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Equal-loudness levels measured with the method of constant stimuli ——Equal-loudness level contours for pure tone under free-field listening conditions (II)——

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1. Introduction

The current international standard on equal-loudness level contours as well as minimum audible sound field, *i.e.* ISO 226,[1] is mainly based on the data provided by Robinson and Dadson[2,3] in 1956. At the meeting of ISO/TC43/WG1 in 1985, however, a new experimental finding was presented by Fastl and Zwicker.[4] The data showed a significant difference from the standard at around 400 Hz. On the basis of the data, ISO/TC43/WG1 decided to conduct a full-scale revision of ISO 226 as a new work item.

Since that decision, we have been conducting a series of experiments to obtain fundamental data of equal-loudness level contours for Japanese subjects since 1986 and have published two papers.[5,6] The first study was carried out to obtain equal-loudness levels for the mid-frequency range, and the second study dealt with only the thresholds of hearing. Similar experiments have been made by Betke and Mellert (1989),[7] Fastl *et al.*(1990),[8] Watanabe and Møller(1990),[9] and Poulsen and Thøgersen (1994).[10]

Table 1 shows frequency ranges of loudness levels examined in the present study as well as those in our previous two papers. In this study, additional equal-loudness levels particularly at low frequency region below 125 Hz were measured.

2. Experiments

2.1 The sound field and the experimental setup

The experiments were performed in an anechoic room at the Electrotechnical Laboratory in Tsukuba. The interior dimensions of the room are a width of 9.5 m, a depth of 8.0 m, and a height of 7.2 m. The interior surface of the room is covered with sound absorbing wedges 2 m in length with a lower cut-off frequency of 40 Hz.

Two loudspeakers, one with a diameter of 80 cm (DIATONE D-80) and the other with a diameter of 16 cm (Technics 16F20), were used. The former was used for reproducing low frequency pure tones from 31.5 Hz to 160 Hz, and the latter was used for radiating middle and high frequency pure tones from 200 Hz to 12.5 kHz.

As to the harmonic distortions in the radiated sound, the preferred test conditions defined by ISO/TC43/WG1[11] specify that the level of the second harmonic should be below -30 dB, the third harmonic below -40 dB, and the fourth and higher harmonics below -50 dB relative to that of the fundamental wave. To satisfy the preferred conditions,[11] the harmonic distortions were suppressed, when necessary, by adding antiphasic signals to cancel the harmonics of the stimuli. The suppression of the distortions were carried out for the measurements of 125 Hz at 90 phon, and 63 Hz, 80 Hz and 100 Hz at 70 phon.

The free-sound field condition is also defined in the preferred test conditions.[11] We measured the sound pressure level at seven points for pure tones from 31.5 Hz to 14 kHz. One of the seven points was the reference point, set at the midpoint between the subject's ear, and the other six were points 15 cm apart from the reference point; they were on the right-left, up-down, and front-back axes. According to the preferred test conditions, the difference between the sound pressure levels at the reference point and the other points should be less than ± 1 dB for any frequency below 4,000 Hz, and less than ± 2 dB for any frequency above 4,000 Hz. On the front-back axis, we took the inverse distance law into consideration. As a result, the requirement was satisfied for almost all conditions. Moreover, even for a few positions where the requirement was not satisfied,

Table 1 Frequencies of tones measured equal-loudness level in our published study and in this study. f_1-f_2 means frequencies from f_1 [Hz] to f_2 [Hz] at 1/3 octave intervals.

	S. Suzuki *et al.*[5]	H. Takeshima *et al.*[6]	This study
MAF	125,250-4 k, 8 k	31.5-20 k	
20 phon	63, 125, 250, 500, 1 k, 2 k, 4 k-12.5 k		31.5-63, 125, 250, 500, 1 k-4 k, 8 k, 12.5 k
40 phon	125, 250-4 k, 8 k		31.5-63, 125, 250, 500
50 phon			63
60 phon			63
70 phon	125, 250-4 k, 8 k		63-125, 250, 500
90 phon			125

[Unit: Hz]

the excess was small, namely, from 0.1 dB to 0.3 dB. Therefore, we regarded the sound field as being a free field.

A small head-rest was used to fix the head position. To examine the effect of the head-rest, sound pressure levels at the ear entrance were measured with and without the head-rest using a head and torso simulator, KEMER. The differences between both conditions were less than 1 dB at all frequencies tested.

The experimental setup and the environment for the present study are the same as those used in the measurement of the threshold of hearing, and their detailed description can be found in a previously published paper.[6]

2.2 Experimental procedure

The method of constant stimuli was used. The reference stimulus was a 1 kHz pure tone. The sound pressure level of the reference stimulus was fixed during a single run. The sound pressure level of test stimuli was prepared at nine levels with steps between 1.5 and 2.5 dB depending on the frequency of the test stimuli. The stimuli were presented for 1.0 s with a 0.7 s pause between test and reference stimuli, and with a 2.5 s interval between pairs of stimuli. During a single run, the frequency of the test stimulus was also fixed. One-hundred eighty pairs of stimuli were presented to a subject at random order in a single run : *i.e.*, 9 levels × 2 sequences (a test tone precedes a reference tone and v.v.) × 10 trials. Subjects were asked to judge which stimulus of the pair was louder. The point of subjective equality (PSE) of each subject was calculated using the method of maximum likelihood.[12]

2.3 Subjects

The number of subjects was 9-30, depending on measured frequency and loudness level. All subjects were 19 to 25 years old and their hearing acuity was checked before the experiments by measuring their monaural hearing threshold level. Their hearing threshold levels were less than 10 dBHL up to 4 kHz and less then 15 dBHL up to 8 kHz. These criteria are described in the preferred test conditions.[11]

3. Results and discussion

Figure 1 indicates the mean of equal-loudness levels. The filled marks show data obtained in this experiment, while open marks show the results in our previous experiment.[5] The error bars indicate 95% confidence intervals.

