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Equal-loudness level contours for pure tone under free field listening conditions (I)—Some data and considerations on experimental conditions—

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This paper describes new experimental results on equal-loudness level contours and the minimum audible sound field (MAF) as well as a supplementary consideration on experimental procedures. Our equal-loudness level contours for 20 phon or greater are close to those obtained by Fletcher and Munson rather than to those by Robinson and Dadson. On the other hand, the minimum audible sound field reported herein is similar to that in ISO 226 which was obtained by Robinson and Dadson. Supplementary experiments to clarify the discrepancies among various research studies suggested that the experimental condition, e.g., whether the level of the standard tone or the level of the test tone is varied, could be a possible cause to explain a part of the discrepancies.

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1. INTRODUCTION

Herein we re-examine the equal-loudness level contours for pure tone under free field listening conditions.

It is well known that loudness of sound is a subjective impression depending not only on sound intensity, but also on the frequency of the sound. The equal-loudness level contours express the relationship between sound pressure level and the frequency that gives an impression of equal magnitude to subjects. Several studies on the equal-loudness relationship have been carried out by researchers during the past sixty years. The earliest measurements were made by Kingsbury[1] under telephone listening conditions. A complete set of contours under free field listening conditions was first published by Fletcher and Munson[2] in 1933, and the contour for 40 phon was used as the basis of the A-weighting function for the sound level meter. They carried the measurement with headphones and the constant method, and converted the data into those for free field listening conditions. Churcher and King[3] presented their data in 1937, which showed some differences in the low frequency region from the contours of Fletcher and Munson. In 1955 Zwicker and Feldtkeller[4] reported a study on the loudness level of band-limited noise, in which they showed the equal-loudness level contours. No depression was seen at frequencies below 1 kHz in their contours, though they used headphones and the method of adjustment.

Robinson and Dadson[5] published new contours in 1956, which were obtained under free field listening conditions and using the constant method. Their data are adopted in ISO 226.[6]

At the meeting of ISO/TC43/WG1 in 1985, new experimental data were presented by a member body.[7] It showed slight difference from ISO 226 at around 400 Hz, and accordingly ISO/TC43 decided to undertake the revision of 226 as a new work item. This proposal was approved by the member bodies, and its implementation was referred to WG1.

In response to this decision, we decided to take part in the experiments for obtaining the new equal-loudness level contours under free field listening conditions. We also planned to obtain the minimum audible sound field. The results of our first stage experiment were reported at the meeting of WG1 in 1987,[8] and after the meeting, the second draft for the experimental conditions necessary to obtain the equal-loudness level contours and MAF[9] was circulated among WG1 members. As the condition mentioned in the draft are basically similar to ours, we decided to continue our experiments and obtained some new results. This paper describes the results of a series of experiments as well as those of additional experiments which were conducted to clarifty the cause of discrepancies among various research studies.

2. MEASUREMENT OF EQUAL-LOUDNESS LEVEL CONTOURS

2.1 Experimental Method

Three equal-loudness level contours for 20 phon, 40 phon and 70 phon, as well as the minimum audible sound fields for pure tones under free field listening conditions were examined. The experiments consisted of two parts, which we will hereafter refer to as EX1 and EX2. In EX1, we obtained contours of 40 phon and 70 phon, and the experimental frequencies were 125 Hz, every 1/3 octave band from 250 Hz to 4 kHz, and 8 kHz. In EX2, we obtained the contour for 20 phon, and the frequencies from 63 Hz to 4 kHz at 1 octave intervals, and from 5 kHz to 12.5 kHz at 1/3 octave intervals were tested. Experiments on the minimum audible sound field were carried out in both EX1 and EX2 at the frequencies used for the measurement of the equal-loudness level contours.

We used the constant method to obtain equal-loudness level contours, in which the point of subjective equality (PSE) was calculated using the method of maximum likelihood.[10] Figure 1 shows the time pattern of a pair of stimuli. The reference

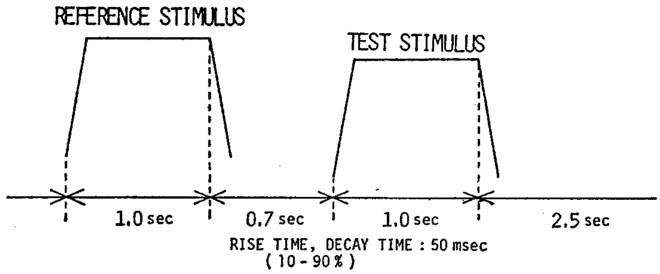

Fig. 1 Time pattern of a pair of stimuli for equal-loudness level measurements.

