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Frequency response of headphones measured in free field and diffuse field by loudness comparison*)

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ABSTRACT

Loudness comparisons were performed by four subjects, under two experimental conditions: free field (anechoic room) and diffuse field (reverberation room). Each subject adjusted the headphone level of critical band noise bursts until they were equally loud as those from a reference loudspeaker (70 dB SPL). Measurement scatter was smaller in the diffuse field than in the free field. To examine the reliability of loudness judgments at high frequencies, another method--hearing thresholds by Békésy tracking--was employed. Each subject's threshold was measured with both loudspeakers and headphones. After compensation was made for the loudspeaker and room transfer functions, headphone frequency response was extrapolated from the results. This method led to high-frequency responses similar to those from loudness comparison. A loudness comparison experiment in which the subjects continuously wore a headphone was performed. However, the method of sound pressure loss measurement should be reconsidered.

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INTRODUCTION

In various psychoacoustical experiments, headphones are preferably used for stimulus presentation. As is often the case for electric-acoustic transducers in general, frequency response is a crucial factor in determining the quality of the sound reproduced with headphones. 'Real-ear' frequency response is especially important for psychoacousticians who use headphones in experiments (Fastl, 1979a,b). For instance, the loudness of a sound with wide-band spectral energy distribution was affected by the real-ear frequency response of headphones (Fastl et al., 1985). The estimated values of critical bandwidth were also similarly influenced (Fastl and Schorer, 1986). Moreover, identification results of synthetic vowels (or, more precisely, harmonic complex tones) differed considerably according to the difference in the real-ear frequency response between the two headphones used (Ueda and Hirahara, 1990; Hirahara and Ueda, 1990).

How then can we get the 'real-ear' frequency response of headphones? Possible measurement methods are largely divided into two categories: physical and psychophysical. Within the first category, there are three specific methods which utilize different measurement apparatus: couplers (Burkhard and Corliss, 1954; Miura et al., 1982; Miura et al., 1983), dummy heads (Schröter and Els, 1982; Okabe et al., 1984), and probe tube microphones (Show, 1966; Villchur, 1969, 1970; Cox, 1986) or a miniature microphone (Fastl et al., 1985; Fastl, 1986; Theile, 1986). The second category, the psychophysical method, includes a loudness comparison method (Zwicker and Maiwald, 1963; Fastl and Fleischer, 1978; Fastl and Zwicker, 1983; Fastl et al., 1985; Miura et al., 1985; Ueda and Hirahara, 1989).

For each of these methods, however, some problems are pointed out. Coupler measurement of headphone frequency response may be incorrect at high and low frequencies (Burkhard and Corliss, 1954; Zwicker and Maiwald, 1963; Shaw, 1966; Fastl and Zwicker, 1983; Fastl et al., 1985; Cox, 1986; Fastl, 1986; Zwislocki et al., 1988; Ueda and Hirahara, 1990; Hirahara and Ueda, 1990). Dummy head measurement may also be incorrect at low frequencies partly because of incomplete simulation of the human pinna elasticity and partly because of incomplete simulation of the acoustic impedance of the human ear (Schröter et al., 1986; Theile, 1986; Ueda and Hirahara, 1990; Hirahara and Ueda, 1990). Measurement in the ear canal using probe tube microphones or miniature microphones can avoid these problems, i.e., the incomplete simulation of the human ear. However, the fundamental problem with this method is that "there is no single 'eardrum location'" (Chan and Geisler, 1990), and the measured sound pressure differed up to 15 dB from one edge of the eardrum to the other (Stinson and Shaw, 1982). It is difficult to reproduce the same results using a probe tube microphone (Killion et al., 1987; for review, see Buus et al., 1986).

Whereas psychophysical methods, including loudness comparison, are free from the 'eardrum location' problem. However, some researchers suspect that loudness comparison at high frequencies may be unreliable since the sensation of loudness becomes less unambiguous at frequencies higher than 8 kHz (Miura et al., 1985).

The purpose here is to investigate psychophysical methods, mainly a loudness comparison method, assessing the real-ear frequency response of headphones. To examine the influence of field characteristics on the reliability of the measurement, the experiments were run under two conditions: free field and diffuse field. To examine the reliability of loudness judgments at high frequencies, another psychophysical method, hearing threshold measurement by Békésy tracking, was employed. Moreover, to reduce the scatter caused by putting on and removing headphones, a loudness comparison experiment in which the subjects continuously wore a headphone, was performed.

I. EXPERIMENT 1

A. Method

1. Stimuli

Twenty-four critical band noise bursts were used as stimuli. The center frequencies of these noise bursts were spaced every 1 bark from 1 to 24 bark. Critical bandwidths were calculated according to the equation of Zwicker and Terhardt (1980). The stimuli were synthesized on a computer (MASSCOMP MC 5600), adding sine and cosine waves of the same amplitude (samples at 48 kHz, quantized into 16 bits). The frequency components were equally spaced on a linear scale, and their initial phases randomly chosen. For stimuli centered on 1 to 22 bark, the frequencies of adjacent components were spaced 1 Hz. Stimuli centered on 23 and 24 bark were spaced 10 Hz. The duration of each stimulus was 1 sec, including the 20 ms rise- and fall-time.

The stimuli were D/A converted with a 16-bit converter (PAVEC MD8300 MKII), then passed through lowpass filters (NF FV665; 20 kHz cutoff, 96 dB/Oct).

In the loudness comparison experiment under diffuse field conditions, the stimuli presented via headphones were not the original stimuli but those recorded at the subject position in the experiment room so that the room reverberation was included.

2. Procedure

The headphone investigated in this experiment was the STAX SR Lambda Professional with a STAX SRM-1/MK 2 adaptor. This headphone has an electrostatic, open, and circumaural type structure.

The experiment was run under two conditions: free field and diffuse field. For the free field condition, an anechoic room was used. A loudspeaker (JBL 4410) was placed 2.5 meters in front of the subject. For the diffuse field condition, a reverberation room was used. The ATR Variable Reverberation Time Room (Tohkura, 1989) at full reflection setting was used as the reverberation room. Four loudspeakers (two JBL 4344s and two YAMAHA NS-2000s) were placed, with their fronts facing the corners of the room. Figure 1 shows the settings in the experiment rooms.

Method of adjustment was employed in the loudness comparison experiments. First, the subject heard the reference stimulus presented through the loudspeaker(s) and memorized its loudness. The sound pressure of the loudspeaker output was set at 70 dB SPL at the subject position. Then the subject put on the headphone and heard the stimulus presented diotically through it. He or she was required to adjust the sound pressure of the headphone output until its loudness equaled to that of the loudspeaker(s). Subjects were allowed to repeat the sequence as many time as they like, until they reached to the final decision. Four adjustments were accomplished for each stimulus whose order of presentation was random.

To check the reliability of loudness comparison at high frequencies, another method was employed: a method measuring subjects' hearing thresholds by Békésy tracking. Each subject's hearing threshold was measured both with the loudspeaker(s) and the headphone. After compensating for the loudspeaker and room transfer function, the headphone frequency response was extrapolated from the results.

