher (1995) examined results from several studies based on the doubling and halving of loudness, tenfold magnification and reduction, and the multi-tone method. As a result, a value of 0.33 was proposed. Stevens (1955) examined available data measured with various methods at that time and suggested 0.3 as the median of the data. Robinson (1953) measured this exponent based on doubling and halving loudness and tenfold magnification and reduction. He derived a value of 0.29 but later, in 1957, he adjusted the central tendency and order effect and obtained a slightly corrected value of 0.30 (Robinson, 1957). The typical exponent value obtained by the AME method is 0.27 (Hellman and Zwislocki, 1961, 1963; Lochner and Burger, 1961; Rowley and Studebaker, 1969; Hellman, 1976). In 1963, Hellman and Zwislocki reconfirmed this value by a combination of magnitude estimation and magnitude production (Hellman and Zwislocki, 1963). Zwicker denoted the value for the 1-kHz tone as 0.3 (Zwicker and Fastl, 1990) based on an experiment with doubling and halving loudness (Zwicker, 1963).

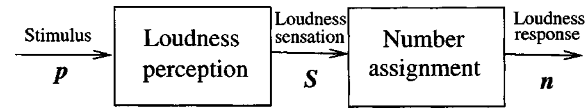

FIG. 5. A block diagram of a model for the loudness rating process.

The meaning behind this exponent derived from the method of magnitude estimation and production and exponents derived from other methods such as doubling and halving loudness based on the additivity of loudness may be different. Atteneave (1962) argued that there are two different processes used in absolute magnitude estimation (AME) for assessing the functional relation between assigned numbers and the corresponding perceived magnitudes (i.e., loudness) of a tone presented at a certain sound pressure level. One process was denoted as a ''loudness perception process'' and the other was as a ''number assignment process'' (Fig. 5). In addition, Atteneave (1962) proposed a two-stage model in which the outputs of both processes are described by separate power transformations. This idea is important in estimating the appropriate values for the exponent α in the loudness function. According to this model, the exponent observed in psychophysical experiments must be the product of the exponents of the two underlying processes. This two-stage model was used successfully by Zwislocki (1983) and by Collins and Gescheider (1989) to account for loudness growth measured by AME.

The loudness function based on a method of magnitude estimation and production is determined by the output of the ''number assignment process.'' On the other hand, loudness functions based on other methods based on the additivity of loudness are determined by the output of the ''loudness perception process.'' Since judgment of equal loudness between two sounds must be based on the comparison of the output of the ''loudness perception process,'' the exponent value based on the loudness additivity may be used as it is (Allen, 1996). Values based on the method of magnitude estimation and production should be corrected to eliminate the effect of the number assignment process. The number assignment process can be expressed by Stevens's power law (Atteneave, 1962). We assume, in accordance with Zwislocki (1983), that the transformation in the number assigning process is independent of frequency and estimated as 1.08. By this account, the value of 0.27 based on the method of magnitude estimation and production is equivalent to 0.25 (0.27/1.08) for values from experiments based on the additivity of loudness.

The average of the above-mentioned values is 0.296. In the present paper, by rounding this, a value of 0.30 is used as the value of the exponent of the loudness function at 1 kHz, α_r. It is noteworthy that a preliminary examination showed that this value scarcely affects the resultant shape of the equal-loudness-level contours at least in the range of 0.20 and 0.33 so long as the ratio of the exponent components of the 1-kHz reference tone and the f-Hz comparison tone, α_r/α_f, is appropriately established (Takeshima *et al.*, 2003).

C. Derivation of equal-loudness-level contours

A set of equal-loudness-level contours was estimated by applying Eq. (6) to the data obtained from the 12 *recent*

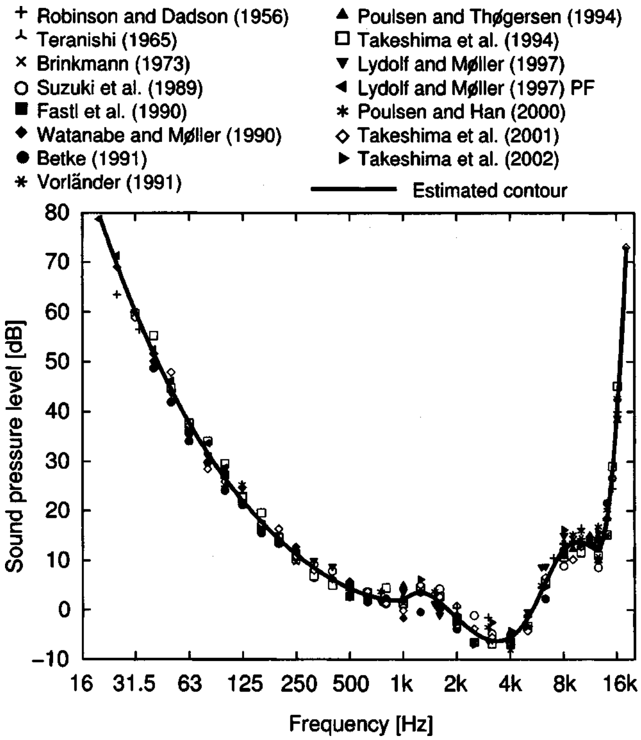

FIG. 6. Threshold of hearing for pure tones. The solid line represents a smoothed line of the averages of the experimental data, the symbols were generated by a cubic B-spline function for the frequency range from 20 Hz to 18 kHz.

studies plotted in Fig. 2. The estimation of the contours was carried out for the frequency range 20 Hz to 12.5 kHz. Above 12.5 kHz, equal-loudness-level data are relatively scarce and tend to be very variable.