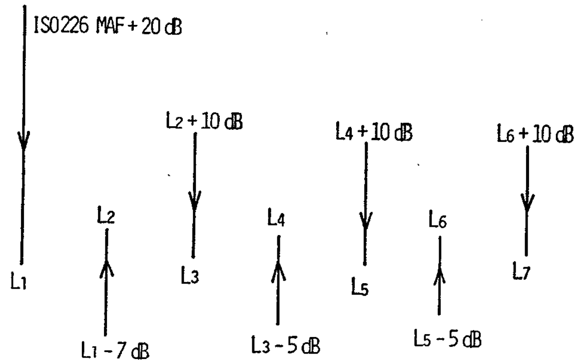

Fig. 2 Level diagram of test stimuli for obtaining the minimum audible sound field.

stimulus was a 1 kHz pure tone with level fixed at either 40 or 70 dBSPL in EX1 and at 20 dBSPL in EX2. Nine levels of test stimuli were prepared at 1.5 dB steps (at frequencies around 1 kHz) and 4.5 dB steps (at frequencies distant from 1 kHz) according to the frequencies of the test tone. During a single run, the frequency of the test stimulus was fixed, and 180 pairs of stimuli were presented in random order to each subject. That is, 9 levels × 2 sequences (a test tone precedes a reference tone and v.v.) × 10 trials.

On the other hand, the method of limits[10] was used in order to get the minimum audible sound field. Figure 2 shows the level diagram of the test stimuli. A test stimulus of 1.5 s duration was presented at a certain level. After a 0.5 s pause the next stimulus, whose level was changed by 1 dB, was given. L_1 to L_7 in Fig. 2 indicate critical levels reported by a subject. Referring to the critical level just determined, the starting level for the next trial was set automatically. The average value of L_2 to L_7 is used as the minimum audible sound field at each frequency condition.

The experiment was performed in an anechoic room. The interior size of the room is 9.5 m ×

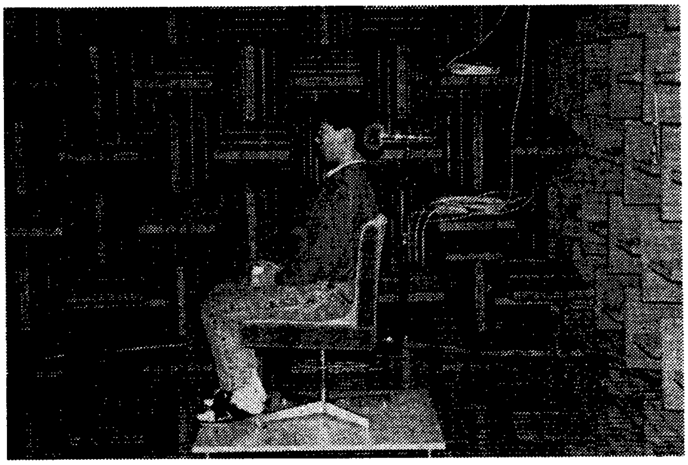

Fig. 3 Appearance of subject sitting on the chair and provided the headrest. The line casted around ear indicate the hearing point.

8.0 m × 7.2 m, with surface covered with about four-thousand sound absorbing wedges, each 2.0 m in length. Free sound field condition is satisfied above 40 Hz[11] in this room. The band pressure level of ambient noise in the room are more than 10 dB below the minimum audible sound pressure level given in ISO 226–1987 at every critical band. A loudspeaker with a diameter of 16 cm was used in EX1, while a loudspeaker with diameter of 46 cm or 10 cm was used in EX2 for frequencies below or above 1 kHz, respectively. We used pure tone output from the loudspeaker with harmonic distortion less than −50 dB in the relative level.

