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ABSTRACT

To simulate actual usage conditions, the frequency response of hearing aids was measured on the head of a manikin over the frequency range of 0.2 to 8 kHz. The acoustic pressure around the head can vary rapidly as a function of frequency and location. In order to compare and interpret the hearing aid response at various frequencies and locations on the head, it is necessary to precisely know the pressure variations. The amplitude and phase of the acoustic pressure were measured in increments ranging from 2 mm to 5 mm alongside a manikin's head with frontal sound incidence. The acoustic driver was located in front of the manikin at a distance of 1.0 m from the ear canal axis. The test frequencies were the octave band center frequencies from 0.5 kHz to 4.0 kHz and the third octave band center frequencies from 4.0 kHz to 8.0 kHz. It will also be shown that pink noise of 6% and 29% bandwidth at 6.3 kHz and 8.0 kHz has a smoothing effect on the acoustic pressure variation with location.

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*As presented at the 91st meeting of the Acoustical Society of America, Statler-Hilton Hotel, Washington, D.C., April 7, 1976.

NOTATION

a = radius of the sphere

$D_m(ka)e^{-i\delta_m(ka)} = i\,\dfrac{dh_m^{(2)}(ka)}{d(ka)}$ where $h_m^{(2)}(ka)$ is the spherical Hankel function of the second kind.

$i = \sqrt{-1}$

k = acoustic wave number

m = summation index

p_i = incident pressure on the sphere's surface

p_o = free field plane wave pressure

p_s = scattered pressure on the sphere's surface

P_m = m-th order Legendre Polynomial of the first kind

r = radial distance from the center of the sphere

θ = angle between the incident wave field and a point on the sphere's surface

INTRODUCTION

In the past, the gain, the frequency response, the saturation level and the distortion in hearing aids have been measured between 0.2 and 5.0 kHz in a (approximate) free field using a 2-cm^3 coupler (ANSI, 1975; IEC, 1958). It can be expected that in the near future the useful frequency range of hearing aids will be extended to approximately 8 kHz. Furthermore, it is well known that the head and/or the torso causes the sound pressure level around the head, where hearing aids are typically placed, to differ considerably with position and with frequency, from the free-field pressure level (Wiener, 1947a, 1947b; Rschevkin, 1963; Burkhard and Sachs, 1975; Kuhn, 1976). In order to test and compare the performance of different hearing aids (see for example, ANSI, 1975 and Veterans Administration, 1975), under conditions which resemble those that are actually encountered in practice, it is desirable to account for the diffraction effects of the wearer's head and torso. An electroacoustic manikin has recently been developed (Burkhard and Sachs, 1975) which dimensionally represents the median sized person. Using frontally incident sound, Madaffari (1974) measured the acoustic pressure as a function of frequency on the side of this manikin's head at 30 points, spaced 2 cm apart on a rectangular grid. These pressure measurements do show severe pressure minima and maxima both as a function of frequency and location. As expected from theoretical predictions (Wiener, 1947b; Rschevkin, 1963) the pressure level behaves smoothly with position at low frequencies but becomes less and less well behaved as the frequency is increased above 2 kHz.

Since the head is not perfectly spherical or spheroidal and since it has several protrusions and indentations such as the eyes, nose, mouth and pinnae, analytical predictions of pressure at the surface of the head can only be approximate. The purpose of this investigation, therefore, is to measure the acoustic pressure alongside this manikin's head at 2-5 mm intervals for fixed center frequencies. Pressure measurements were made with discrete tones at preselected frequencies. Since the pressure level, at high frequencies, changes rapidly with position and since sharp pressure minima exist, the microphone location is critical. Therefore, at the upper frequencies pressure measurements were also made with 6% and 29% bandwidth pink noise (around those same center frequencies) in order to investigate the spatial "smoothing effect" that noise would have on the pressure maxima and minima alongside the head.

THEORY

Diffraction of sound by a rigid sphere has been treated by many authors (for example, Firestone, 1930; Wiener, 1947a; Morse, 1948; and Rschevkin, 1963) and a derivation is therefore not repeated here. The formulation by Rschevkin (1963) for the total pressure on the surface of a rigid sphere is particularly useful. His solution for the total pressure, that is, the incident pressure plus the scattered pressure, normalized to the incident free-field pressure, is

$$\left[\frac{p_i+p_s}{p_o}\right]_{r=a} = \left(\frac{1}{ka}\right)^2 \sum_{m=0}^{\infty} \frac{i^m P_m(\cos\,\theta)(2m+1)}{D_m(ka)e^{-i\delta_m(ka)}} \tag{1}$$

wherein the harmonic frequency dependence has been suppressed.

Morse (1948) generated a set of tables (and small and large argument functional approximations) which allow Eq. (1) to be readily evaluated. Equation 1 will be used to evaluate the head surface pressures up to 2.0 kHz (see section on Results).

Spherical coordinates (r,θ,ϕ) were used to derive Eq. (1). However, the measurements were made in a cartesian coordinate system (x,y,z). Therefore, to compare theory and experiment, the experimental results around the side of the head were transformed to a spherical coordinate system with $\phi = 0°$, using the expression

$$\theta° = 360° \frac{\text{distance from the head's median plane to the measurement point}}{\text{head's circumference in the measurement plane}} \quad (2)$$

EXPERIMENT

The pressure measurements were made on the manikin in the upright position in a 500 m^3 free volume anechoic room as shown in Fig. 1. The mouth of the acoustic driver shown on the left is 49 mm in diameter and is 1.0 m* from the ear canal axis in the horixontal plane. A "1/4-inch" microphone, on the axis of the mouth of the driver, was used as a feedback microphone to maintain the same pressure at all frequencies at this feedback microphone. (This feedback microphone was not used for measurements with noise.) A "1/2-inch" microphone with a 9.3 cm long, 2-mm internal diameter probe, filled with damping material, was used to measure the pressure alongside the head. The probe microphone is shown in Fig. 2.

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*The 1.0 m distance is typical of conversational speech and is being considered for hearing aid testing (Burkhard, 1976). These and other pressure measurements were also made at a source to ear canal-axis distance of 3.5 m and will be the subject of a future paper.

Since the pressures around the head were normalized to the free field incident pressures at any one frequency, the microphone probe does not need to be calibrated. However the probe microphone must be stable. Initially, some foam was wrapped around the microphone and preamplifier but later removed since it had no effect on the pressure near the head surface. The microphone probe was mounted on x-y-z coordinate mechanical slides which can be adjusted to a resolution of 0.01 mm. The slides themselves were mounted behind the manikin, in its acoustic shadow, to minimize the effect of the scattered pressures on the measurements (see Fig.3).

The free field (incident) pressure was measured with the microphone probe at a point vertically above the ear canal axis on contour 2 (see Fig. 4), with the manikin removed. The measured pressures were normalized to this free field pressure and converted to pressure levels (dB).