The subjects were two males and two females. Each subject was tested under in both conditions.

B. Results

The results expressed as medians are shown in Figs. 2 and 3. Dots refer to the loudness comparison results. Open circles refer to the threshold measurement results. In Fig. 3, the results obtained by Theile (1986) through physical measurement are also shown: He measured the diffuse field response of the same headphone with a miniature microphone placed in the ear canal. All curves are plotted so that the average along the frequency axis is zero. None of the methods produced a flat response, under either sound field condition.

Interquartile ranges were calculated for the loudness comparison results. The interquartile ranges averaged over each subject were 2.2 dB for the free field condition, and 1.8 dB for the diffuse field condition. Averaged over all subjects, they were 3.1 dB and 3.2 dB, respectively.

Under free field conditions, the result of the loudness comparison and the threshold measurement agree very well (Fig. 2). Under diffuse field conditions, however, the threshold measurement results show a low frequency response several dB higher than the loudness comparison experiment results (Fig. 3). The physical measurement results (Theile, 1986) are similar to the loudness comparison results.

The two figures are remarkably different at frequencies above 2 kHz: The free field response shows a larger difference between the dip around 3 kHz and the peak around 10 kHz than the diffuse field response.

C. Discussion

The difference between the free field response and the diffuse field response at high frequencies can be attributed to the directivity of the head and the outer ear.

Concerning the measurement scatter of the loudness comparison results, it is not clear whether the difference between the two conditions is statistically significant, because method of adjustment was employed in the experiments. At the very least, however, the averaged values of measurement scatter in each subject *per se* were smaller in the diffuse field than in the free field. One hypothesis to explain this result is that head movement causes less change in level in a diffuse field than in a free field. To examine this hypothesis, we obtained the sound pressure level distribution in the two rooms (Fig. 4). In the free field, we could not choose measuring points symmetrically along the X axis. Thus the graph looks asymmetric. Our hypothesis is supported by the fact that the SPL distribution is flatter in the diffuse field than in the free field.

Under both conditions, the measurement scatter within the subjects was smaller than that averaged over all subjects' data, for the loudness comparison results. This means that the individual differences were significant.

As far as medians are concerned, loudness comparison is a reliable method even at high frequencies, since the loudness comparison results were similar to the threshold measurement results. There may be a problem about headphone linearity in low levels. However, judging from the results, this would not be a serious problem.

The diffuse field response measured with threshold measurement shows a low frequency response several dB higher than that measured with the loudness comparison method (Fig. 3). Whereas concerning the free field response, the difference between the results of the two methods are well within the measurement scatter. We regard the difference observed in the diffuse field response as due to the ambient noise of the experiment room (the reverberation room) at low frequencies, which is several dB above the hearing threshold. There is no audible ambient noise under free field conditions, in the anechoic room. In addition, loudness overestimation for loudspeaker sound (Rudmose, 1982) might occur at low frequencies under diffuse field conditions, because the subjects were not insulated from floor vibration.

There are small differences observed in Fig. 3, between the loudness comparison results and the physical measurement using a miniature microphone (Theile, 1986). One possible explanation for this, is the fact that loudness equality between loudspeaker sound and headphone sound does not always mean equal sound pressure in the ear canal: Except frequencies around 3 kHz, an SPL 3-4 dB higher is needed for headphone sound to attain equal loudness to loudspeaker sound (Fastl et al., 1985; Fastl, 1986). It is problematical, however, whether the measured ear canal pressure truly represents the 'eardrum' pressure, especially at high frequencies, since it is impossible to decide a single eardrum location.

II. EXPERIMENT 2

To examine whether the same tendencies are observed for a largely different type headphone, we ran an additional experiment.

A. Method

The stimuli and the experiment procedure were generally the same as in Experiment 1. The only differences were:

(1) A largely different type headphone, the Beyer DT 48, was used. This is a dynamic, closed, circumaural type headphone. The headphone was driven with an ACCUPHASE E-305 amplifier.

(2) One male subject participated in the experiment. He was one of the subjects in Experiment 1.

B. Results and discussion

Results are shown in Figs. 5 and 6. The averaged interquartile ranges of the loudness comparison results were 2.9 dB and 2.0 dB, respectively. Once again, the frequency response of the headphone was not flat, irrespective the measurement methods. The difference in the results obtained using different methods shows the same tendencies observed in Figs. 2 and 3. However, the generality of these results is somewhat uncertain, since only one subject participated in this experiment.

III. EXPERIMENT 3

To reduce measurement scatter, and to husband experiment time, it would be possible to perform a loudness comparison experiment in which the subjects continuously wore a headphone. To check the reliability of this procedure, a further experiment was performed.

A. Method

A STAX SR Lambda Professional headphone was used. The stimuli were the same as in Experiments 1 and 2 but the procedure was different. Each subject continuously wore his headphone, and heard loudspeaker sound. The experiment was performed only under free field conditions.

If we knew exactly how much sound pressure loss will take place when the loudspeaker sound goes through the headphone, we could extrapolate its true frequency response from the experiment data. To measure the sound pressure loss caused by the headphone, we used a dummy head (KOHKEN, SAMRAI).

Two male subjects participated in the experiment.

B. Results and discussion

Results obtained both with the previous procedure and this procedure are shown in Fig. 7. The averaged interquartile range for subject A (Fig. 7a) was reduced from 2.8 dB to 2.1 dB by employing this procedure, whereas that for subject B (Fig. 7b) was unchanged (1.5 dB). This can be explained by the fact that subject B needed about twice as much time to perform the 'putting on and removing' procedure compared to subject A: Scatter would have been reduced had the subject made many adjustments before he reached a final decision.

The extrapolated frequency response does not agree well with the results obtained using the previous procedure, especially for subject A. One obvious problem with the dummy head compensation method, is that it does not take individual differences into account. For more exact compensation, measurement utilizing a probe tube microphone would be needed.

IV. GENERAL DISCUSSION

Since human subjects can detect spectral changes less than 1-2 dB irrespective of frequency (Spikofski, 1988), measurement scatter of frequency response should be reduced at least to this level. If we consider to calibrate headphones for each subject, the measurement scatter in the case of STAX SR Lambda was very near to this level. However, larger scatter was observed for Beyer DT 48. Obviously, the difference was caused by headphones, not the method.

It is difficult to measure absolute 'ear-drum' pressure physically. However, as Theile (1986) has shown theoretically, it is quite possible to measure relative frequency response of headphones physically, if one has a probe-tube or a miniature microphone whose influence on the sound pressure in the ear canal can be negligible. It is also possible to use a dummy head for this purpose, provided that there is no mechanical problem, such as insufficient elasticity of the pinna (Shroeter and Poesselt, 1986; Schröter et al., 1986).

These physical methods have many advantages, compared with psychophysical methods (Theile, 1986; Schröter et al., 1986). The results of our experiments can be regarded as a proof to justify Theile's method.