The subject sat on the frontal axis of and directly facing the sound source, and a headrest was provided to fix the head position (see Fig. 3). The midpoint between the subject's ears was defined as his listening point. The loudspeaker and the listening point were placed at a distance of three meters from each other in EX1 and 5.2 m in EX2. The sound pressure levels at the listening point were calibrated under conditions without subject nor chair. The range of sound pressure levels, measured on a sphere of 20 cm in diameter centered at the central position of the head, were less than 0.3 dB for the frequencies used. The subjects were 14 males and 9 females in EX1, and 6 males and 4 females in EX2. Their ages range from 19 to 25. The hearing of each subject was checked and judged as normal using two methods, i.e., measurement of hearing acuity and medical examination by an otologist.

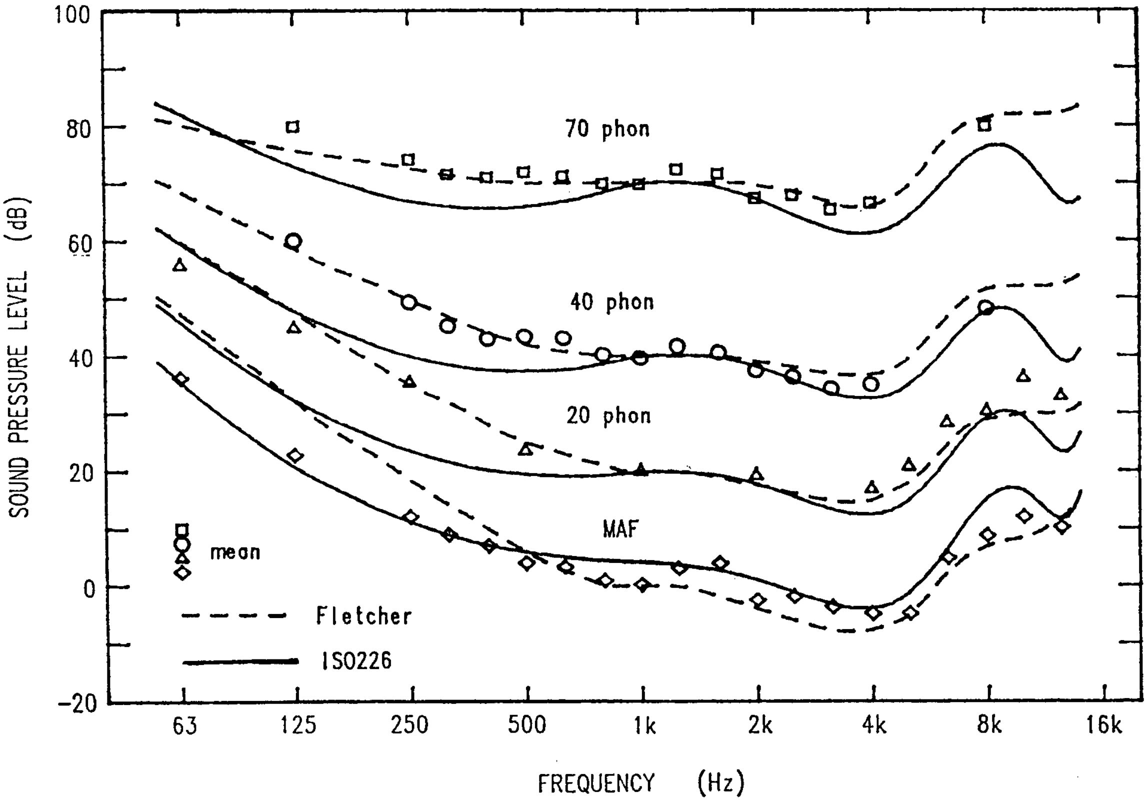

Fig. 4 The equal-loudness relation and minimum audible sound field (MAF) for pure tones under free field listening conditions.

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Table 1 Comparison of experimental conditions among three studies.