The shape of the head along the contours (but on the opposite side of the head), shown in Fig. 4, was mapped out by noting the appropriate x-y-z coordinate of the microphone probe when it just came in contact with the head surface. The contours shown in Fig. 4 are typical of hearing aid microphone locations. Contours 1, 2, and 3 are spaced 5 mm apart as are contours 4, 5 and 6. Contour 4 was chosen so that the microphone probe just touches the outside perimeter of the pinna. The measurement positions along contours 1 through 6 were spaced exactly 2 mm, 4 mm, and 7 mm from the head surface. However, for the sake of brevity, this presentation will report only the results measured 4 mm from the head surface and along contours 2 and 4.* The probe was moved in 4 mm increments along

*The measurements of the pressure amplitude and phase for the other contours will be described in a future paper.

contour 2 over a total distance of 10 cm. Since contour 4 follows the shape of the head and the microphone probe is set in a cartesian coordinate system, it is extremely complicated to move along this contour at exactly 4-mm intervals. Therefore, the increments were chosen to be 4 mm in either the horizontal plane or 4 mm in the vertical plane depending on whether the contour lay primarily in the horizontal or vertical plane, respectively.

The test frequencies were the octave band center frequencies from 0.5 kHz to 4.0 kHz and the third octave band center frequencies from 4.0 kHz to 8.0 kHz. The measurements were repeated at all test frequencies using 6% (of the center frequency) bandwidth pink noise. Additional measurements were made with 29% (of the center frequency) bandwidth pink noise at 6.3 kHz and 8.0 kHz.

The measurements were made with the equipment shown in Fig. 5 with the exception that the "1/4-inch" feedback microphone was not used for the measurements using noise.

RESULTS

The sound pressure levels along contour 2 at 0.5, 1.0, 2.0, and 4.0 kHz, normalized to the free field sound pressure level are shown in Fig. 6. It can be seen that the pressure levels near the front of the head are greater than those at the back of the head. The pressure is smooth and well-behaved with position at frequencies $\leq$ 2.0 kHz. At 4 kHz the pressure levels range from approximately + 6 dB to - 2 dB from the front to the back of contour 2.

Theoretical pressure levels on the surface of a rigid sphere are shown in Fig. 7, along with measured results, for frequencies of 0.5, 1.0, and 2.0 kHz. The theoretical pressure predictions for a sphere lie within 1.5 dB of the measured results. At 2.0 kHz, however, the theoretical level predictions are lower than the measured data.

Burkhard and Sachs (1975) show that the pressure at the ear canal is increased by approximately 2.5 dB by the reflection from the torso/shoulder. As can be seen from Fig. 7, if a correction of a nominal + 2.5 dB is applied to the predicted pressure levels along the side of the head, then the resulting pressure levels are in good agreement with the measurements.

The pressure levels alongside the head at 5.0, 6.3, and 8.0 kHz are shown in Fig. 8. As the frequency is increased, the number of relative pressure minima and maxima also increase, i.e. the pressure field becomes less and less well-behaved with increased frequency. At frequencies of 5.0 kHz or less the pressure level is greater near the front than the back. However, above 5.0 kHz, at 6.3 and 8.0 kHz, the pressure levels change rapidly with position forming sharp minima and maxima. Also, the pressure maxima near the middle and the rear of the head have the same magnitude as the pressure levels near the front. Such sharp pressure minima and maxima make the hearing aid microphone location on the head critical.

The pressure levels along the outside perimeter of the pinna, on contour 4, are shown in Figs. 9 and 10. Again, the pressure is well-behaved and smooth at frequencies of 4 kHz and less, with a maximum spread of approximately 6 dB, as shown in Fig. 9. However, a sharp pressure minimum is formed, which is probably a shadow from the pinna, at frequencies above 5 kHz. Thus, near the pressure minimum, a change in sound pressure level of 15-16 dB occurs over a distance of less than 2 cm. These minima, behind the pinna, are much steeper and more severe than those alongside the head.

The pressure field becomes smoother if the signal is not a discrete tone, but a band of noise. The sound pressure level alongside the head using 6% bandwidth and 29% bandwidth pink noise is compared to the discrete frequency pressure levels at 6.3 kHz in Fig. 11. The pressure-versus-distance curve becomes increasingly smoother as the bandwidth is increased. Thus the change in the overall pressure level relative to the discrete frequency change is reduced by approximately 2 dB and 5 dB with 6% and 29% bandwidth noise, respectively. In particular, the nulls become less sharp between the - 2 cm and the - 3 cm positions. Thus the microphone location becomes less critical as the bandwidth of the noise signal is increased.

The effect of the signal bandwidth on the maximum and average change in sound pressure level resulting from a 5-mm change in the hearing aid microphone location is summarized in Table 1. Column 1 of Table 1 refers to the "vertical difference" in sound pressure level in going from contour 1 to contour 2 or 3. Column 2 refers to the "longitudinal difference" which represents the change in sound pressure level along contour 2 when the microphone position changes by 5 mm. The third column refers to the lateral difference in the sound pressure level when the microphone is moved from the position 2 mm from the head surface to 7 mm from the head surface, normal to the head surface.

CONCLUSIONS

The spatial variation of the sound pressure level along the head of a manikin is smooth and decreases monotonically, within ± 1 dB, from the front to the back of the head for frequencies ≤ 2 kHz. For frequencies between 4 and 8 kHz the spatial pressure variation is less well-behaved and oscillates by as much as 14 dB from the front to the back of the head over the 10-cm range of contour 2.

The pressure variation immediately behind the pinna is smooth at low frequencies. However, a sharp null in the spatial pressure variation is formed at frequencies of 5.0 to 8.0 kHz. Thus, hearing aid microphones behind the pinna would be exposed to severe level differences from position to position and frequency to frequency since the null shifts position with frequency. The pressure measurements at such a location are therefore unreliable unless particular care is used in the microphone placement.

It has also been shown that it may be useful to test hearing aids with random noise of finite bandwidth (see Fig. 11 and Table 1), particularly above 5 kHz, where the sharp minima and maxima, formed under discrete tone excitation, are smoothed out and less severe. However, this smoothness of the spatial pressure variation is at the expense of some frequency resolution due to the bandwidth of the noise.

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TABLE 1

DIFFERENCES IN AMPLITUDE CAUSED BY 0.5-CM VARIATIONS IN MEASUREMENT POSITION

Frequency Hz	Direction: Vertical difference dB		Longitudinal difference dB		Lateral difference dB	
	Ave	Max	Ave	Max	Ave	Max
≤ 2000	< 0.5	< 0.5	< 0.5	0.5	< 0.5	0.5
4000	1.0	1.6	0.5	2.4	< 0.5	1.5
4000 6% BW noise	0.7	1.3	0.4	2.2		
5000	1.1	2.3	0.7	1.9	< 0.5	1.5
5000 6% BW noise	0.5	1.4	0.7	1.6		
6300	1.1	2.1	1.2	3.2	< 0.5	1.5
6300 6% BW noise	0.6	1.9	0.9	2.1		
6300 29% BW noise	0.4	0.8	0.5	1.5		
8000	1.2	2.5	1.6	4.0	0.5	1.5
8000 6% BW noise	0.6	1.8	1.2	3.2		
8000 29% BW noise	0.5	1.4	0.6	1.6		