V. CONCLUSION

The results of our investigation indicated that the loudness comparison method is reliable in assessing real-ear frequency response of headphones, even at high frequencies. Measurement scatter was less in the diffuse field than in the free field. Both the investigated headphones had non-flat frequency response. A loudness comparison experiment in which the subjects continuously wore a headphone was performed. However, the method of sound pressure loss measurement should be reconsidered.

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CAPTIONS

FIG. 1. Experimental settings. (a) Free field condition in an anechoic room. Room size: 5.4 X 4.8 X 4.0 (m). (b) Diffuse field condition in a reverberation room. Room size: 10.9 X 6.7 X 4.2 (m).

FIG. 2. Free field response of STAX SR Lambda Professional. Medians of four subjects data.

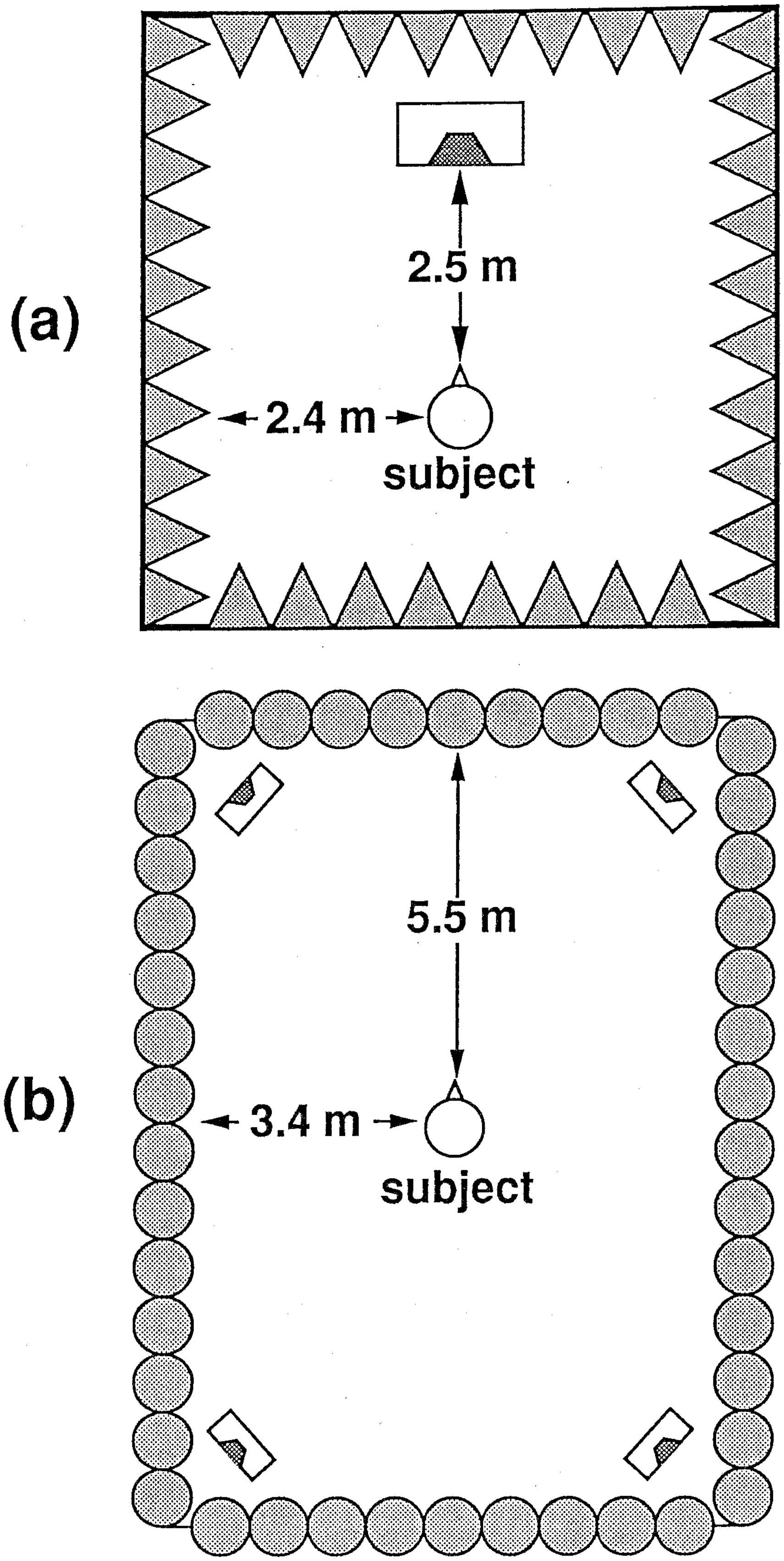
FIG. 3. Diffuse field response of STAX SR Lambda Professional. Medians of the same four subjects data as in the Fig. 2. Physical measurement data, based on Theile (1986), are also shown.

FIG. 4. Sound pressure level distributions measured under the both conditions. The X- and Y- coordinates denote the measureing points. In the anechoic room, the distance between the each adjacent measuring point was 50 cm, whereas in the reverberation room, it was 1 m. The vertical axes indicate sound pressure level. (a) In the anechoic room: 16 kHz. (b) In the reverberation room: 16 kHz. (c) In the anechoic room: 1 kHz. (d) In the reverberation room 1 kHz. (e) In the anechoic room: 100 Hz. (f) In the reverberation room: 100 Hz.

FIG. 5. Free field response of Beyer DT 48. Medians of one subject data.

FIG. 6. Diffuse field response of Beyer DT 48. Medians of the same subject data as in Fig. 5. Physical measurement data are based on Theile (1986).

FIG. 7. Free field response of STAX SR Lambda Professional. The results obtained with the previous procedure and that with the procedure of Experiment 3. are compared. (a) Subject A. (b) Subject B.