Researchers		Fletcher & Munson	Robinson & Dadson (ISO226)		The authors	
Year Country		1933 U.S.A.	1956 U.K.		1988 Japan	
Experimental method		Constant stimulus method	Constant stimulus method		Constant stimulus method	
Method of obtaining PSE		Authors estimated the 50% judgements by manual curve fitting on a graph.	Authors estimated the mid-point of the ranges of uncertainty in the upper and lower limits of judgements.		Maximum likelihood estimation	
Subjects	Number	11	Group 1 90	Group 2 30	EX1 23	EX2 10
	Sex	Uncertain	45 males 45 females	17 males 13 females	14 males 9 females	6 males 4 females
	Age	Uncertain	16～63	average 30	19～25	
Stimuli	Standard stimulus	1 kHz	1 kHz*		1 kHz	
	Variable level	Reference stimulus	Reference stimulus		Test stimulus	
	Duration	1 s	1～3 s		1 s	
	Tone sequence T: test tone S: standard tone	TSTS	TSTS and STST		TS and ST	
Electro-acoustic transducer		Headphones (The contours were obtained for pressure field condition and then converted into the free field condition.)	Low frequency: Duct whose size was 0.7×0.6×6.8 m. High frequency: A plane array of twenty-eight 2.5 in. cone speakers with the reflex horn.		EX1: 16 cm cone speaker EX2: Low frequency: 46 cm High frequency: 10 cm cone speaker	
Distance		(1 m of reference distance)	Uncertain		EX1: 3 m, EX2: 5.2 m	
Experimental room		Sound proof booth	Lagged room		Anechoic room 9.5×8×7.2 m	
Number of level steps for variable stimuli		9 for reference tone 3 for test tone	About 18		9	
Number of trials		3	1		20	
Number of judgements in a single run		9 reference tone levels×3 times×3 test tone levels=81 judgements	Mostly 18 judgements		9 levels×20 times=180 judgements	
Number of data for one PSE		9 reference tone levels×3 times×11 subjects=297	18 times×30 subjects=540		180 for each subject.	
The total number of judgements by each subject		9 reference tone levels×3 times×143 points=3,861	Mostly 18 judgements×112 points=2,000 (group 2)		180 times×30 points=5,400 in EX1 180 times×12 points=2,160 in EX2	
The total number of judgements for the contours		3,861 judgements×11 subjects=42,471	About 2,000 judgements×30 subjects=About 60,000		5,400 judgements×23 subjects+2,160 judgements×10 subjects=145,800	

* In low frequency region the intermediate reference tone was used so that subjects could easily make a loudness judgement.

Table 1 (continued)

Researchers		Fletcher & Munson	Robinson & Dadson (ISO226)	The authors
MAF	Experimental method	Method of limits	Method of limits	Method of limits
	Sequence used	↓↑×2 (examined before and after contour experiments)	↓↑↓↑	↓↑↓↑↓↑↓ (average of 6 data except the first ↓)
	Step level	Uncertain	2 dB (level point is shifted by 1 dB for the succeeding.)	1 dB
Harmonic distortion		Less than −20 dB in loudness level	Londness comparison between pure tone and tone with distortion → no problem for −40 dB relative level. Observer indicated awareness of presence of distortion → this was used to determine the maximum sound levels to be presented.	Less than −50 dB on relative level

2.2 Results and Discussion

Figure 4 shows the equal-loudness levels for 20, 40 and 70 phon as well as the minimum audible sound field obtained in the experiments. The contours by Fletcher and Munson, and of ISO 226 are also shown in the figure. According to the results of the experiments, the depression at frequencies around 400 Hz in the contours of ISO 226 is not seen. Two recent studies also reported a similar trend at frequencies around 400 Hz.[12,13] Moreover, the shapes of the equal-loudness level contours up to 1 kHz are rather similar to those given by Fletcher and Munson. In the frequency range higher than 1 kHz, our 40 phon contour is similar to that of ISO 226.

2.3 Difference in Experimental Conditions among Researchers

In order to speculate on the experimental factors that cause the difference in contours, we examined the effect of methodological differences on results. Table 1 shows a comparison of experimental conditions of three groups, i.e., Fletcher and Munson, Robinson and Dadson, and our group. Some differences are found among these groups. In particular, we have to take note of the difference in the choice of stimulus levels for a single run of experiment. Robinson and Dadson fixed the level of the test tone and varied the level of the reference tone in random order. Fletcher and Munson used a method similar to that of Robinson and Dadson, but the level of the test tone was randomly selected from among three different levels. In this way, they intended to lessen the possibility of error caused by presenting test tones at a constant level throughout a test run. They called the effect which may cause this type of error the "memory effect."[2] On the other hand, we fixed the level of the reference tone and selected the level of the test tone at random. In order to consider the effect of such a difference of experimental procedure on the results, we conducted supplementary experiments in the next section.