As the exponent at 1 kHz was fixed as 0.30 in this study, the procedure outlined below was used to estimate the equal-loudness-level contours.

(1) To obtain the best-fitting threshold function, the experimental threshold data selected in Sec. II B were compiled and averaged at each frequency from 20 Hz to 18 kHz. The data reported by each study were median values except for Brinkmann (1973) in which only mean values were available. The data were averaged by arithmetic mean in terms of dB. Then, the averages were smoothed across frequency by a cubic B-spline function for the frequency range from 20 Hz to 18 kHz. No weighting was used for this procedure. The result is shown by the solid line in Fig. 6. The numerical values calculated for p_{ft} and p_{rt} were used in Eq. (6) to obtain the equal-loudness-level value for any given comparison-reference frequency pair.

(2) Equation (6) was then fitted to the experimental loudness-level data at each frequency by the nonlinear least-squares method. A computer program package for general-purpose least squares fittings called SALS (Nakagawa and Oyanagi, 1980) was used for estimating the values of α_f and U_f. The residual for the least-square method was calculated in terms of dB. The estimated values of α_f are shown by the symbols in Fig. 7; the curve shows the fit to these values. To obtain the curve in Fig. 7, the estimated α_f values were smoothed by the cubic B-spline function using the assumption that α_f does not change abruptly as a function of frequency.

(3) The third step in our process was to reestimate the values of U_f at each frequency. This was accomplished with the help of the smoothed curve in Fig. 7 together with Eq. (6). Using the values of α_f obtained from the smoothed curve in Fig. 7, reestimated values of U_f were obtained. The circles in Fig. 8 show the results in log-log coordinates. The ordinate shows U_f in dB, i.e., $20\log(U_f)$. The change in the values of U_f from the initial to the final estimation ranged from -3.0 to 2.5 dB. This third step was introduced to realize a smoother frequency characteristic than that available with the initial values. The solid line is the cubic B-spline function fitted to the reestimated U_f values. It relies on the assumption that U_f, like α_f, does not change abruptly with frequency.

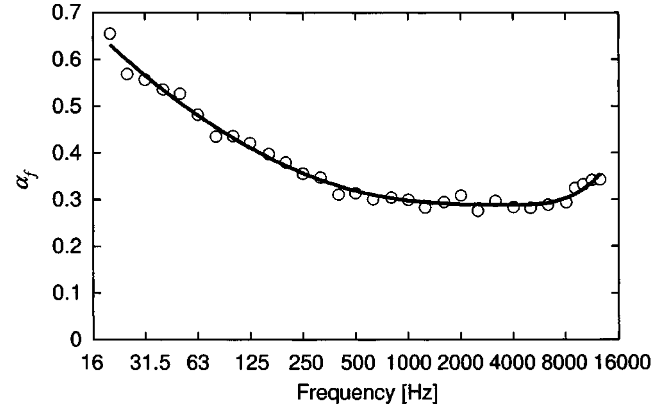

FIG. 7. Estimated α_f's from the nonlinear least squares method. Solid line shows a smoothed line generated by a cubic B-spline function.

Following these computations, equal-loudness relations were generated using the data reported in the 12 *recent* studies. For each comparison-reference frequency pair the values of p_{ft}, p_{rt}, α_f, and U_f entered in Eq. (6) were determined from the smoothed curves in Figs. 6–8. The results of these calculations are shown in Fig. 9 for 31 frequencies ranging from 20 to 12 500 Hz. The solid lines show the calculations

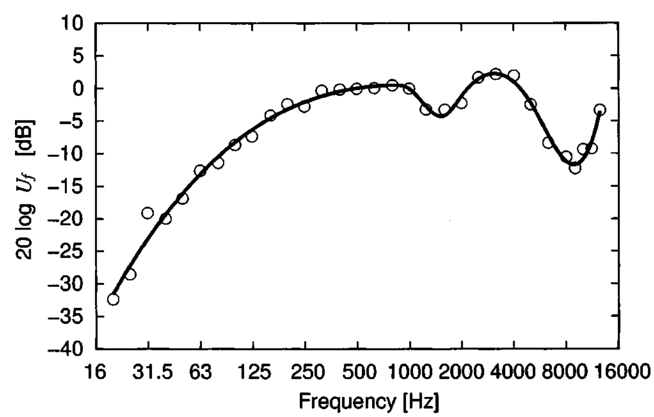

FIG. 8. U_f, a parameter in Eq. (6), reestimated using the interpolated α_f shown in Fig. 7 as a solid line. Values of U_f's are transformed into dB to show the plots in the figure. Solid line shows a smoothed line generated by a cubic B-spline function.