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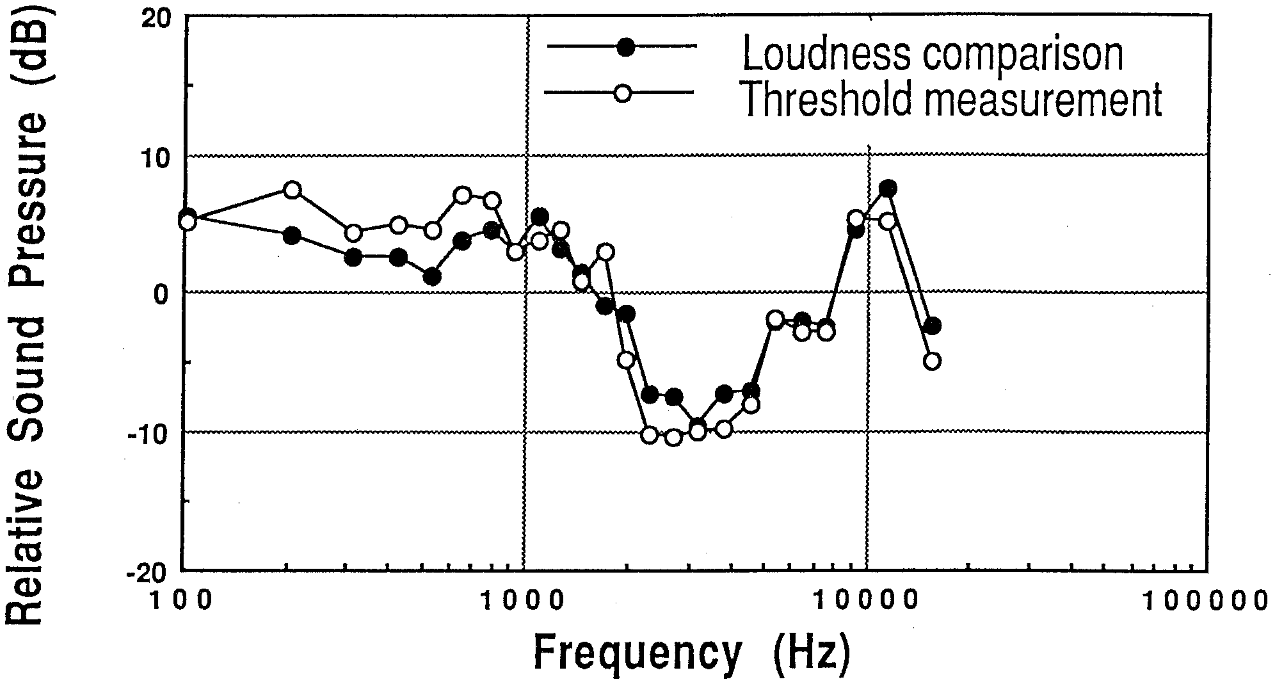
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10
0
-10
-20
100
1000
10000
100000
Frequency (Hz)
Loudness comparison
Threshold measurement

FIG. 2

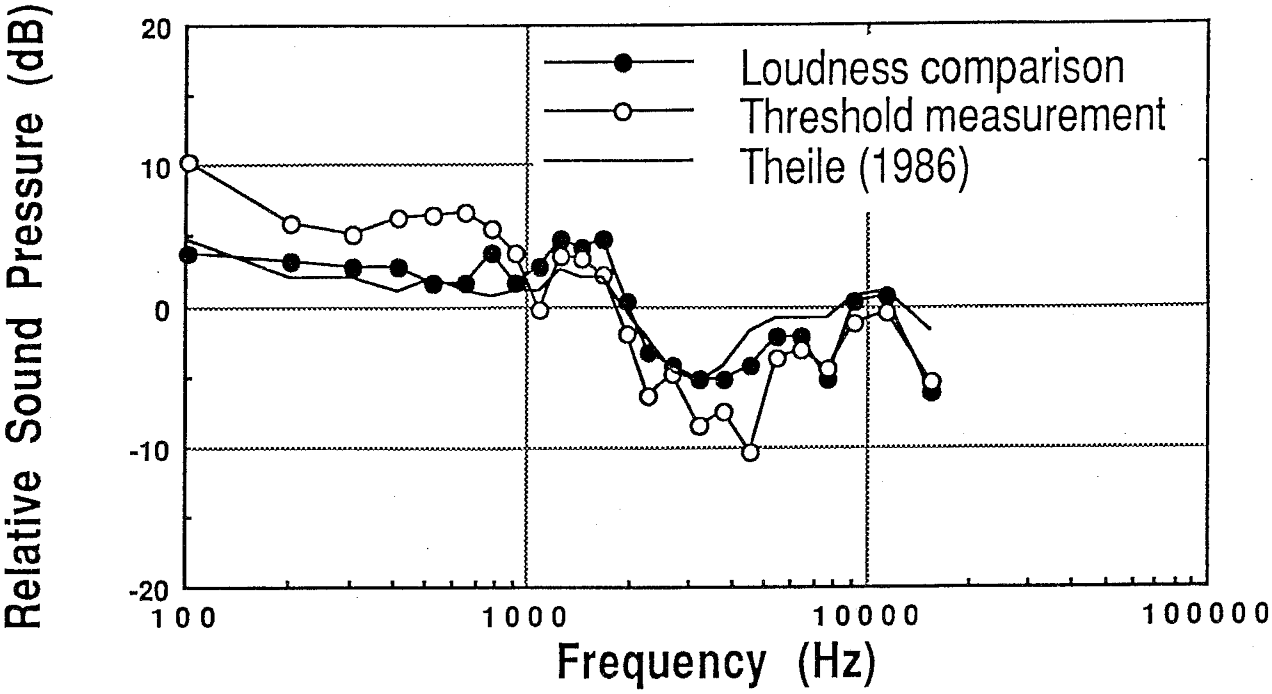
Relative Sound Pressure (dB)
20
10
0
-10
-20
100
1000
10000
100000
Frequency (Hz)
● Loudness comparison
○ Threshold measurement
Theile (1986)