3. SUPPLEMENTARY EXPERIMENTS

3.1 Purpose and Procedure of Experiments

In this section, we describe two additional experiments carried out to examine the effect of variations in experimental procedure. The first one was to examine the effect of varying the level of either the reference or the test tones. This experiment consisted of two kinds of tests. In Test 1, the reference tone (1 kHz tone) was fixed at a constant level for both EX1 and EX2. In Test 2, the level of the test tone was fixed as in the experiment of Robinson and Dadson. We call this experiment EX-A1.

The purpose of the other experiment was to examine the effect of varying the levels of both reference and test stimuli, i.e., levels of neither the reference tone nor the test tone were fixed. We call this experiment EX-A2. The experimental paradigm used in EX-A2 is essentially the same as that pro-

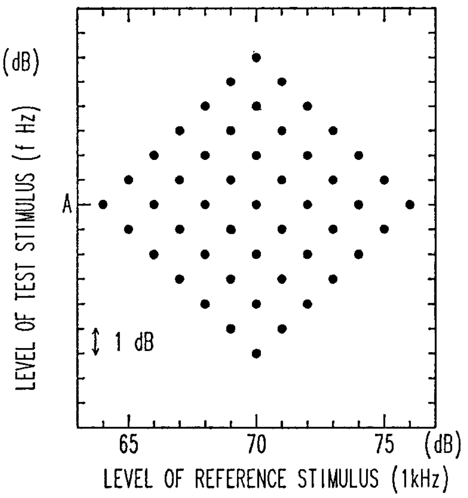

Fig. 5 Description of stimulus condition in EX-A2. In this figure, A is PSE for each subject in Test 1 of EX-A1.

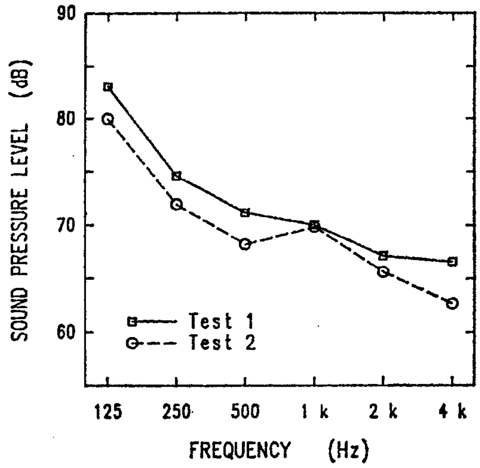

Fig. 6 Results of the supplementary experiment EX-A1. Test 1: the reference tone is fixed, Test 2: the test tone is fixed.

posed by Robinson in his comments on the proposal of TC43/WG1 chairman on experimental methods.[14)]

As mentioned above, EX-A1 included two tests. In Test 1, the level of the reference tone was fixed at 70 dBSPL while the level of the test tone was selected from among 9 levels. In Test 2, on the other hand, the level of the test tone was fixed at the integral level nearest to 70 phon measured in Test 1 for each subject. There were 20 repetitions for each level. The test tone frequency ranged from 125 Hz to 4 kHz at intervals of one octave.

In EX-A2, levels of the reference tone and the test tone were randomly selected from among the lattice points shown in Fig. 5. The median of the sound level of the reference tone is 70 dBSPL. Only the test frequencies of 125, 250 and 500 Hz were used in EX-A2 since we were particularly interested in the existence of the depression at frequencies around 400 Hz. The number of repetition was 20 for each combination of reference and test stimuli (lattice points).

In both EX-A1 and EX-A2, the sound stimuli were presented through a loudspeaker in the anechoic room at Tohoku University. In EX-A1, the number of subjects was six, five of whom also took part in EX-A2. All were male in their early twenties and had normal hearing acuity.