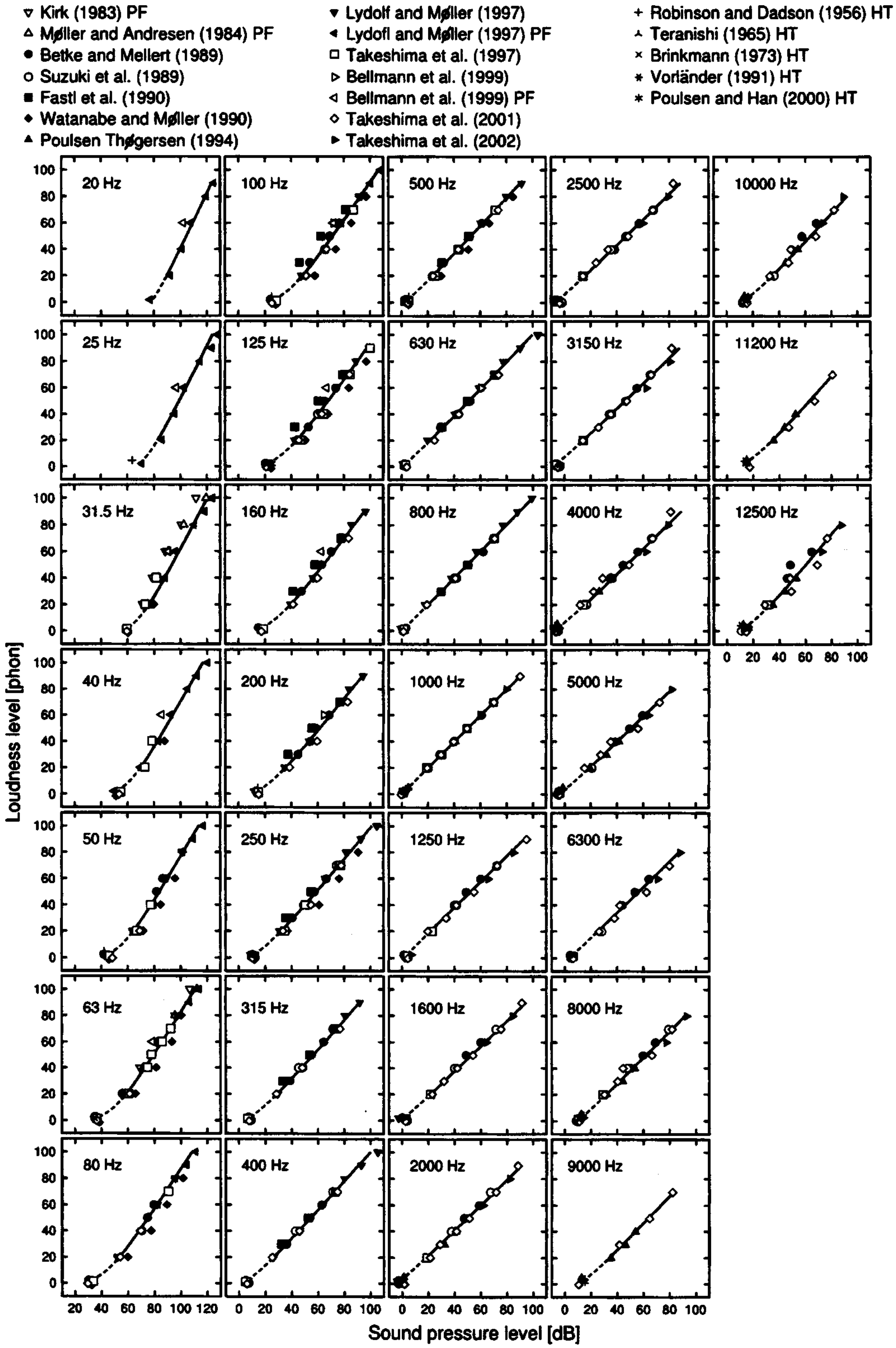

FIG. 9. Equal-loudness relations drawn by the model equation, Eq. (6), and the experimental data used for the estimation. In the legend, HT means that the study was only referenced in the panel of hearing threshold.

fit with the data values obtained for a loudness-level range from 20 to 100 phons; the dashed lines are extrapolations down to the threshold. Despite parametric drawing with smoothed values for the parameters, over the loudness-level range where equal-loudness-level data are available, the calculated functions provide good fits to the measured values.