FIG. 3

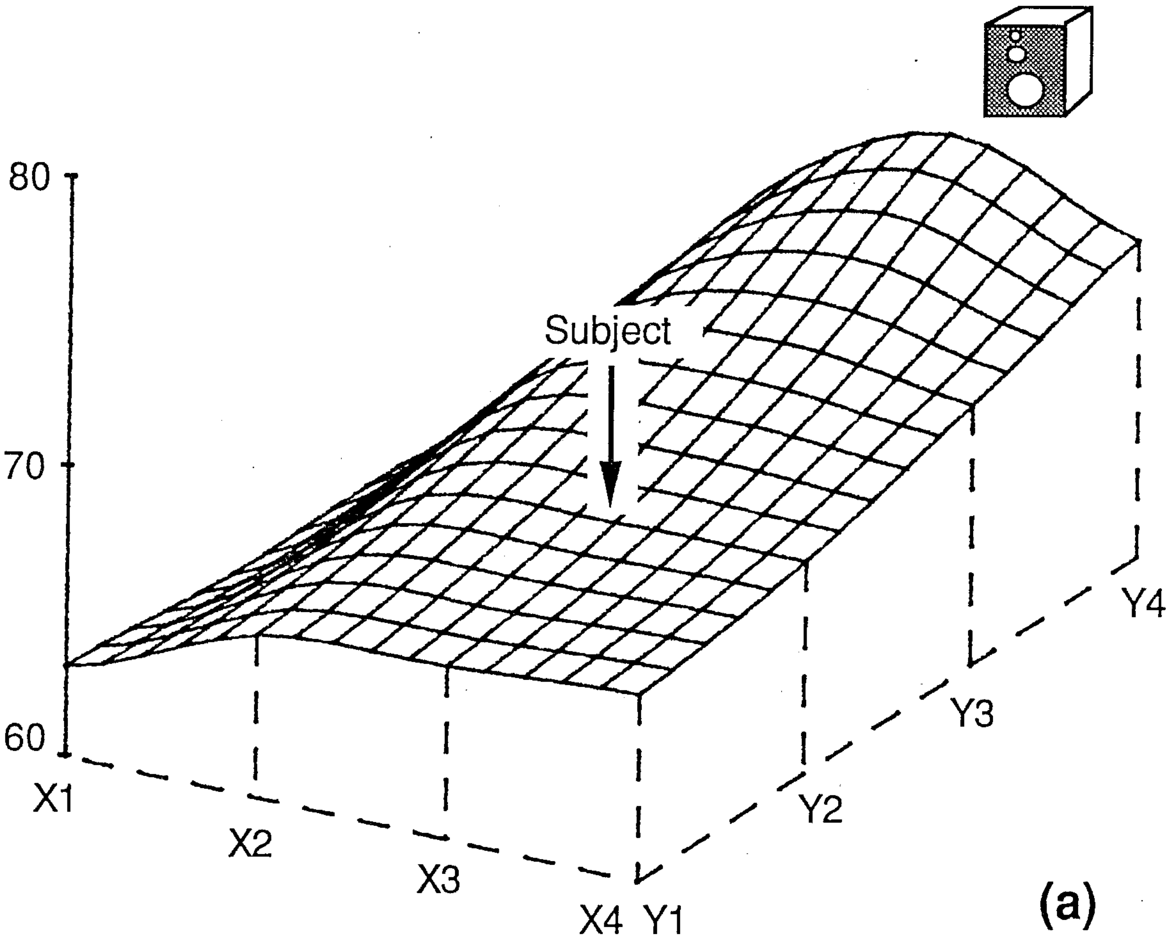

Fig. 4

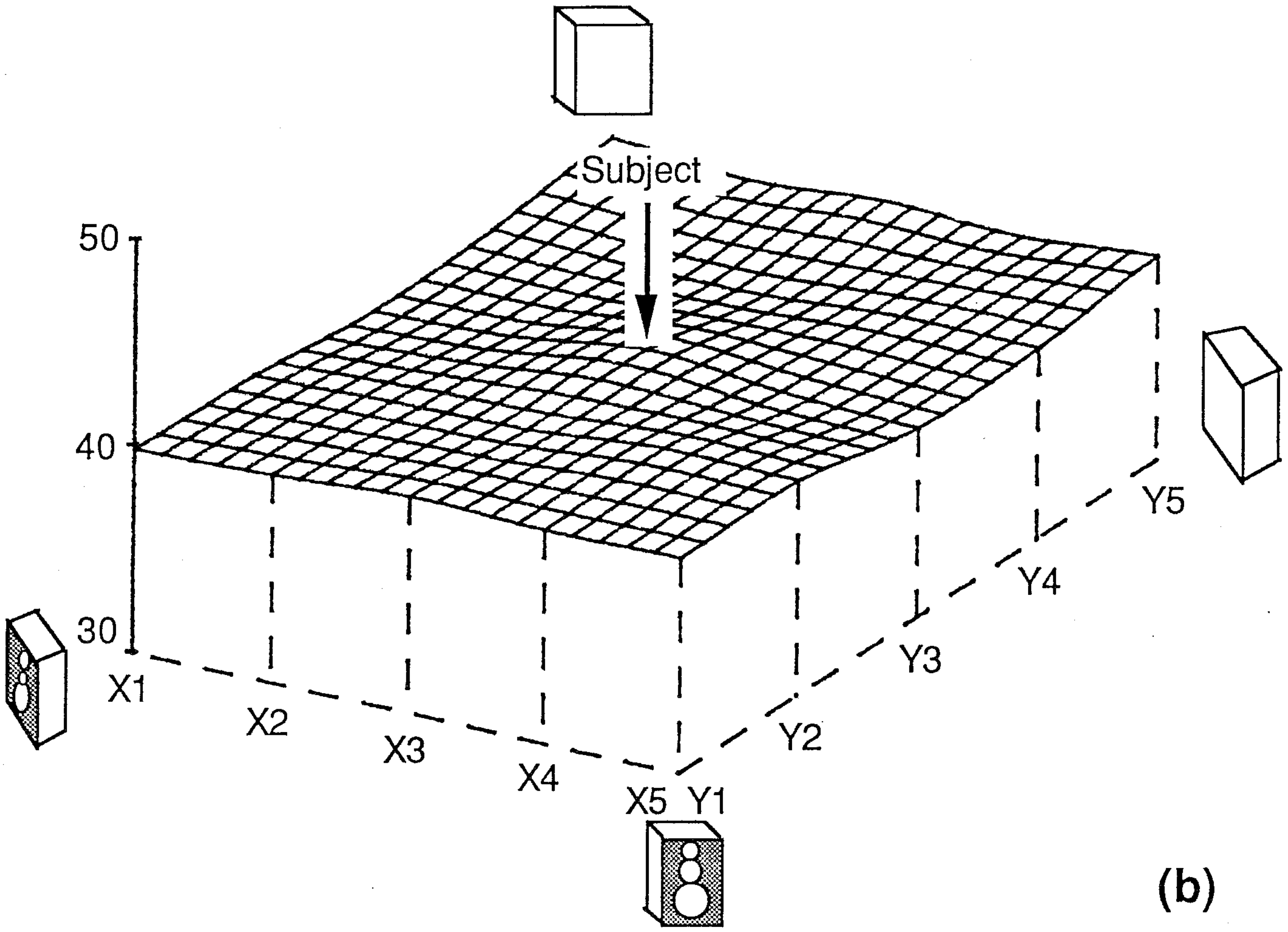

Fig. 4

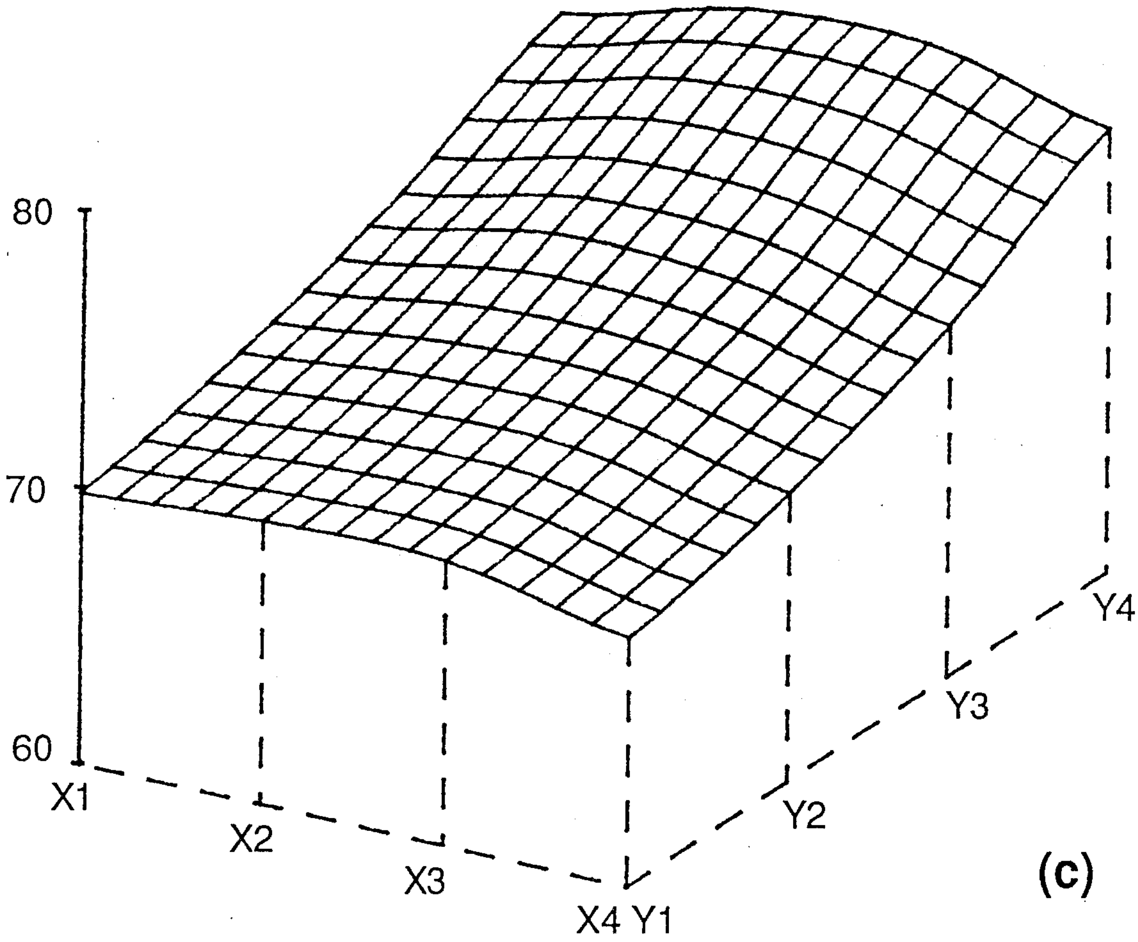

Fig. 4