3.2 Results and Discussion

Figure 6 shows the average values in Test 1 and Test 2. The values obtained in Test 2 were calculated as follows: First, we calculated the PSE of the 1 kHz tone, i.e., the level of the reference tone which was felt to be as loud as the test tone of 70 phon according to the results of Test 1, EX-A1. The PSE is essentially but not exactly 70 dBSPL since the level of the test tone is 70 phon. The difference between PSE and 70 dBSPL was then obtained. Next, the difference was subtracted from the presented level of test tone, so that the level of the test tone at 70 phon in Test 2 was obtained. In this procedure it was assumed that there was a linear relation between the sound pressure level and the loudness level of the stimulus tone as the difference was always smaller than a few decibels. As seen from Fig. 6, the depression at frequencies around 400 Hz is noticed only in Test 2. This is very interesting because the manner of selecting the level combinations of standard and test tones in this test was the same as in Robinson and Dadson's experiment. These results also suggest that the subjects perceive the tone with a fixed level to be louder than that with a level that is varied. According to the analysis of variance, the difference between Test 1 and Test 2 is significant beyond the 0.01 level, while the difference between Trial 1 and Trial 2 is not significant even at the 0.05 level. This result seems to show that the difference between Test 1 and Test 2 is substantially irrespective of the lapse of time.

Figure 7 shows a sample of the experimental results of EX-A2 obtained for a subject under a certain condition. The PSE level of the test tone is expressed by a straight line as a function of the level of the reference tone. The intercept and slope of the line were calculated for each experimental condition by means of the maximum-likelihood estimation. Figure 8 shows the results of EX-A2. In Fig. 8, the experimental results of Fletcher and Munson, Robinson and Dadson, and EX1 are represented by different symbols. The experimental results of EX-A1 are also indicated by numerals corresponding to each subject. The upright numerals represent the results of Test 1, while the prostrate ones indicate the results of Test 2. The straight lines are located near the data points from EX1 and those of Fletcher, but far from Robinson's data. The differences between the results of EX-A1 and those of EX-A2 were tested. Table 2 shows the differences between the results of Test 1 and Test 2 in EX-A1 from the straight lines which represent the results of EX-A2. These were calculated as the differences along the vertical axis in Test 1 and along the horizontal axis in Test 2, since the level of the test tone (abscissa) was varied in Test 1 and the level of the reference tone (ordinate) was varied in Test 2. A positive difference indicates that the tone at the fixed level in EX-A1 is felt to be louder than the variable tone at the same level in EX-A2. A significance test, to examine whether the average difference is zero or not, shows that the difference is significantly positive beyond the 0.01 level in Test 2. On the other hand, the average difference in Test 1 cannot be said to be significant. In summary, a test tone might be felt to be louder than it is when its level is fixed and the level of the reference tone is varied, while it would be correctly perceived in loudness when the level of standard tone is fixed and the level of the test tone is varied.

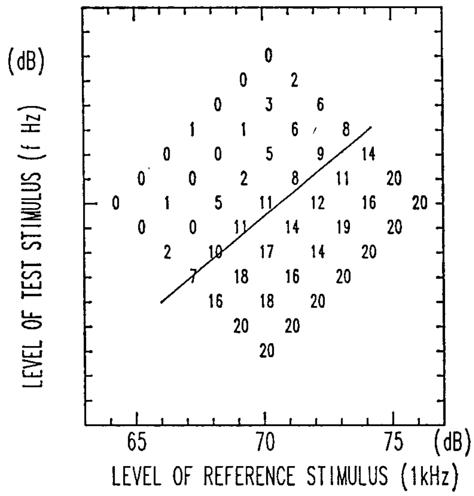

Fig. 7 An example of experimental results of EX-A2. The numbers indicate the number of judgements of the reference tone being louder. There were twenty trials for each pair of stimuli.