Figure 10 compares directly the estimated contours to the equal-loudness levels obtained in the 12 *recent* studies. Overall, the equal-loudness-level contours estimated with the calculated functions provide a reasonable description of the experimental results. A family of equal-loudness-level contours obtained in this manner is shown in Fig. 11. The resultant contours exhibit a pattern of parallel displacement in accord with the contours of Fletcher and Munson (1933) and

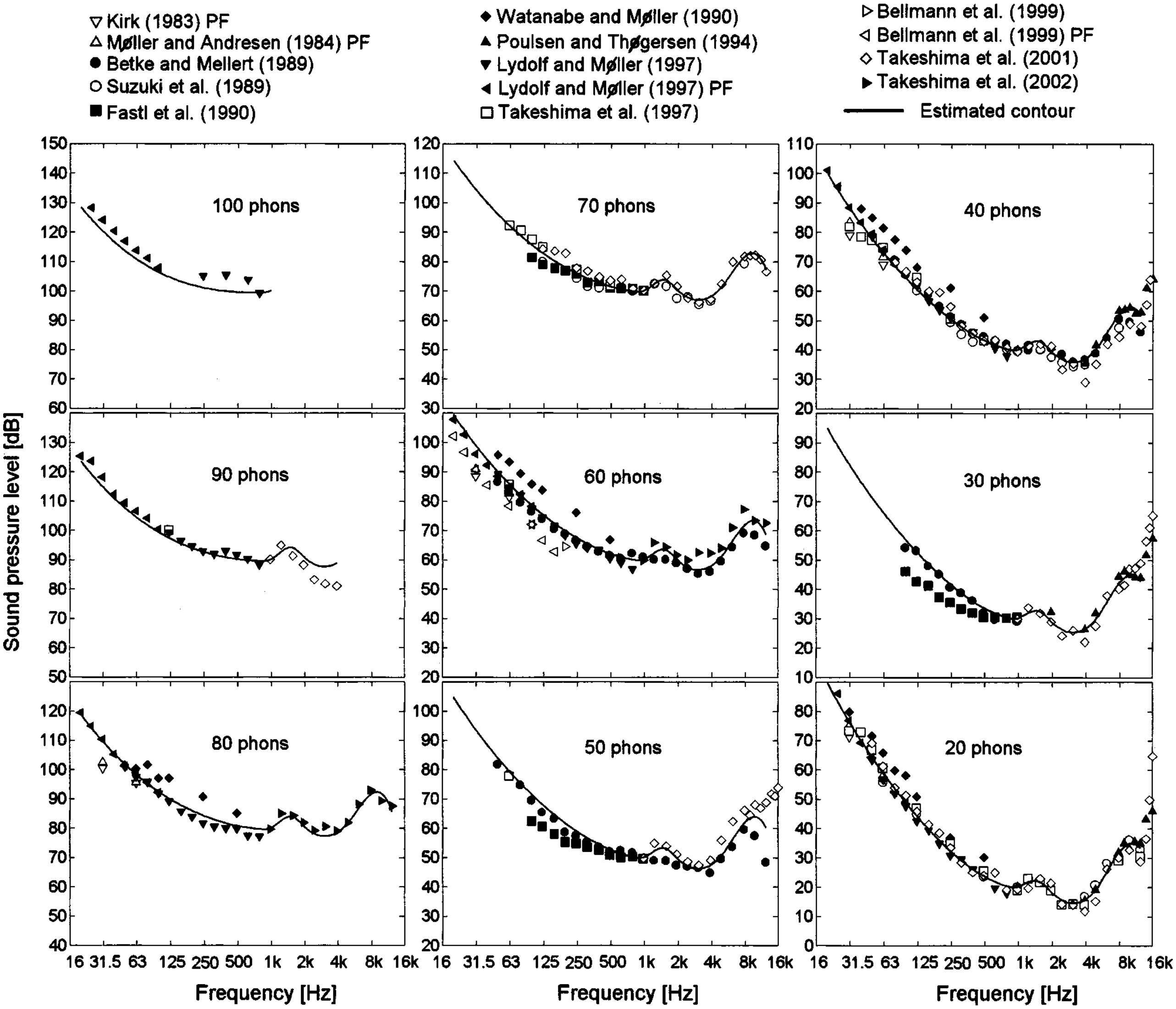

FIG. 10. Estimated equal-loudness-level contours drawn with the experimental data used for the estimations.

Robinson and Dadson (1956). If the contour for each loudness level had been estimated separately and independently of the other contours, then the pattern of parallel displacement may not have been as good.

The contours in Fig. 11 show several notable aspects. First, owing to the lack of experimental data at high loudness levels, the 90-phon contour does not extend beyond 4 kHz and the 100-phon contour does not extend beyond 1 kHz. Second, because data from only one institute are available, the 100-phon contour is drawn by a dotted line. Third, owing to the lack of experimental data between 20 phons and the hearing threshold curve, the 10-phon contour is also drawn with a dotted line. Finally, the hearing threshold curve is drawn with a dashed line just to show the "lower boundary" of the audible area.

IV. DISCUSSION

In this section the relation between the equal-loudness-level contours estimated from our calculations in Fig. 11 and the results of other studies are assessed and evaluated.

Individual panels in Fig. 12 compare the newly estimated contours with those published by Fletcher and Munson (1933; panel a), Churcher and King (1937; panel b), Zwicker and Feldtkeller (1955; panel c), and Robinson and Dadson (1956; panel d). The threshold contour from Fig. 11 is also shown. This contour is compared with the threshold contour measured in each of the four classic studies.