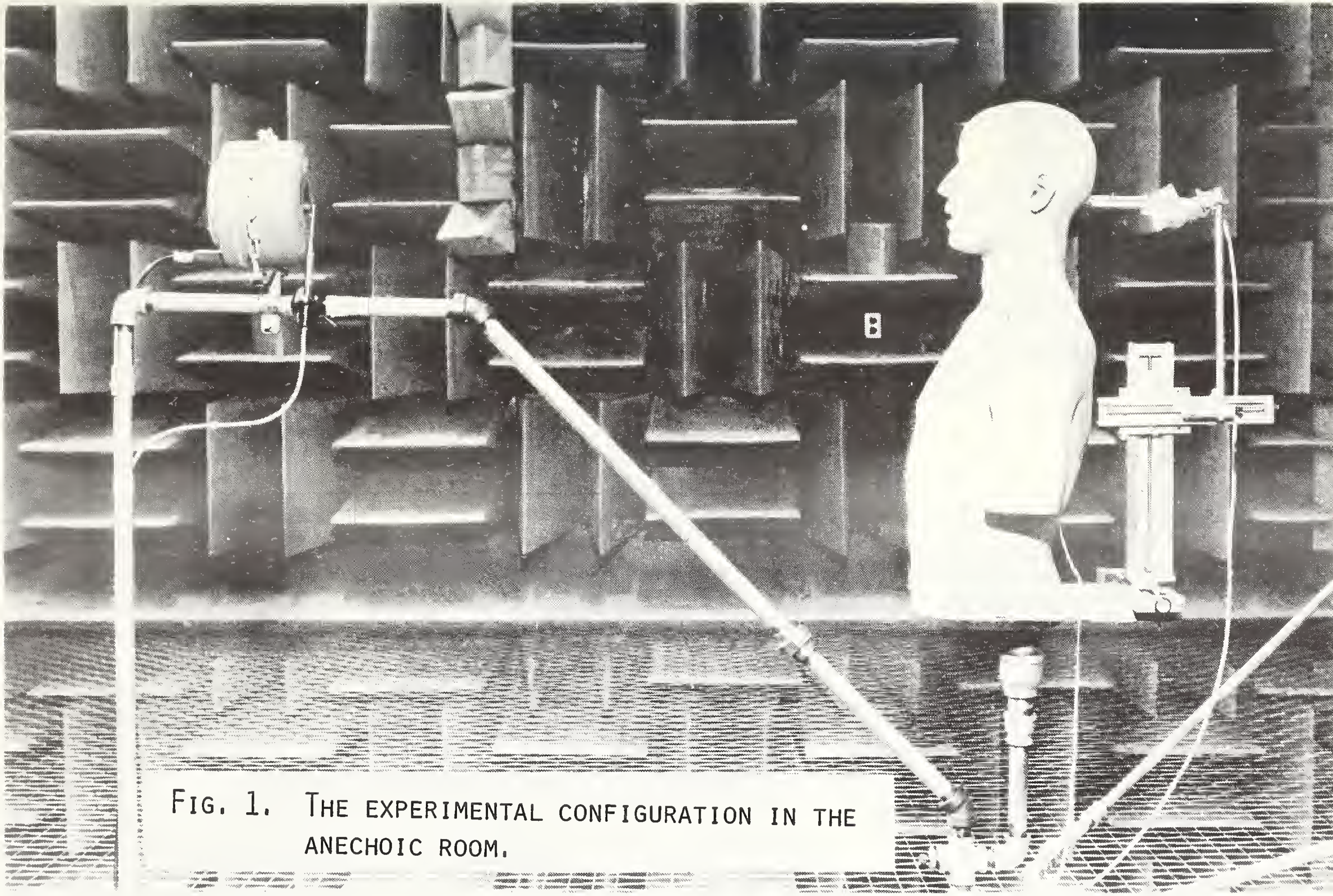


FIG. 1. THE EXPERIMENTAL CONFIGURATION IN THE ANECHOIC ROOM.

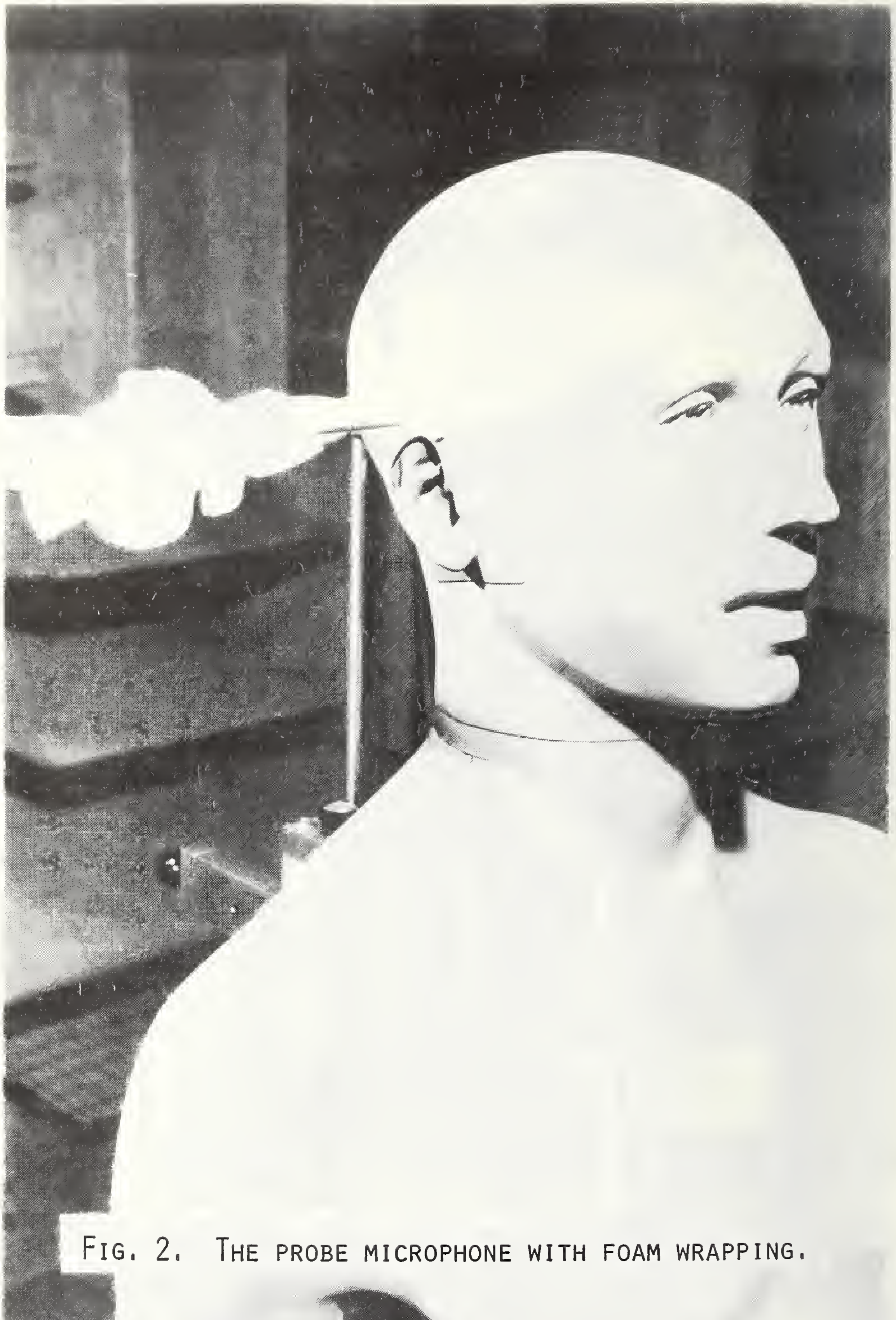


Fig. 2. The probe microphone with foam wrapping.