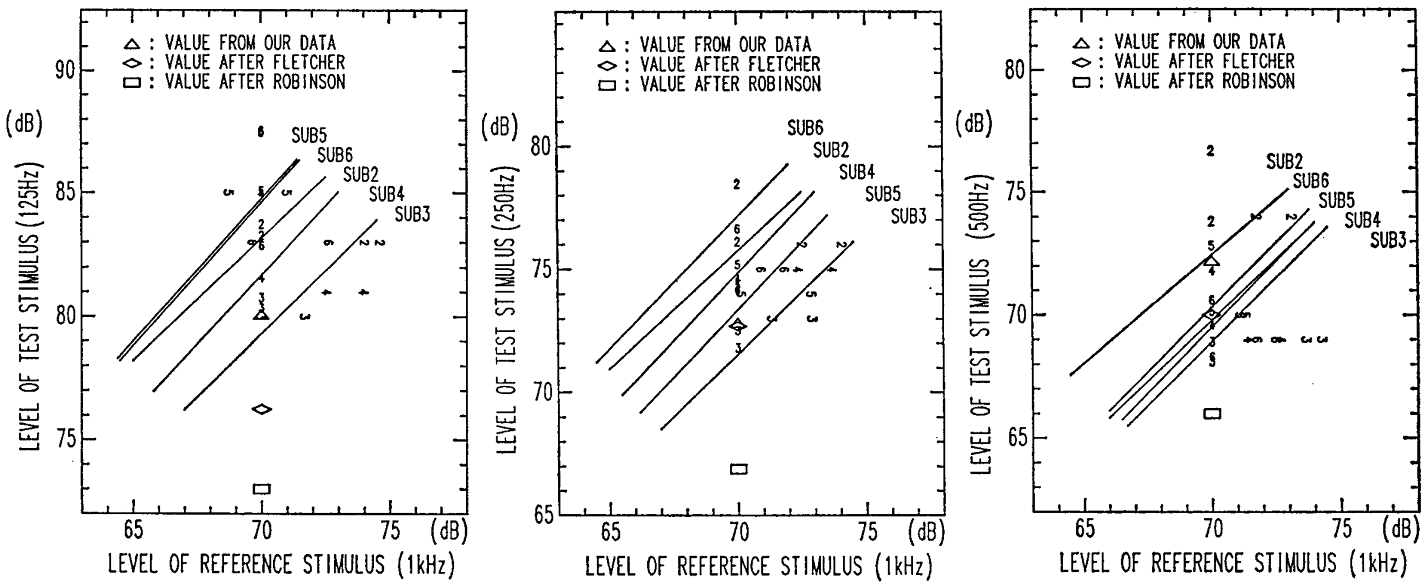

Fig. 8 Results of the supplementary experiment EX-A2. (a) 125 Hz, (b) 250 Hz, (c) 500 Hz.

Table 2 Discrepancy of the results of Test 1 and Test 2 in EX-A1 from the straight lines which represent the results of EX-A2.

	Trial	125 Hz		250 Hz		500 Hz	
		Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
SUB2	1	−0.21	4.19	0.39	2.26	1.37	0.02
	2	0.24	4.79	2.72	3.81	4.26	1.39
SUB3	1	1.13	1.00	0.97	1.47	0.00	3.60
	2	0.71	−0.70	0.27	−0.09	−0.80	4.20
SUB4	1	−0.43	4.59	−0.63	3.52	−0.20	3.49
	2	2.96	3.14	−0.23	2.20	2.03	2.24
SUB5	1	−0.03	0.78	1.00	−0.45	0.64	0.84
	2	2.39	−1.48	1.85	2.27	3.31	0.64
SUB6	1	−2.06	4.01	−2.97	2.90	−1.98	3.73
	2	2.60	1.04	−0.47	3.80	0.30	3.01
Average		0.73 dB	2.14 dB	0.29 dB	2.17 dB	0.89 dB	2.32 dB
S.D.		1.49 dB	2.17 dB	1.47 dB	1.42 dB	1.80 dB	1.42 dB
Significance of the average		*	**		**		**

* Significant beyond 0.05 point.
** 〃 0.01 〃

4. DISCUSSION

As mentioned above, we fixed the level of the reference tone and varied that of the test tone in order to obtain the equal-loudness level contours. We measured the contours for 20, 40 and 70 phon levels in this study. Those curves are similar to the ones obtained by Fletcher and Munson but not so similar to those obtained by Robinson and Dadson. Particularly, the depression at frequencies around 400 Hz in the contours of Robinson and Dadson could not be seen. Two recent German studies show a similar tendency to ours as to the equal loudness levels at frequencies around 400 Hz.[12,13)]