The contours in Fig. 12(a) reported by Fletcher and Munson (1933) were based on equal-loudness levels measured binaurally with earphones. The levels were calibrated relative to free-field listening conditions by means of loudness matching. To obtain the free-field levels, a sound source was placed in a free field 1 m in front of the listener. Fletcher and Munson (1933) did not measure the equal-loudness levels below 62 Hz, and their curves below 62 Hz represent extrapolations based on the available data. Taking this factor into consideration, their contours of 20 and 40 phons at 62 Hz and above are very similar to those estimated in the present study. However, at loudness levels above 40 phons their contours lie below the estimated contours at frequencies below 1 kHz. As the loudness level increases their contours

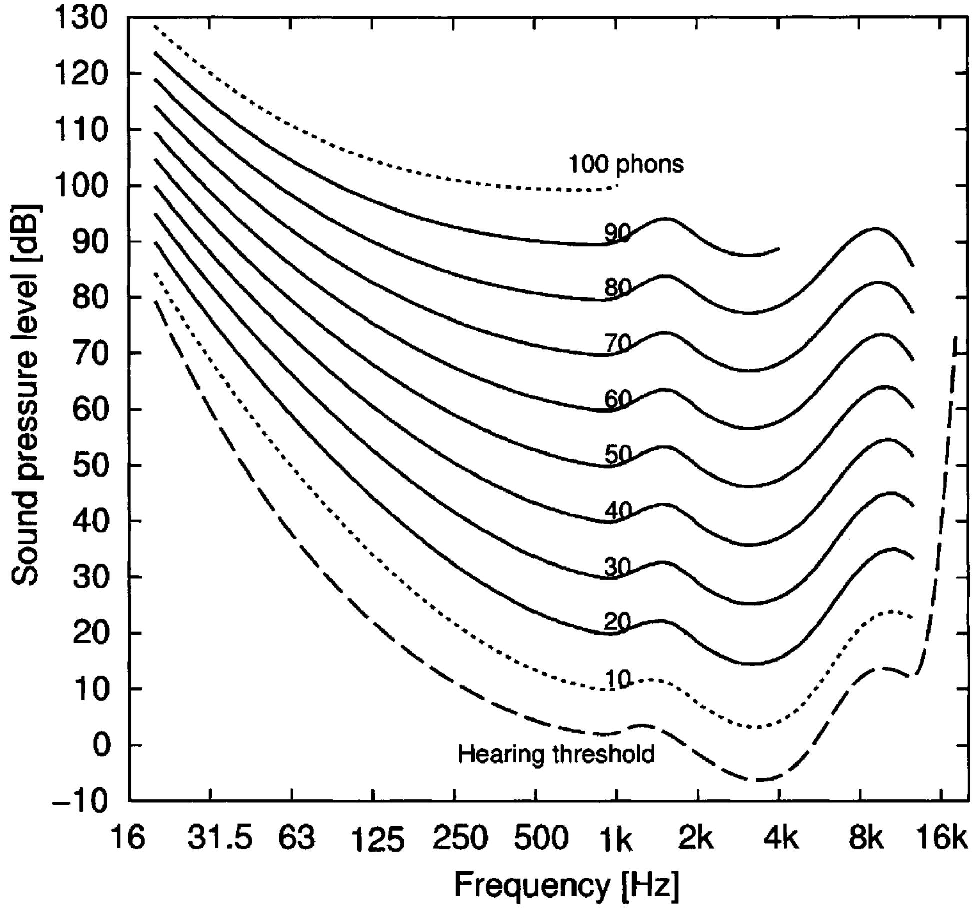

FIG. 11. Estimated equal-loudness-level contours drawn by the equation (6). The dashed line shows the threshold of hearing shown in Fig. 6. The contour at 100 phons is drawn by a dotted line because data from only one institute are available at 100 phons. The contour at 10 phons is also drawn by a dotted line because of the lack of experimental data between 20 phons and the hearing thresholds.