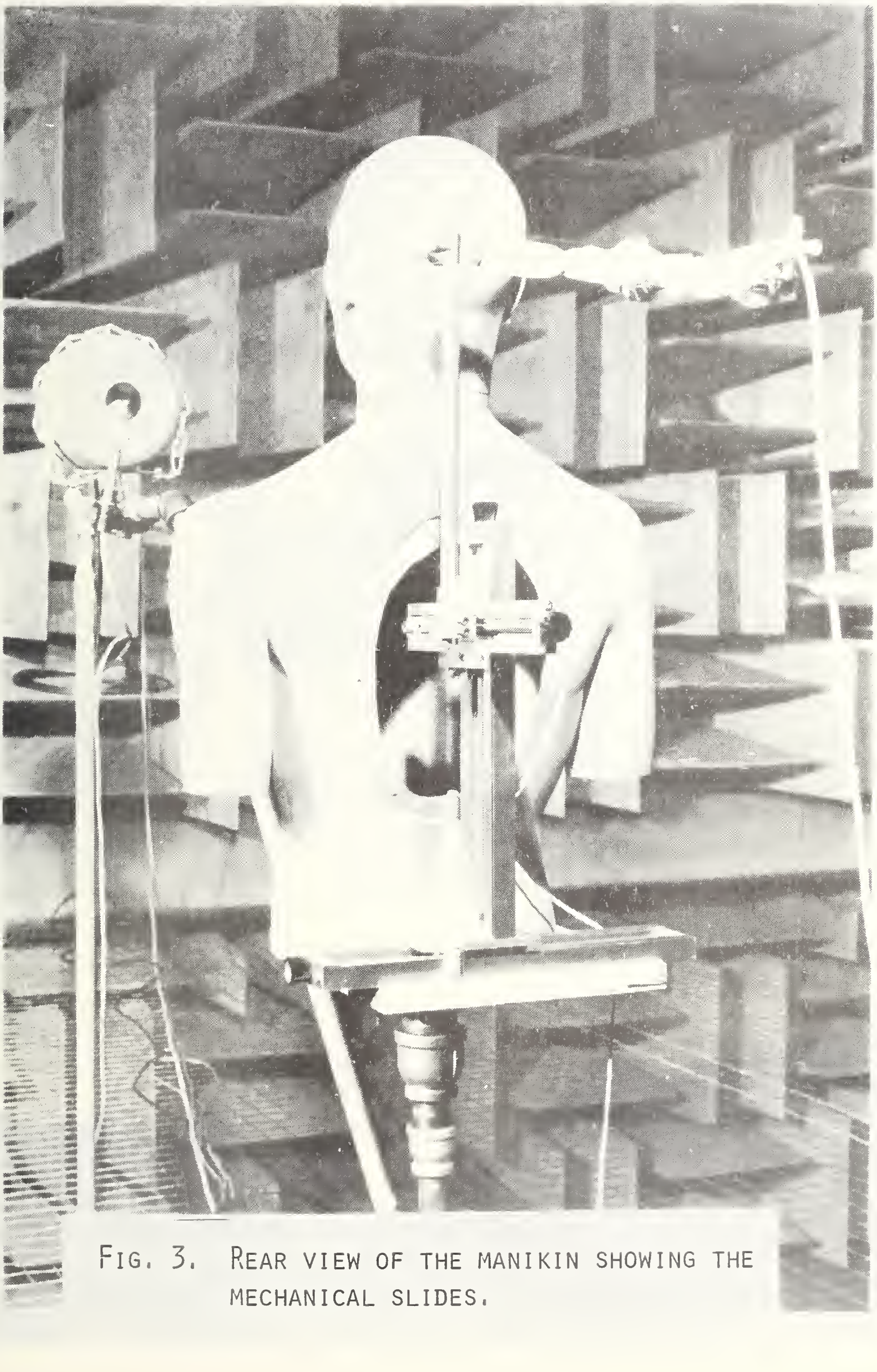


FIG. 3. REAR VIEW OF THE MANIKIN SHOWING THE MECHANICAL SLIDES.

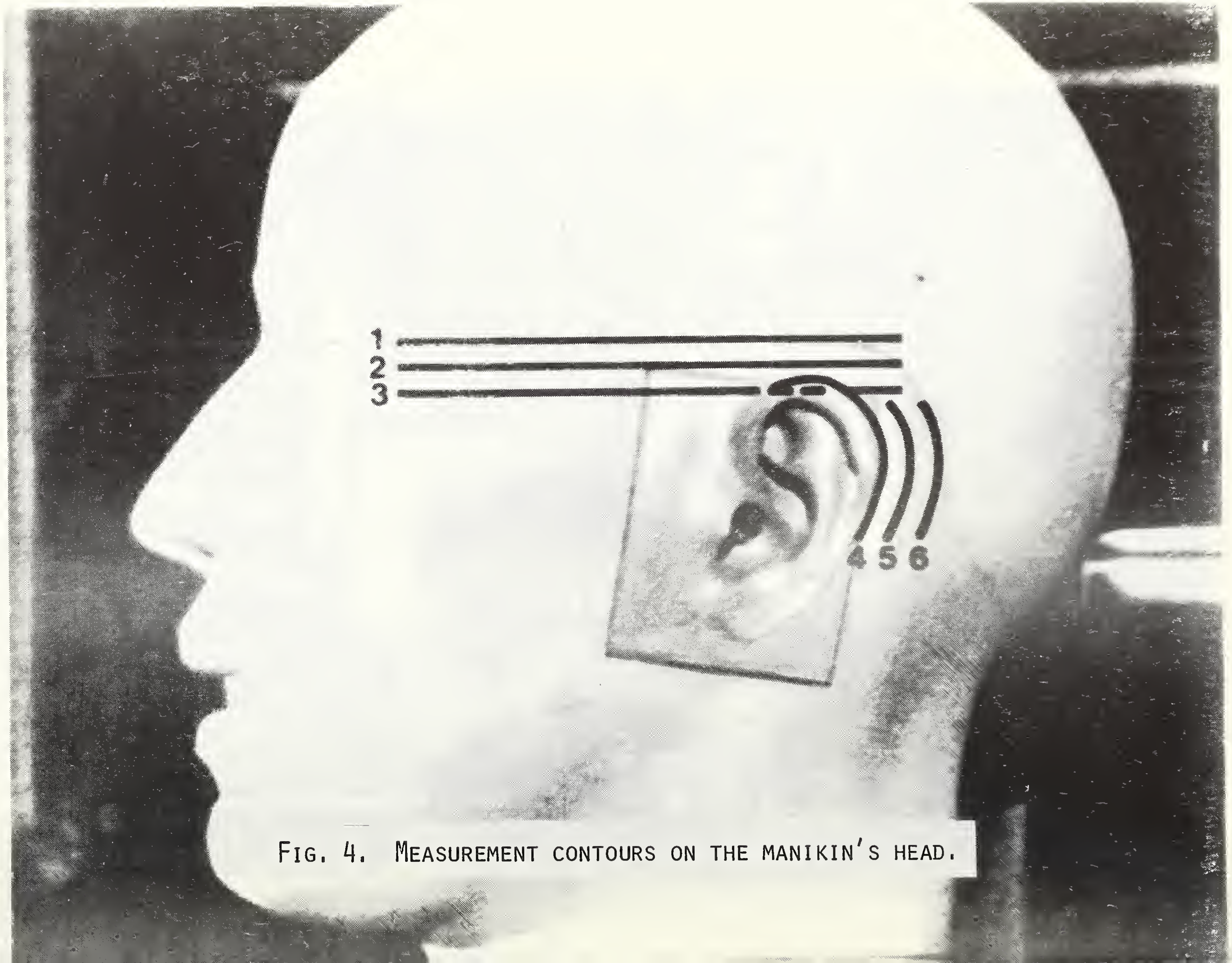


Fig. 4. Measurement contours on the manikin's head.