In those papers the sound pressure levels of pure tones for 70 phon at several frequencies below 1 kHz were obtained through psychoacoustic measurement and compared with those estimated from ISO 532B. According to ISO 532B, the loudness of 400 Hz tone, which was perceived as loud as 1,000 Hz tone at 70 dBSPL, is estimated at 8.34 sone, while that of 100 Hz tone at 70 dBSPL corresponds to 8.21 sone in loudness.[12)] Hence the difference between both values if only 0.13 sone or 1.6%. According to ISO 226, on the other hand, the sound pressure level of 400 Hz tone for 70 phon should be 65.8 dB and its loudness is estimated at 5.76 sone after ISO 532B. This value differs by 2.45 sone or 29.8% from that of 1,000 Hz tone at 70 dBSPL.[12)]

Our minimum audible sound fields (MAF) are similar to those obtained by Robinson and Dadson. The MAF obtained by Fletcher and Munson, is about 10 dB above our MAF in the low frequency region. They used headphones in their experiment on threshold determination and transformed it into MAF, so this process might have affected their results along with a little higher ambient noise level.

According to the results of EX-A1 and EX-A2, if the level of test tones is fixed, subjects may perceive the test tones to be louder than they are in the experiments in which the levels of test tones are varied. In the experiment of Robinson and Dadson, in which the level of the test tones was fixed, the values of their equal-loudness level are 3∼10 dB lower than those of EX-A2, while the differences between the equal-loudness level contours by Fletcher and Munson and ours are small. The experimental methods used by Fletcher and Munson are similar to those of EX-A2, that is, they set the level of test tones at one of three different levels at random. They stated that such a procedure was useful in lessening the possibility of error caused by presenting test tones at a constant level throughout a single experimental run. In our experiments EX1 and EX2, the level of test tone was varied while the level of reference tone was fixed. The reason why the test tone is judged to be louder when its level is fixed than when the level of reference tone is fixed might be supposed to be as follows: Since the frequency of test tone at a fixed level changes every run of experiment in Robinson's case, subjects might become sensitive to the renewed tone at a fixed level. Meanwhile, subjects might establish a definite criterion for loudness of 1 kHz tone in our case because they hear the same sound from run to run, and hence they might judge the loudness of test tone easily and correctly as compared with the reference 1 kHz tone. This reasoning, however, needs further evidence.

The experimental method as used in EX-A2 may be the best way to examine the equal-loudness relation. However, it takes much time than our EX1 and EX2 or the method of Robinson and Dadson. If we have to select one of these two experimental methods, varying test tone or varying reference tone, we may as well use the variable test tone paradigm such as EX1 and EX2. This is partly because the results obtained are similar to EX-A2, but mainly because the equal-loudness level contour of X phon is defined as the contour representing sound pressure levels of pure tones at various frequencies which are judged to be as loud as the 1 kHz tone at X dBSPL. Namely, in order to obtain a contour, it might be natural to connect points of sound pressure levels of pure tones at various frequencies which might be felt to be equal in loudness to the reference 1 kHz tone at a fixed level.

The supplementary experiments seem to explain the similarity between our contours and those drawn by Fletcher and Munson to some extent, and also the difference between ours and Robinson and Dadson's. However, since the difference in values between Test 1 and Test 2 reaches 4 dB at most, this reasoning can explain only a part of the difference between our contours and Robinson and Dadson's. It is possible that there are some additional factors which cause the difference.

5. CONCLUSION

According to the results of our experiment, our contours are similar to those given by Fletcher and Munson rather than to those of ISO 226. The depression at frequencies around 400 Hz which characterizes the contours of ISO 226 could not be observed. On the other hand, our minimum audible sound field is similar to that in ISO 226.

From the results of the supplementary experiments, the following is suggested: When comparing the loudness between two tones, one with a fixed level and another with a level that changes at every appearance, subjects show a tendency to perceive the former to be louder than the latter, even if both levels are equal. A part of the discrepancy between the contours of ISO 226 and the present ones seems to be explained by this tendency.

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