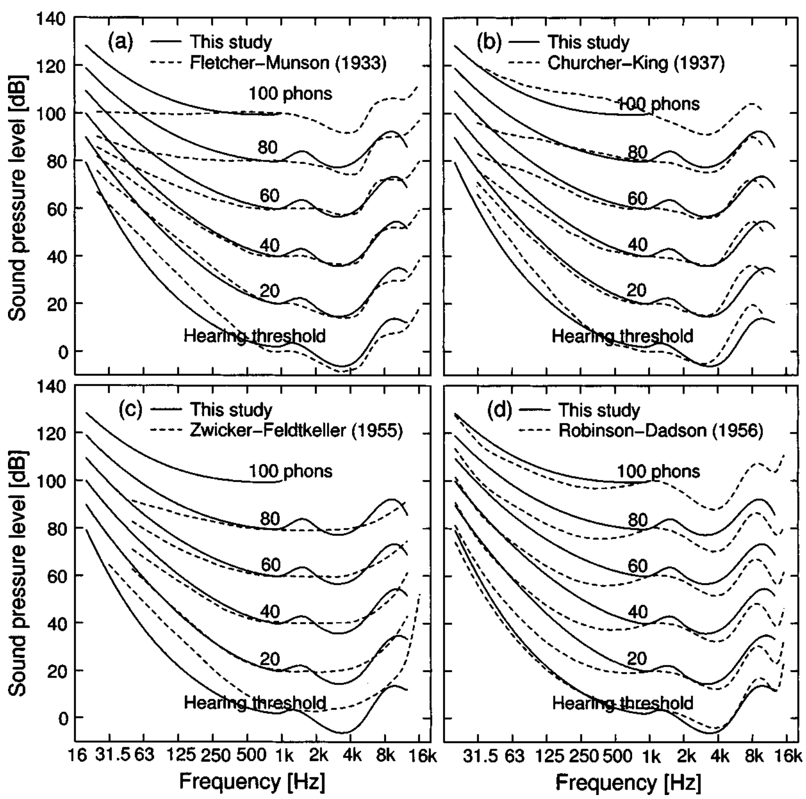

FIG. 12. Comparison of the estimated equal-loudness-level contours in this study with those reported (a) by Fletcher and Munson (1933), (b) by Churcher and King (1937), (c) by Zwicker and Feldtkeller (1955), and (d) by Robinson and Dadson (1956). Note that Fletcher and Munson (1933) did not measure equal-loudness levels below 62 Hz, and their curves below 62 Hz represent extrapolations based on the available data.

become much flatter across frequency than the estimated contours. Despite these differences, it is important to note that the two sets of contours in panel (a) closely agree across a wide range of frequencies at the 40-phon level. This contour, derived from Fletcher and Munson's (1933) pioneering work, is used as the basis of the A-weighting function. Below 1 kHz, the threshold curve measured by Fletcher and Munson (1933) lies above the threshold values reported in the present study. The elevation of their hearing-threshold curve may be attributed to masking caused by physiological noise transmitted by the earphone cushion (Killion, 1978; Rudmose, 1982).

Figure 12(b) shows that the 20-phon contour of Churcher and King (1937) closely resembles the 20-phon contour estimated in the present study. Between 20 and 80 phons their contours are also similar to the present estimated ones above about 250 Hz, whereas at 100 phons the overall shape of their contour below 1 kHz differs from both our estimated contour and the contour proposed by Fletcher and Munson (1933).

Figure 12(c) shows that the contours by Zwicker and Feldtkeller (1955) generally fit the estimated contours at the 20-phon level. Likewise, above 20 phons the overall shape of the contours of Zwicker and Feldtkeller (1955) is similar to the estimations above about 250 Hz. However, there are important differences in their micro-structure, i.e., the rise between 1 and 2 kHz and the dip between 3 and 4 kHz observed in our estimated contours do not appear in the smooth contours of Zwicker and Feldtkeller (1955). By comparison, the dip between 3 and 4 kHz appears in all the other sets of *classic* equal-loudness-level contours as well as in the threshold contours. Moreover, deviations also appear in their threshold curve. Except near 1 and 8 kHz, Zwicker and Feldtkeller's threshold curve lies above the proposed threshold curve and is generally smoother than the threshold contour estimated in this study. This smoothness might be attributable to the use of a free-field equalizer created by a passive filter (Zwicker and Feldtkeller, 1967). Because the passive filter was implemented with only two filter sections, the effect is unlikely to be reproduced in the details of the rather complicated frequency responses of HRTF, such as the peaks and valleys caused by an ear, head, and torso. At low frequencies, the threshold elevation may be explained by physiological noise transmitted by the earphone cushions as in the threshold curve measured by Fletcher and Munson (1933). Above 1 kHz, the detailed shape of their threshold contour may have been obscured by the averaging process inherent in Békésy tracking other than any effects that may come out of the use of the free-filed equalizer. Békésy tracking, unlike the classical method of adjustment, also increases variability in loudness matching (Hellman and Zwislocki, 1964). It is possible that this known increase in variability increased the smoothing observed in Zwicker and Feldtkeller's (1955) equal-loudness-level contours.

Finally, Fig. 12(d) compares the equal-loudness-level contours of Robinson and Dadson (1956) to the present estimated contours. It is notable that their threshold curve closely resembles the one estimated in the present study. Except for the threshold curve, however, the estimated equal-loudness-level curves lie distinctly above the contours recommended by Robinson and Dadson (1956). The deviation between the two sets of contours is especially evident in the frequency region below 1 kHz over the loudness-level range from 20 to 80 phons. A possible cause of this systematic discrepancy was examined by Suzuki *et al.* (1989). They focused on the manner in which the sound pressure levels of the test and reference stimuli were selected. In the 12 *recent* studies a 2AFC paradigm was consistently used. Within each session, the level of the reference tone, usually a 1-kHz pure tone, was fixed, whereas the level of the test tone was varied. This method enables the equal-loudness level of the test tones to be directly determined. In contrast, Robinson and Dadson (1956) fixed the level of the test tone and varied the level of the reference tone. Fletcher and Munson (1933) used a similar methodological approach. However, within each session they also presented the reference tones in a mixed order at three different levels. Suzuki *et al.* (1989) investigated the possible effects of these variations by using the following experimental procedures: (1) the level of the test tone was varied as in the recent studies, (2) only the level of the reference tones was varied as in the work of Robinson and Dadson (1956), and (3) the levels of both the test and reference tones were fully randomized with a range of 12 dB.