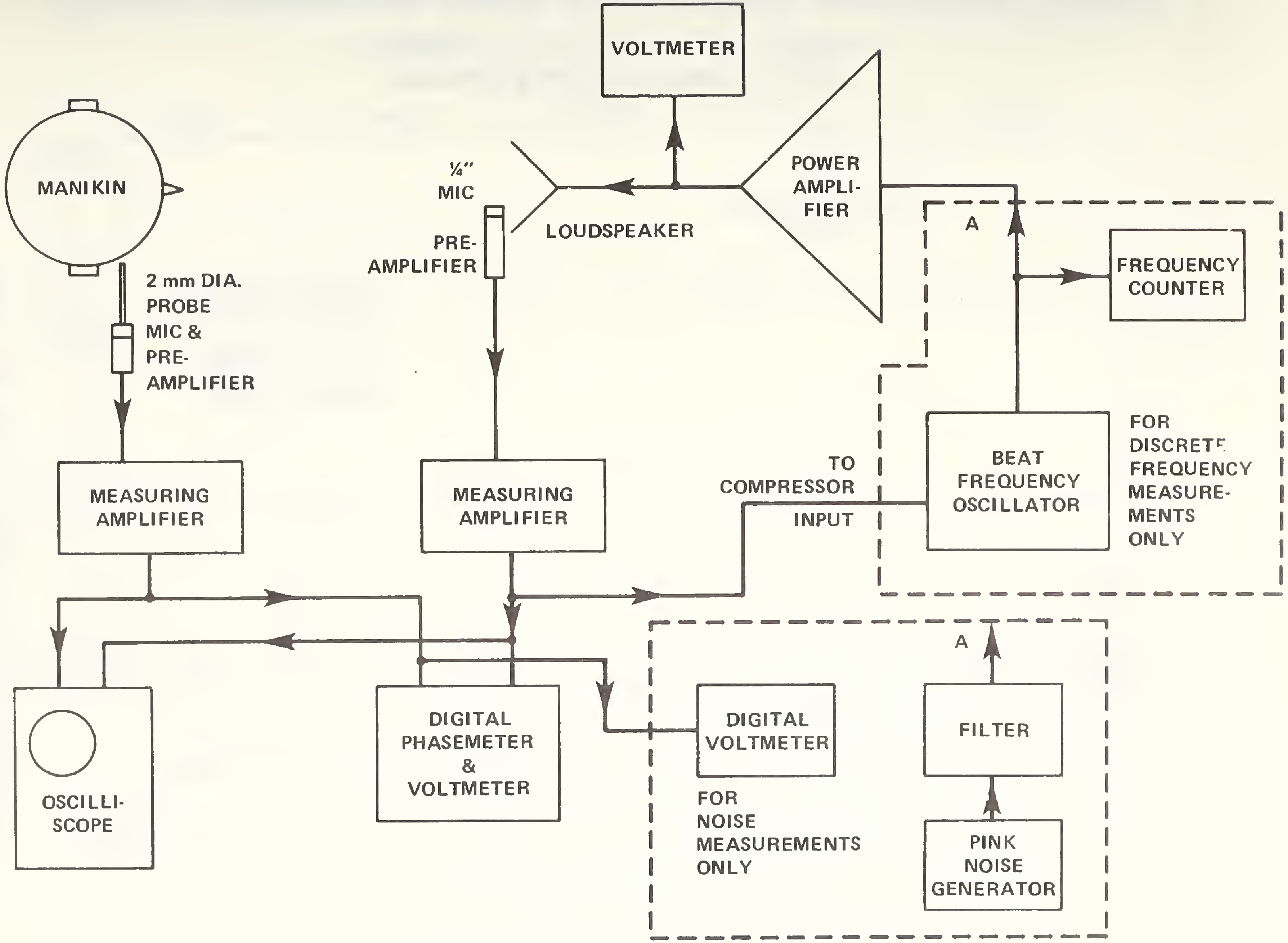
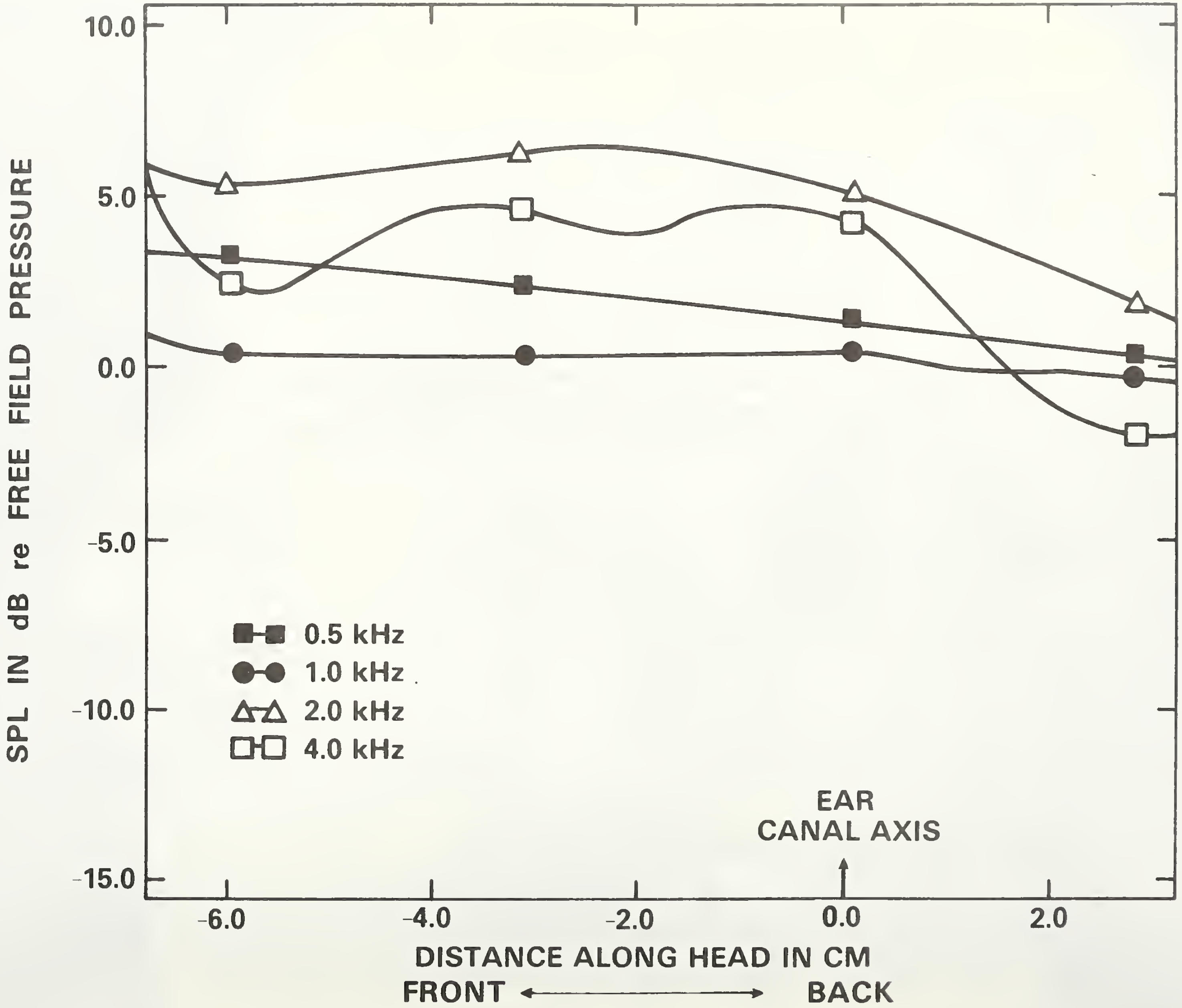
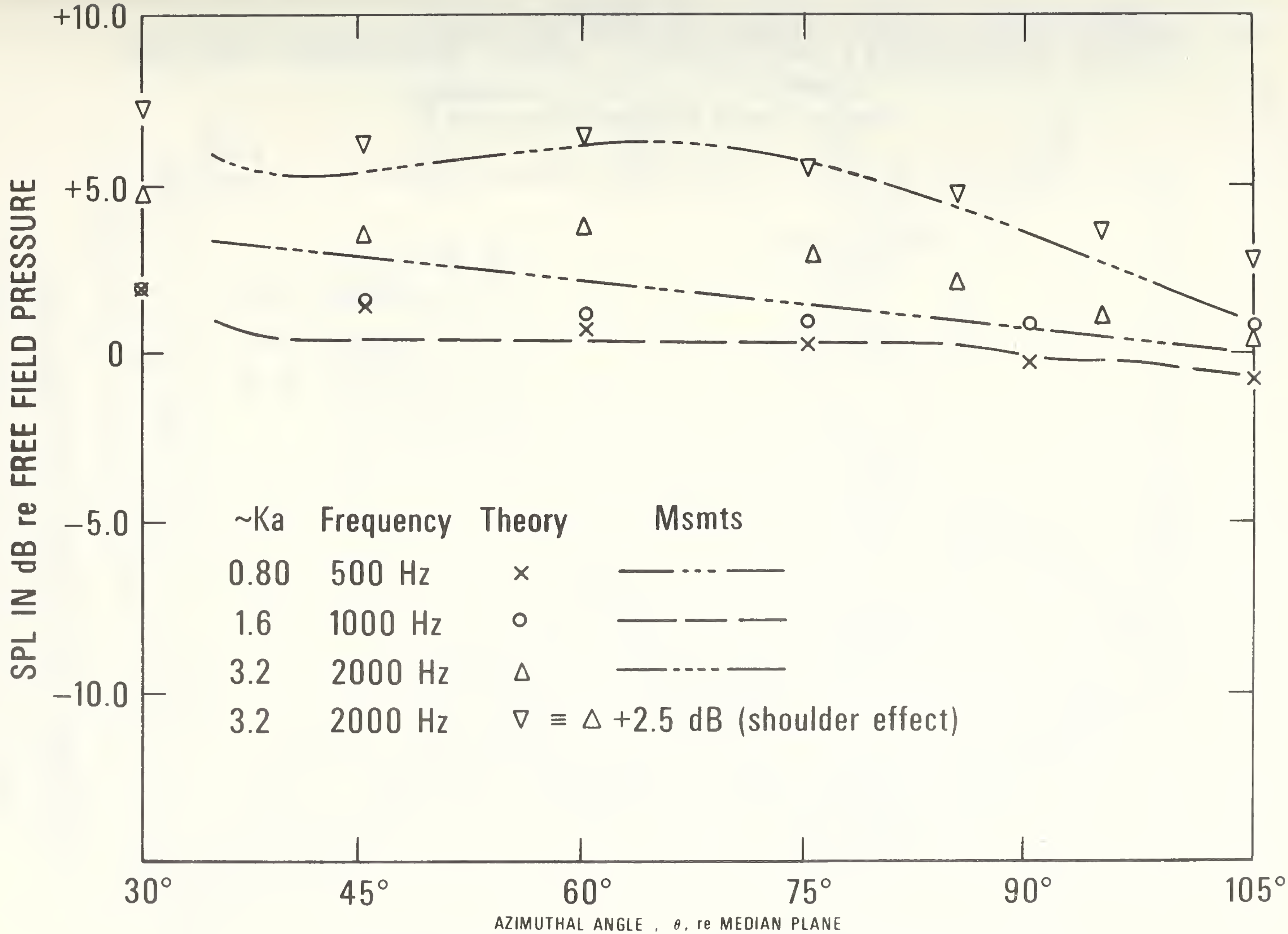