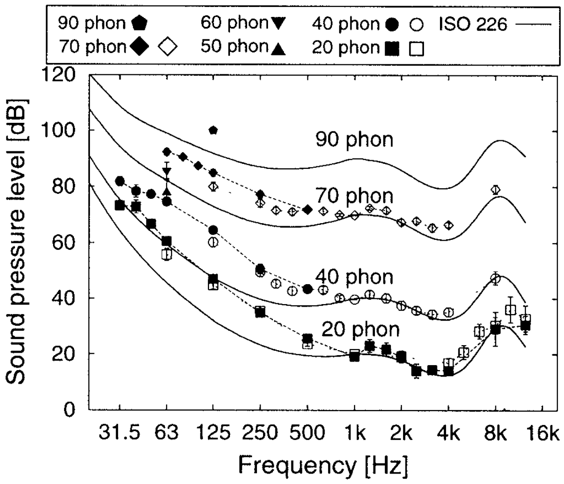

Fig. 1 Equal-loudness levels for pure tones under free-field listening conditions. Filled marks and open marks indicate the means of the equal-loudness levels measured in this experiment and in our published paper,[5] respectively. The vertical bars indicate 95% confidence intervals. The solid lines show the equal-loudness level contours specified in ISO 226.

It can be seen from Fig. 1 that the equal-loudness levels for the frequencies below 1 kHz significantly exceed the corresponding contours specified in ISO 226 which are shown by the solid lines. In particular, the differences are more than 10 dB in the frequency range from 63 Hz to 250 Hz below 70 phon.

Figure 2 shows recent data mentioned in Section 1 and the equal-loudness level contours published by Fletcher and Munson,[13] as well as our data and ISO 226.

Though there are some discrepancies among the recent data at frequencies below 1 kHz, the data points at frequencies below 1 kHz are obviously higher than

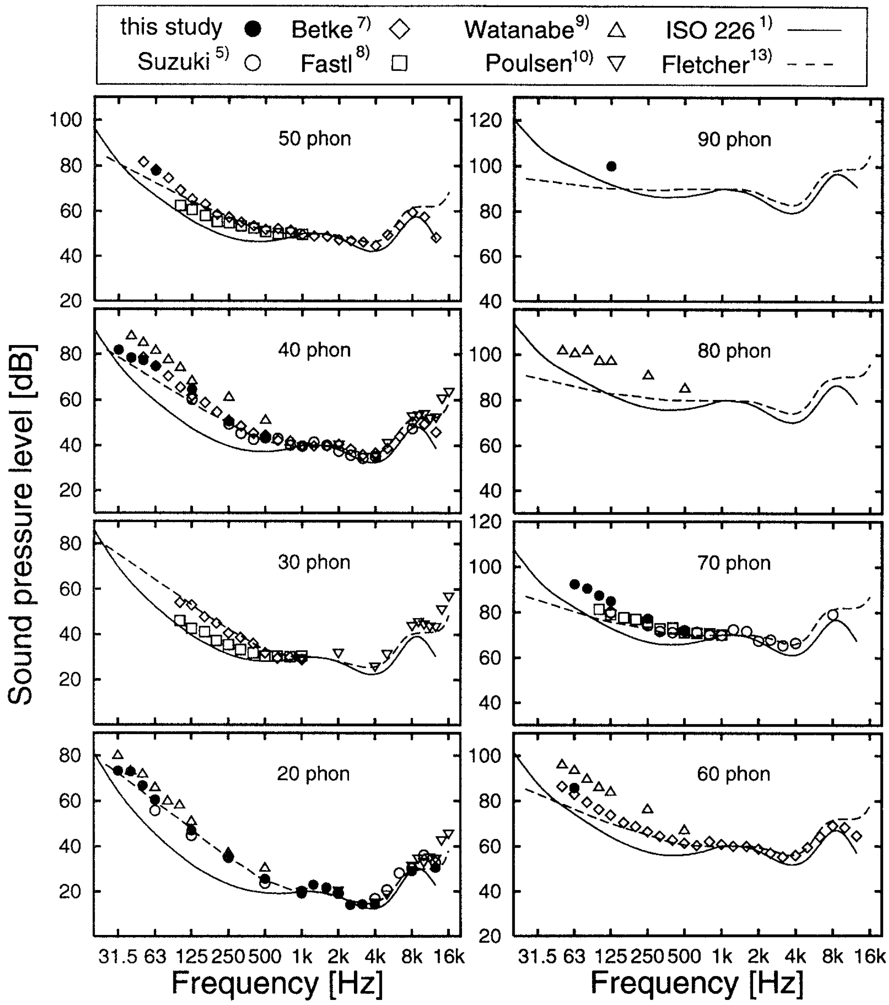

Fig. 2 Comparison among recent data of equal-loudness levels obtained by five groups of researchers. The solid lines and the dashed lines show the equal-loudness level contours specified in ISO 226 and presented by Fletcher and Munson,[13] respectively.

the contours in ISO 226, except for the data by Fastl *et al.*[8] at 30 phon. Moreover, the data are more similar to the contours by Fletcher and Munson[13] at loudness levels below 70 phon than those in ISO 226. In any case, these data clearly indicate that new equal-loudness level contours must be defined as soon as possible.

4. Summary

Equal-loudness levels for pure tones were measured in a free field in an effort to contribute to the full-scale revision of ISO 226. The results show that at frequencies below 1 kHz the equal-loudness levels are significantly higher than those specified in ISO 226.

This strongly indicates the necessity of revising the equal-loudness level contours specified in ISO 226.

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