The latter method is a little different from the one used by Fletcher and Munson (1933), but the basic concept that the levels of both the test and reference tones are randomized within a session is the same. The results showed that procedures (1) and (3) gave almost identical loudness levels, whereas the results of procedure (2) were similar to those of Robinson and Dadson (1956). Although the difference between the results of procedures (1) and (3) and those of procedure (2) amounted to only 5 dB, the outcome suggests that the discrepancy between the contours of Robinson and Dadson (1956) and the proposed estimated contours may be ascribed, at least in part, to methodological factors.

There is one tendency commonly observed in all the sets of equal-loudness-level contours. The spacing of the contours generally becomes narrower as frequency goes down over the medium loudness levels. This means that the exponent of the loudness function, α, becomes large in the low frequency region as shown in Fig. 7. In other words, our hearing system is less compressive in lower frequency regions and this is qualitatively consistent with the experimental results on suppression by Delgutte (1990) suggesting that the cochlea would be close to linear at low frequencies.

Small differences are observable between the *classic* contours and the proposed estimated ones. In the frequency region between 1 and 2 kHz a small peak amounting to a few decibels is seen in the estimated contours but it does not appear in the *classic* contours. A peak between 1 and 2 kHz has been consistently observed in recent work (Suzuki *et al.*, 1989; Takeshima *et al.*, 1994, 2001, 2002; Lydolf and Møller, 1997; Poulsen and Han, 2000). This peak seems to correspond to a small dip in the HRTF near this frequency range (Shaw, 1965; Takeshima *et al.*, 1994). One possible reason to explain the lack of a peak between 1 and 2 kHz in the *classic* studies is that Fletcher and Munson (1933) did not measure any equal-loudness levels between 1 and 2 kHz

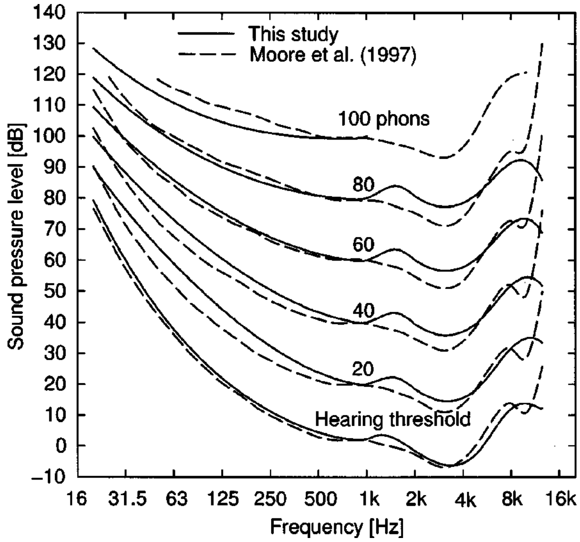

FIG. 13. Comparison of the estimated equal-loudness-level contours in this study with those derived from a loudness calculation method proposed by Moore *et al.* (1997).

whereas Churcher and King (1937) and Robinson and Dadson (1956) measured equal-loudness levels at only one point within this frequency region. As a result, this peak may have been overlooked. In the case of Zwicker and Feldtkeller (1955), they measured equal-loudness levels at several frequencies within the 1-to-2-kHz region, but the greater variability inherent in Békésy tracking as a tool for loudness matching (Hellman and Zwislocki, 1964) may have obscured the effect. Another possible explanation may be the use of the free-field equalizer in their measurements as anticipated in the earlier paragraph.

Another relevant issue is the fine structure of equal-loudness-level contours. It is well known that individual hearing thresholds often exhibit fine, but distinctive, peaks and valleys along the frequency continuum (e.g., Elliot, 1958). This fine structure in the threshold curve is closely related to the OAE (Schloth, 1983; Smurzynski and Probst, 1998). More recently, Mauermann *et al.* (2000a,b) reported that the fine structure observed in the threshold curve is reflected in observed equal-loudness levels up to around 40 phons. However, their data indicate that above 40 phons the influence of the fine structure of the threshold contour on the equal-loudness-level contours is less evident. Moreover, it decreases with level. Since the peaks and valleys in the fine structure are likely to be at different frequencies for different listeners, their effect ought to be strongly diminished when data are averaged across a number of listeners.

Figure 13 compares the equal-loudness-level contours derived from a loudness-calculation procedure suggested by Moore *et al.* (1997) to the ones estimated in this study. The work by Moore *et al.* (1997) in assessing the loudness of sounds at various frequencies is a revision of a previous proposal (Moore and Glasberg, 1996). This is given as a modification of the formulation by Zwicker (1958) based on the auditory excitation-pattern model (Fletcher and Munson, 1937). In their modification, Moore *et al.* (1997) assume that the loudness perception process is followed by a linear block with a transfer function. The specific loudness of a sound is given by an equation equivalent to Eq. (4), whereas an equation equivalent to Eq. (3) was used in the earlier proposal (Moore and Glasberg, 1996). Moreover, the linear block is expressed as the product of HRTF and the middle ear transfer function (Puria *et al.*, 1997). With a few more assumptions, a family of equal-loudness-level contours is predicted.