Fig. 5. Block diagram of the measurement equipment.



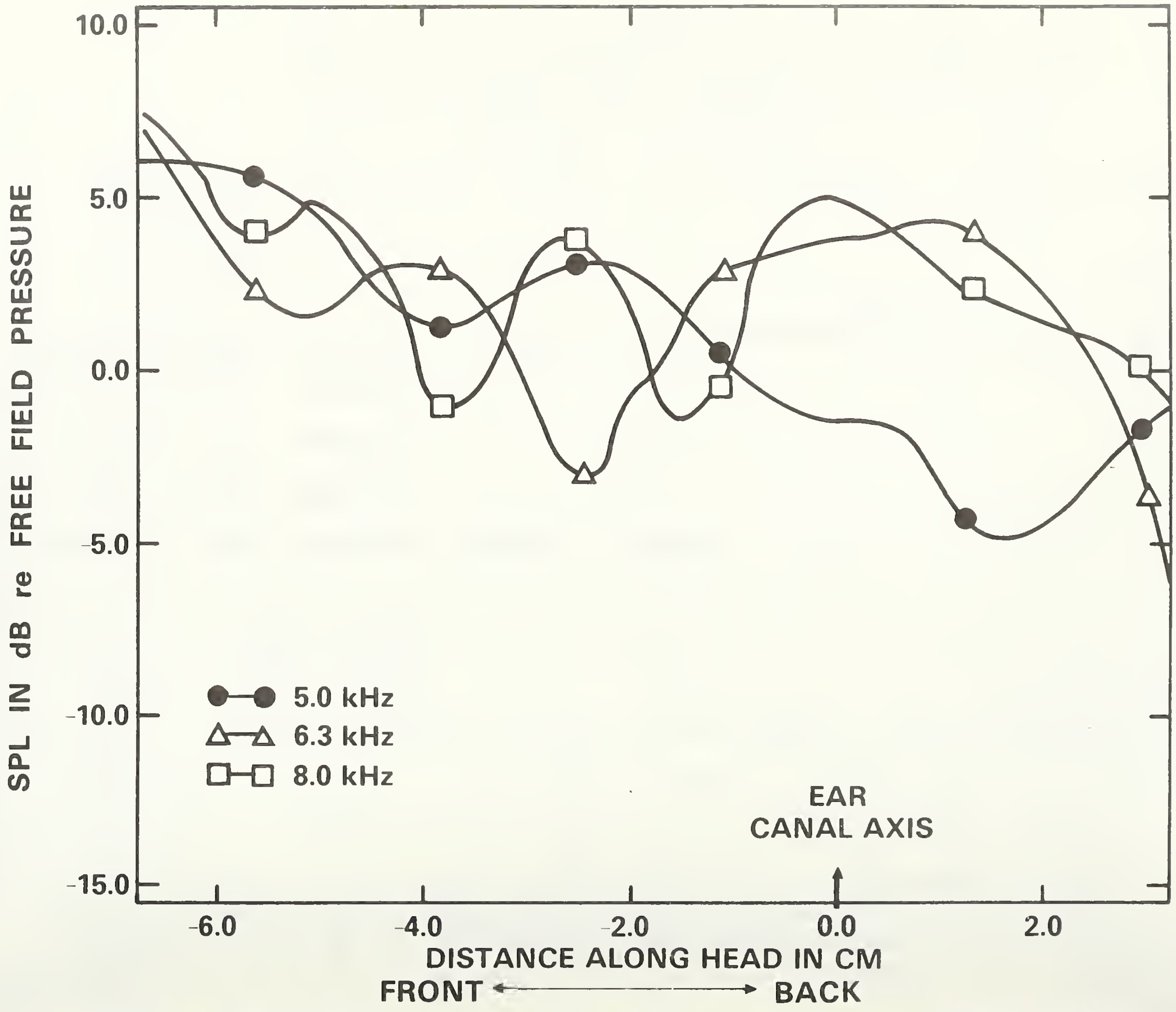
SOUND PRESSURE LEVEL ALONGSIDE MANIKIN'S HEAD