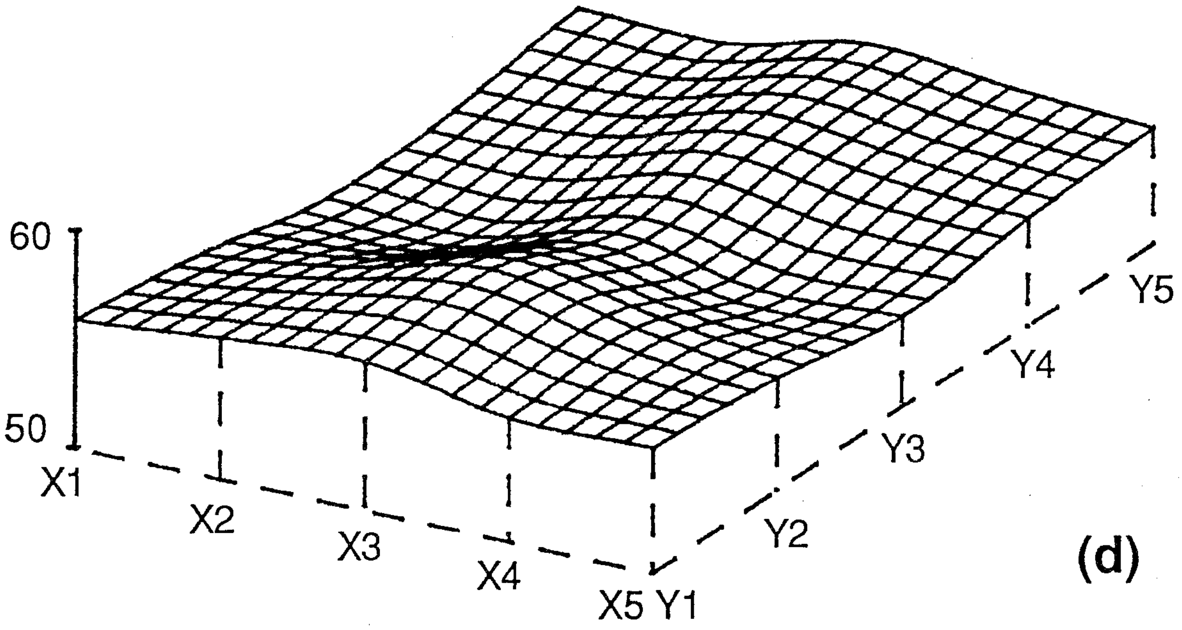

Fig. 4

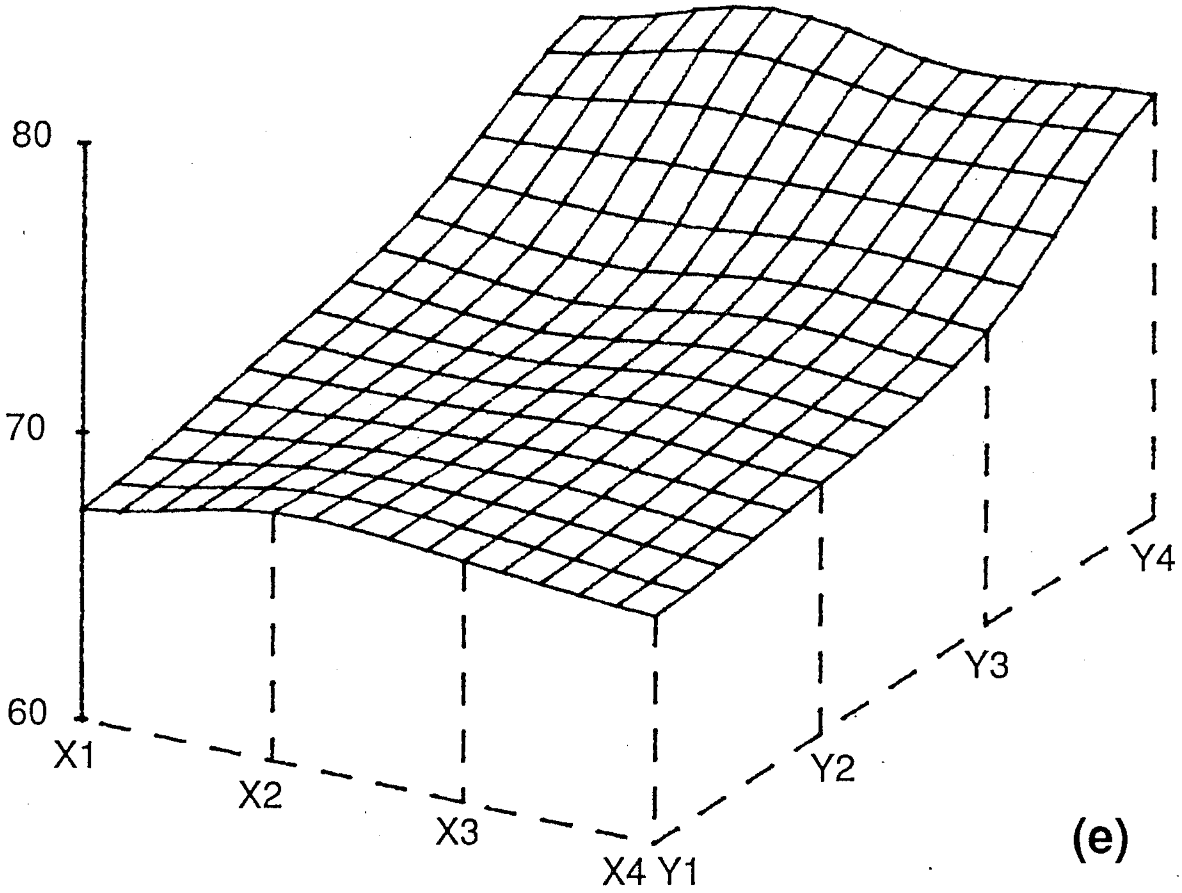

Fig. 4

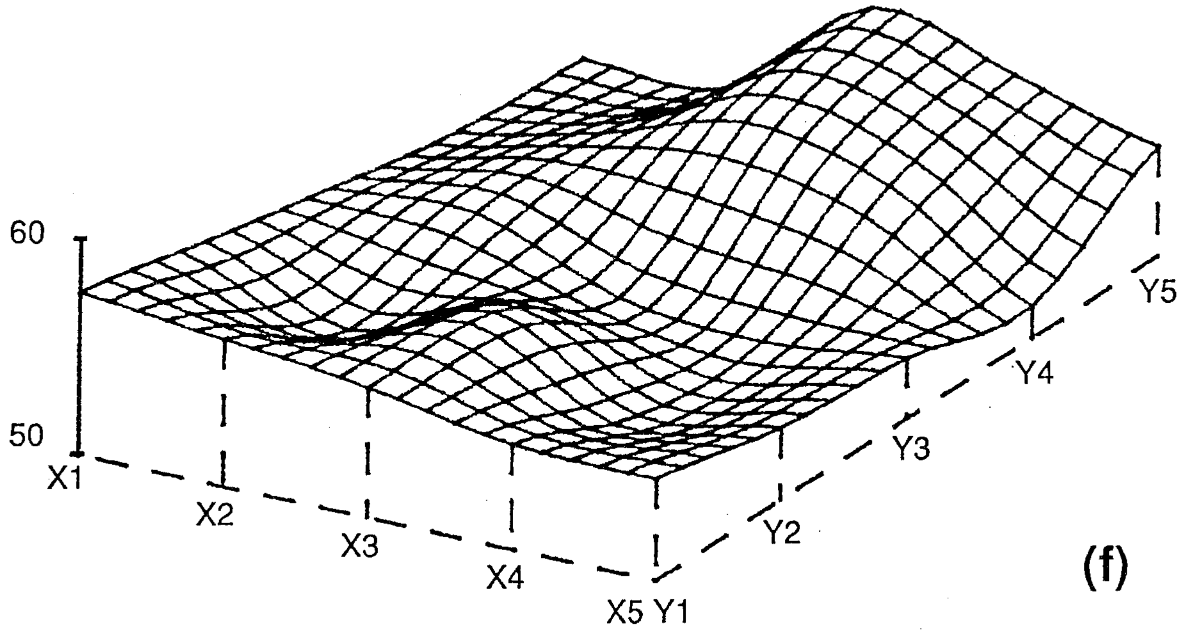

Fig. 4