As shown in Fig. 13, the overall agreement between our estimated contours and those predicted by Moore *et al.* (1997) is much better than the agreement between our contours and those of Robinson and Dadson in Fig. 12(d). However, there are some discrepancies between the two data sets. First, at frequencies below 250 Hz and loudness levels below 60 phons their contours are somewhat lower than ours. However, the differences are small and may be within the error of measurement. Second, and most notable, in the frequency region between 1 and 2 kHz the peak observed in our estimated contours is absent in Moore *et al.* (1997). Third, at the 100-phon level the contour of Moore *et al.* (1997) is somewhat higher than our estimated contour. However, it is similar to the classic contour of Churcher and King (1937). A wider spacing between the contours at high levels is consistent with evidence that at high sound pressure levels the slope of the loudness function at low frequencies is shallower than it is over the middle range of levels (Hellman and Zwislocki, 1968). This level dependency could be consistent with the nonlinear input–output characteristic observed in the basilar-membrane mechanics. After all, recent studies show that the exponent of the loudness function shape may probably be dependent on sound level (Yates, 1990; Buus and Florentine, 2001b). This is supported by recent data, which indicate more compression at moderate levels than at low and high levels (e.g., Florentine *et al.*, 1996; Buus and Florentine, 2001a).

The middle ear acoustic reflex may also affect the shape of the contours, especially at high intensities in the low frequency range. If the loudness at low frequencies was attenuated, then the contours at high SPLs would be elevated relative to the contours estimated with a constant power-function slope α. Borg (1968) found that the transmission loss of the middle ear caused by activation of the reflex is largest at 500 Hz and smallest at 1450 Hz. His results showed that at 500 Hz the transmission of sound is reduced by 0.6 to 0.7 dB for each 1-dB increment in the stimulus level. This result means that at 20 dB above the threshold, the transmission loss at 500 Hz is about 13 dB, whereas at the same level, the loss at 1450 Hz is about 6 dB. According to Borg's measurements, the maximum frequency-dependent difference in the transmission loss amounts to 7 dB. However, Borg's data do not account for the decrease in the slope observed in the loudness function for 100- and 250-Hz tones at high SPLs (Hellman and Zwislocki, 1968).

Another factor to be considered is the latency of the reflex. This latency is estimated to be around 100 ms. This means that the initial 100 ms of a tone burst is not affected by the reflex. Since the time constant for loudness perception is around this value (e.g., Munson, 1947; Takeshima *et al.*, 1988), the loudness of a tone burst longer than 100 ms will be determined to a large extent by the initial part of the burst during which the reflex does not play a role. Thus, the effect of the following attenuated portion of the tone burst would be at most a few decibels. As a result, we conclude that the influence of the reflex on the equal-loudness-level contours is limited. Nevertheless, in accordance with the analysis of the relation between loudness level and sound pressure level in Fig. 9, it is evident that the data at 400 and 630 Hz are all less steep at 80 and 100 phons than the estimated loudness-level curves predict. This reduction in loudness, which is attributable to the reflex activation (Hellman and Scharf, 1984), is compatible with some loudness measurements (e.g., Hellman and Zwislocki, 1968). Since data from only one institute at 100 phons is available, more data are needed to clarify this important issue. Nonetheless, despite the possibility that the acoustic reflex plays some role in the reduced high-level slope of the loudness function at low frequencies, it cannot also account for the reduced high-level slope observed in the loudness function at 12.5 kHz and higher (Hellman *et al.*, 2000). The evidence indicates that at low frequencies the loudness function tends to approach the high-level slope at 1 kHz, whereas at 12.5 kHz and higher, it becomes flatter than the 1-kHz function (Hellman and Zwislocki, 1968; Hellman *et al.*, 2001). In light of these limitations, the exponent α_f used in the estimation of the proposed contours in Fig. 9 can only be regarded as valid over the stimulus range of interest below high sound pressure levels. The slope (exponent) estimated in Fig. 7 does not provide an accurate account of the data above 80 phons for 630 Hz and below and above 60 phons for 12.5 kHz and above.

V. CONCLUSIONS

After reviewing all known published studies of equal-loudness-level contours for pure tones, a new family of equal-loudness-level contours was estimated from 12 *recent* studies. An equation was derived to express the equal-loudness relation between pure tones at different frequencies. The procedure using this equation made it possible to draw smooth contours from discrete sets of data values. Except in the vicinity of the threshold and at very high SPLs, the equation provides a good description of the experimental results. In general, the classic contours proposed by Fletcher and Munson (1933), Churcher and King (1937), and Zwicker and Feldtkeller (1955) exhibit some overall similarity to the proposed estimated contours up to 60 phons. However, at higher levels, they deviate from the proposed contours in the frequency region below about 500 Hz. By contrast, the estimated contours exhibit clear differences from those reported by Robinson and Dadson (1956). The differences are most pronounced below 1 kHz. The proposed threshold curve closely resembles the one reported by Robinson and Dadson (1956) whereas the thresholds given by Fletcher and Munson (1933), Churcher and King (1937), and Zwicker and Feldtkeller (1955) exhibit clear deviations from those obtained in the present study, especially in the frequency region below 1 kHz.

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