FIGURE 6



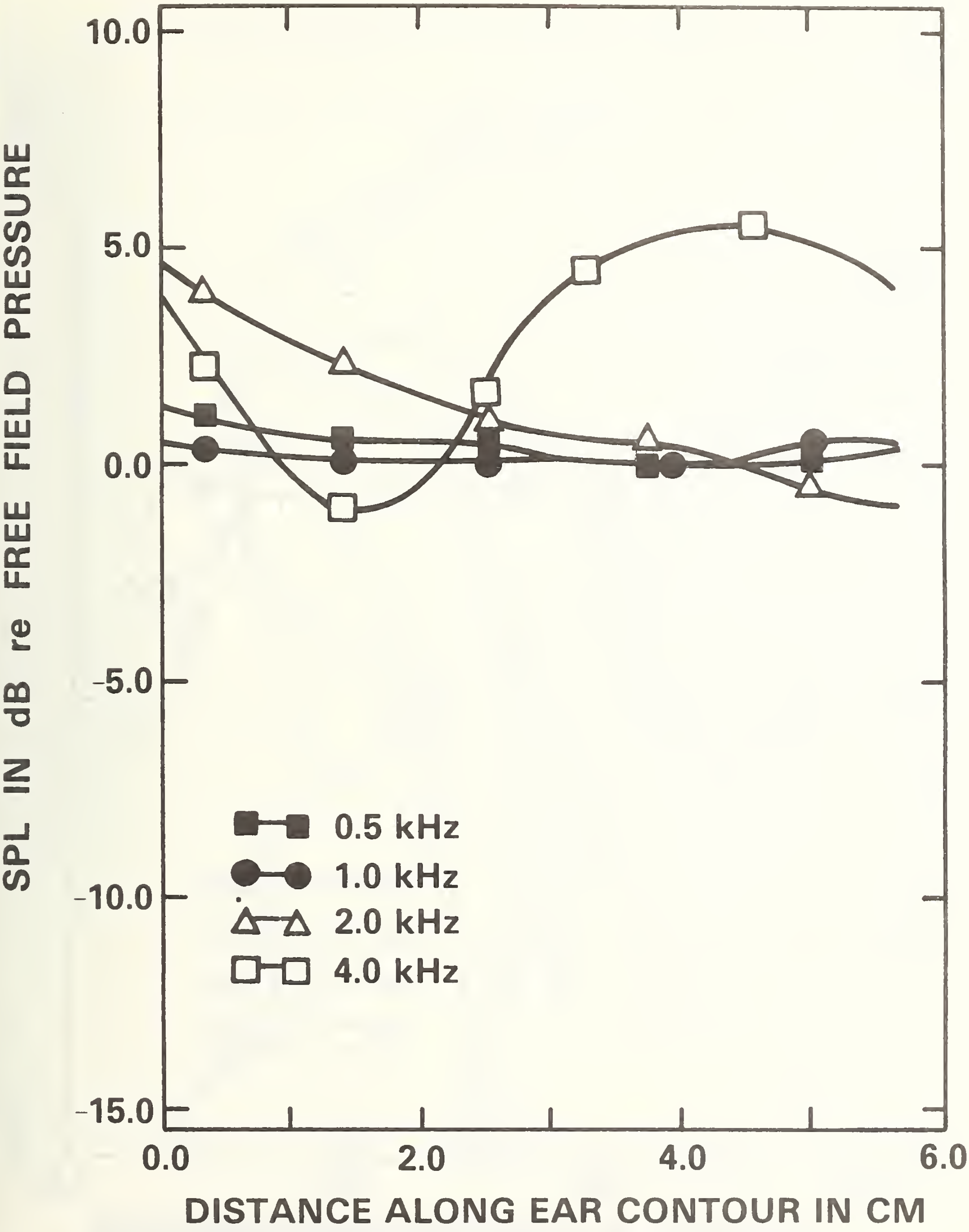
SOUND PRESSURE LEVEL AROUND MANIKIN'S HEAD
AND THEORETICAL PRESSURE LEVEL ON A HARD SPHERE