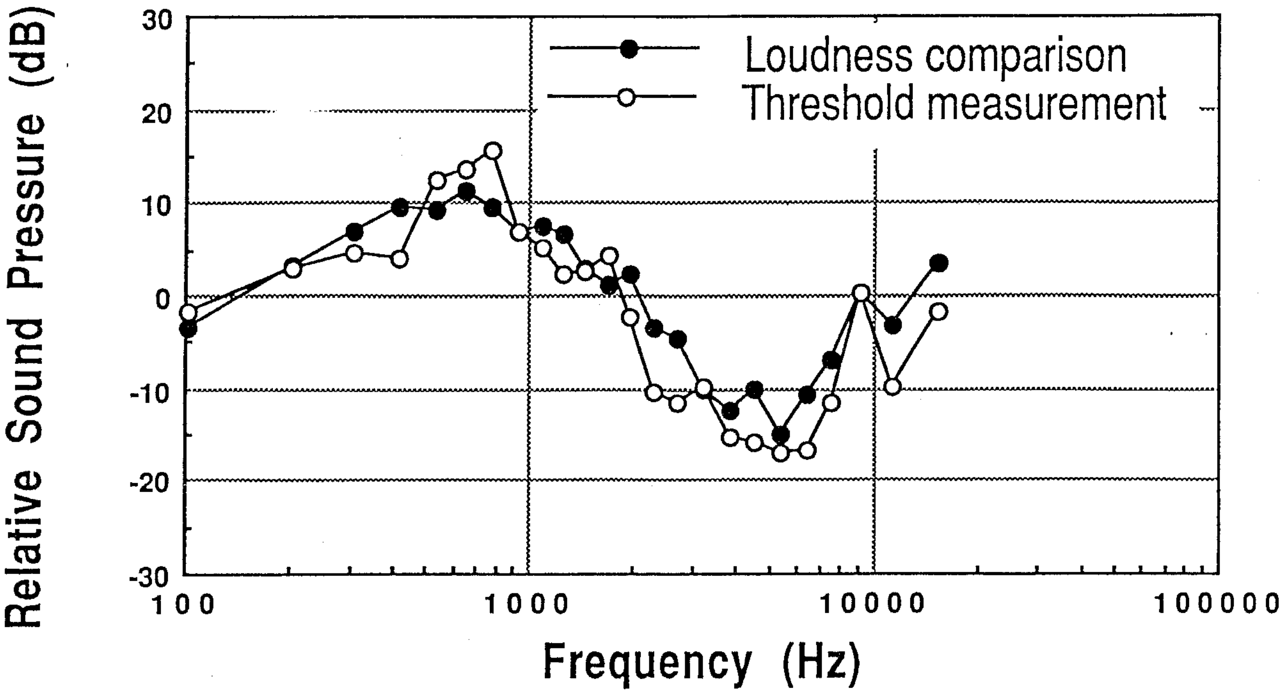
Loudness comparison
Threshold measurement
Relative Sound Pressure (dB)
30
20
10
0
-10
-20
-30
100
1000
10000
100000
Frequency (Hz)