FIGURE 7



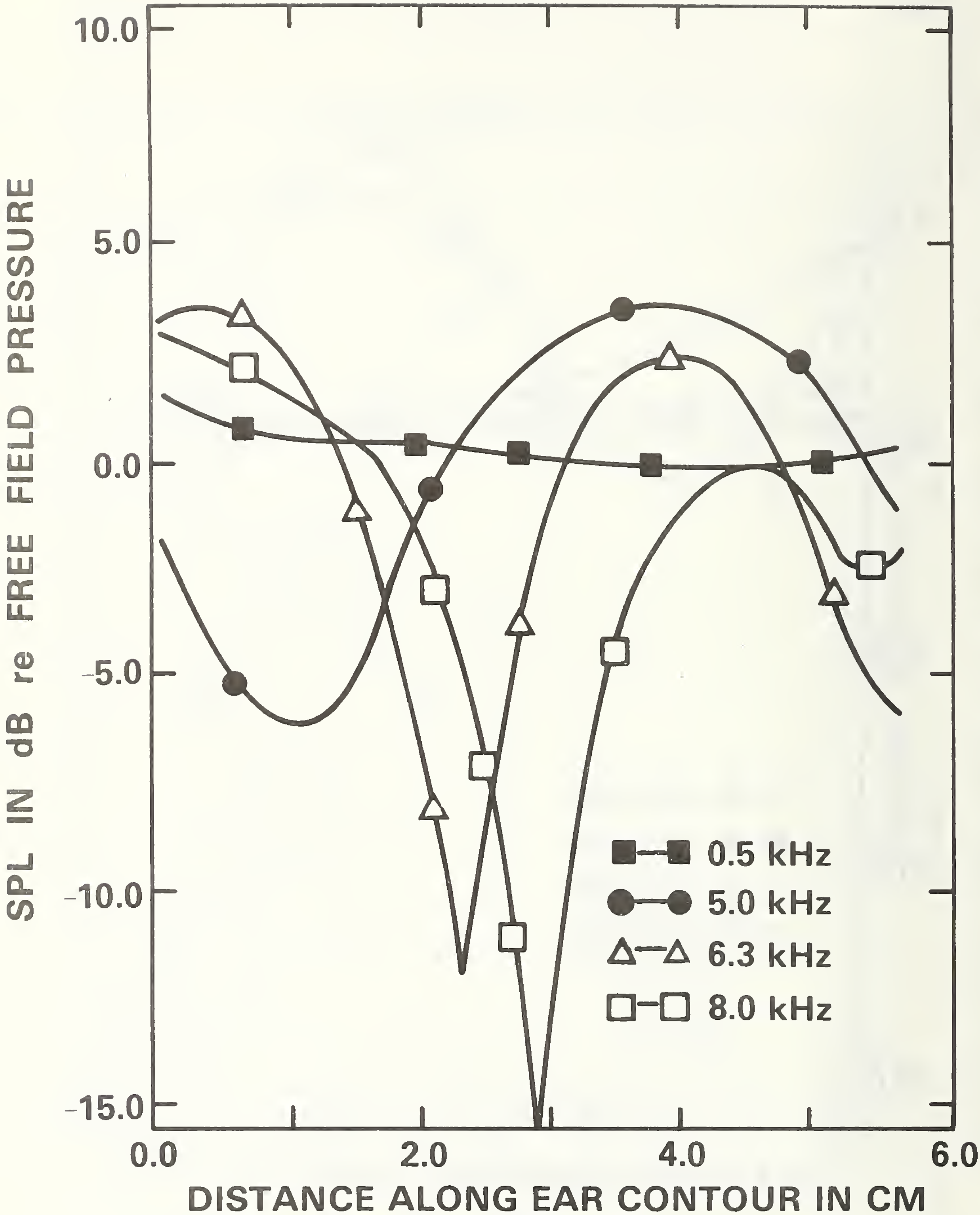
SOUND PRESSURE LEVEL ALONGSIDE MANIKIN'S HEAD

FIGURE 8



SOUND PRESSURE LEVEL BEHIND MANIKIN'S EAR

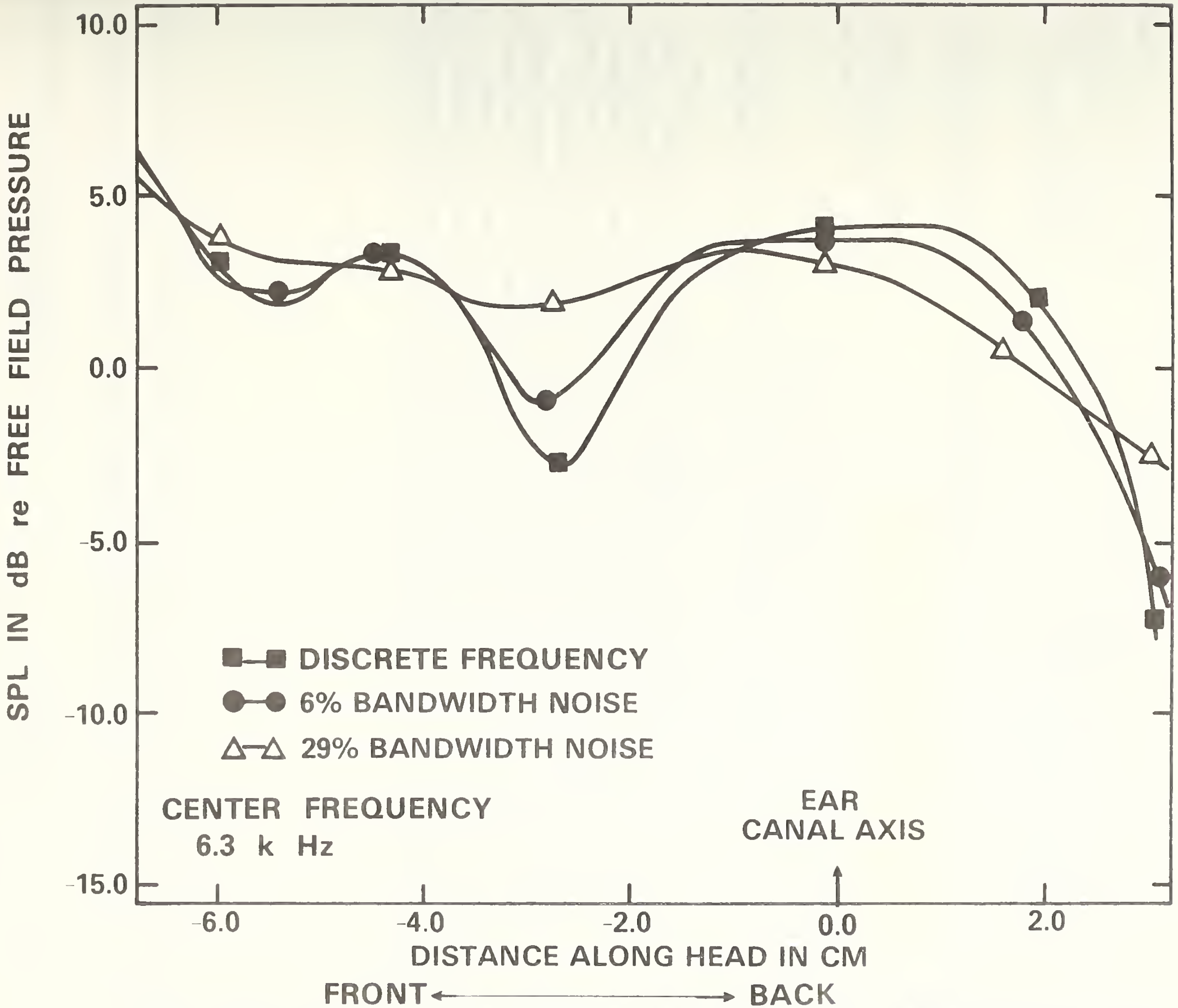
FIGURE 9



SOUND PRESSURE LEVEL

BEHIND MANIKIN'S EAR

FIGURE 10



SOUND PRESSURE LEVEL ALONGSIDE MANIKIN'S HEAD

FIGURE 11

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15. SUPPLEMENTARY NOTES

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

To simulate actual usage conditions, the frequency response of hearing aids was measured on the head of a manikin over the frequency range of 0.2 to 8 kHz. The acoustic pressure around the head can vary rapidly as a function of frequency and location. In order to compare and interpret the hearing aid response at various frequencies and locations on the head, it is necessary to precisely know the pressure variations. The amplitude and phase of the acoustic pressure were measured in increments ranging from 2 mm to 5 mm alongside a manikin's head with frontal sound incidence. The acoustic driver was located in front of the manikin at a distance of 1.0 m from the ear canal axis. The test frequencies were the octave band center frequencies from 0.5 kHz to 4.0 kHz and the third octave band center frequencies from 4.0 kHz to 8.0 kHz. It will also be shown that pink noise of 6% and 29% bandwidth at 6.3 kHz and 8.0 kHz has a smoothing effect on the acoustic pressure variation with location.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Audiometry; diffraction; head diffraction; hearing aids; instruments for hearing; manikin.

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