FIG. 5

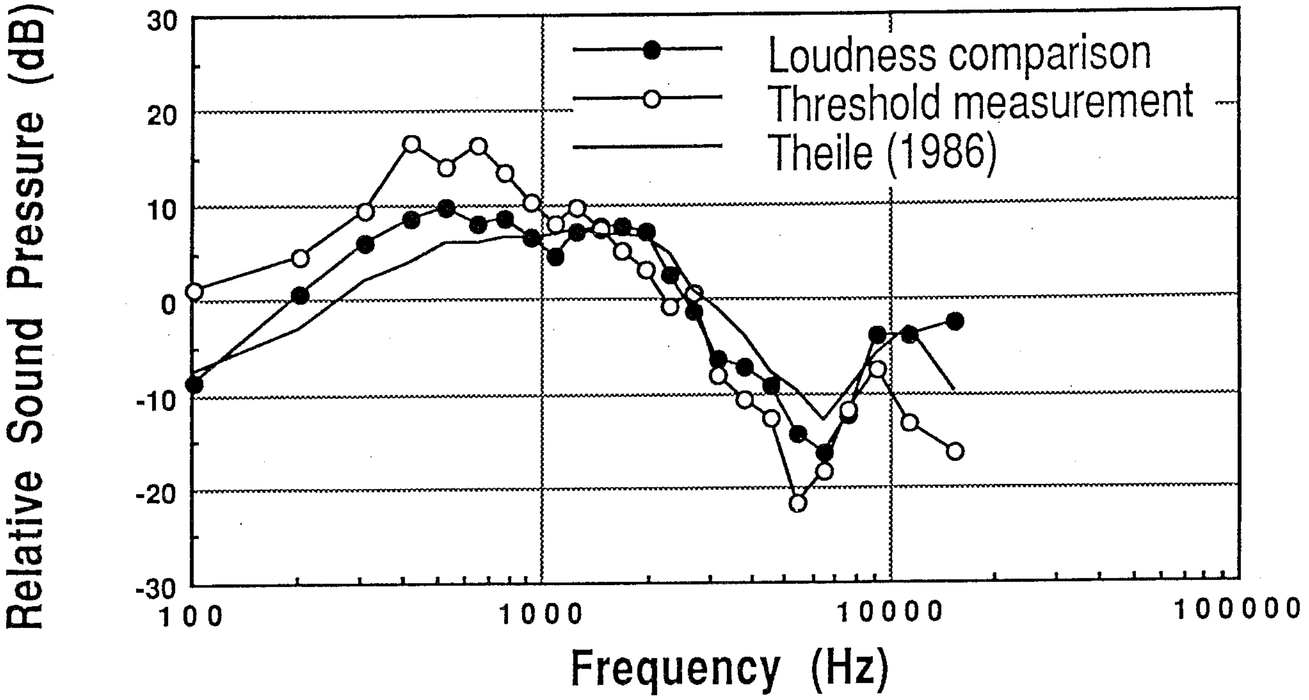
Relative Sound Pressure (dB)
30
20
10
0
-10
-20
-30
100
1000
10000
100000
Frequency (Hz)
Loudness comparison
Threshold measurement
Theile (1986)

FIG. 6

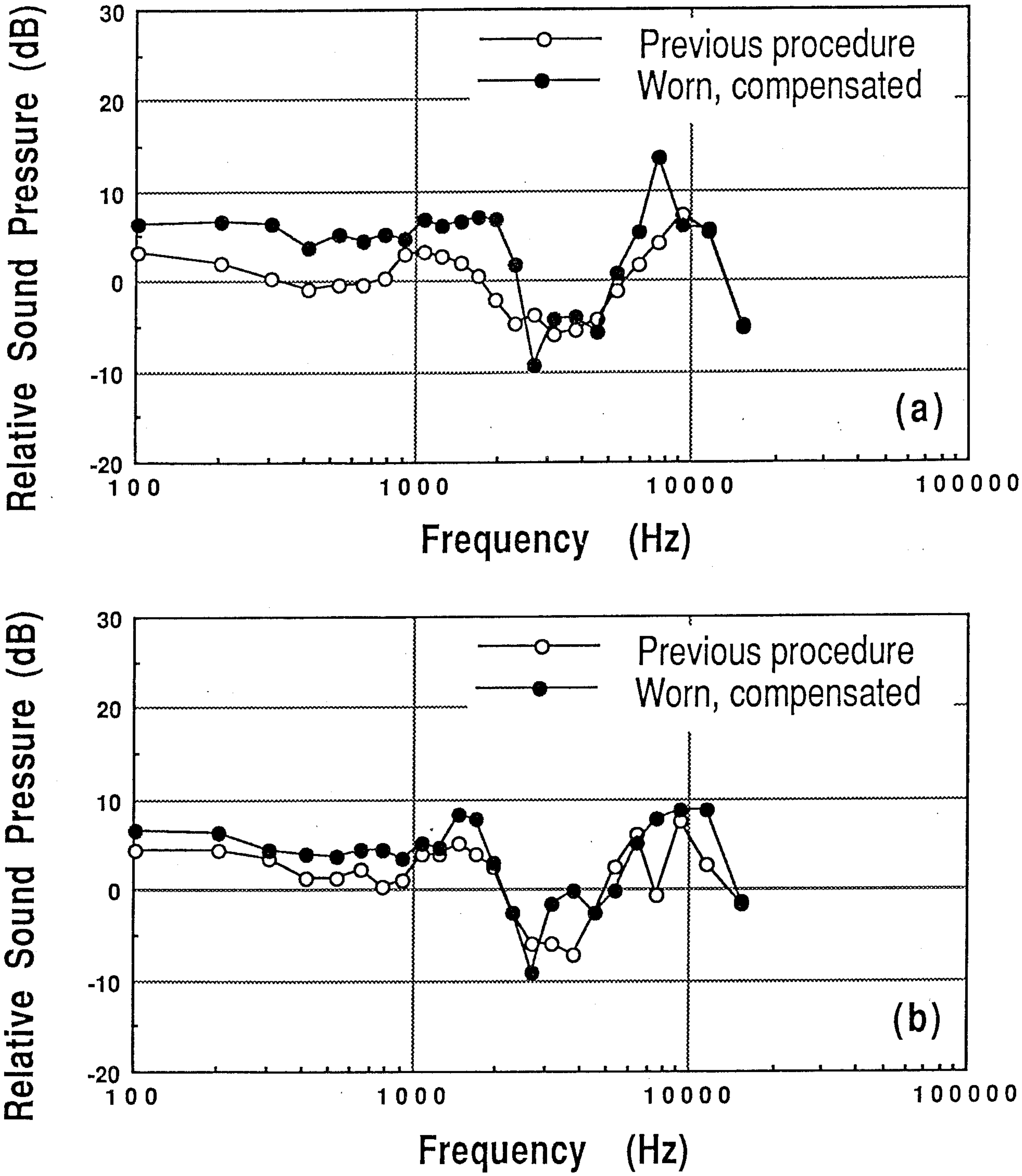
Relative Sound Pressure (dB)
30
20
10
0
-10
-20
100
1000
10000
100000
Frequency (Hz)
Previous procedure
Worn, compensated
(a)
Relative Sound Pressure (dB)
30
20
10
0
-10
-20
100
1000
10000
100000
Frequency (Hz)
Previous procedure
Worn, compensated
(b)

Fig. 7