Earcanal Pressure Generated by a Free Sound Field

E. A. G. Shaw

Division of Applied Physics, National Research Council, Ottawa 7, Ontario, Canada

The pressure levels generated at the entrance to the ear canal by progressive waves from a point source at a distance of 1 m have been measured for a group of ten subjects. Individual curves are presented for all ten subjects at six azimuthal angles of incidence. Measurements at 0°, 45°, 90°, and 180° cover the frequency range 0.2-14 kcps. Measurements at 270° and 315° extend to 8 kcps. The average earcanal-versus-free-field pressure levels are in good agreement with Vieher's data over the common frequency range. Certain features (maxima at 2.4 and 13 kcps, minima at 4 and 10 kcps) appear to be relatively independent of angle of incidence. Others (peak at 7 kcps) have strong azimuthal dependence. Normal modes of the concha may have an important role in the 6- to 10-kcps region.

INTRODUCTION

The measurements presented in this paper were undertaken as part of a program of work concerned with earphone calibration. Since the external ear is an important part of an earphone system, acoustic measurements on the ear alone may be expected to shed light on the behavior of the complete system. More specifically, measurements of pressure in the external ear generated by a free sound field may be compared with measurements of pressure generated in earphone systems. To be of maximum value, such measurements should be made under closely parallel conditions in the two types of experiment, and should extend to a suitably high upper limit of frequency.

At first sight, it might appear that measurements of pressure should be made at the eardrum if the comparison is to be valid. However, eardrum pressure measurements become rather difficult when an earphone is worn. Moreover, Wiener and Ross have shown that the pressure distribution in the ear canal proper is substantially independent of the angle of incidence of progressive plane waves up to 8 kcps. Since the transverse dimensions of the ear canal are usually less than 1 cm and the length is greater than 2 cm, one would expect this result to hold good to at least 15 kcps. In particular, one may feel confident that for each subject and at a given frequency there is a substantially constant ratio between the effective pressure at the eardrum and the mean pressure across the ear canal entrance, independent of the geometry of the external sound field generating the pressure. In the present work, therefore, measurements have been made at a well-defined position in the entrance to the ear canal.

Intersubject variations are known to be large in experiments of this type. This difficulty has been minimized by the use of an identical group of ten subjects in both free field and earphone measurements.

1. EXPERIMENTAL TECHNIQUES

Measurements are made in an anechoic chamber with the subject seated in a simple armchair equipped with a headrest. A point source of sound can be moved around a horizontal circle of radius 1 m with the subject's head at the center. The sound pressure is measured with a resiliently suspended probe microphone, the orifice of which is located in the left ear of the subject.

The sound source consists of a high-frequency horn driver unit feeding a copper tube of convenient length (about 1.3 m), the end of which is the source orifice. The internal diameter of the tube (1.4 cm) is sufficiently small to prevent the propagation of higher-order modes below 14 kcps. The tube is terminated with a matching acoustic resistance at the orifice to suppress standing waves in the tube. Since the source efficiency varies


coupled by a short flexible plastic section, and a rigid sharply bent end section is added. The manner in which the tube is placed in the ear is shown more precisely in Fig. 2. There is a natural valley above the cheek bone that allows one to bring a probe tube into the concha just above the tragus. If the probe tip has the shape and dimensions shown in Fig. 2(c) and is suitably oriented, the orifice may be placed against the front upper wall of the concha at the entrance to the external auditory meatus proper, in all subjects so far examined. The probe system is held in place with surgical tape in front of the ear and is then relatively immune to disturbance.

Since the major cross-sectional dimension of the entrance to the auditory meatus is only about 0.9 cm, and since the normal pressure gradient at the wall is virtually zero, it may be argued that the pressure at the probe-tube orifice is unlikely to differ from the mean pressure across the entrance by more than about 0.5 dB at 5 kcps and 2 dB at 10 kcps. Within these limits, the probe-tube pressure should be an accurate measure of the airborne stimulus presented to the ear.

FIG. 1. Arrangement of probe-microphone system. Microphone case is resiliently suspended from ceiling. Steel-probe tube is divided into two sections, coupled by a flexible plastic tube. Rigid sharply bent end section fits between crus helias and tragus.

Fig. 1, for this type of experiment, the stainless-steel probe tube is divided into two portions, considerably over the 0.2- to 15-kcps frequency range covered in these experiments, the oscillator output is controlled by a Brüel and Kjer ½-in. microphone situated about 4 cm from the axis and 10 cm in front of the orifice. Scattered waves from the control microphone and source tube have a negligible effect on the sound field over a region much larger than the subject’s head. Conversely, scattered waves from the subject are small in amplitude as compared with the sound field at the control microphone.

As is well-known, 4 at a distance of 1 m from a point source, the pressure levels measured around an obstacle of 0.1 m radius are unlikely to differ by more than 1 or 2 dB from those obtained with a plane sound field.

The probe-tube microphone is the National Research Council (NRC) Mk VI design in which a 0.8-mm i.d. stainless-steel tube 10 cm or more in length is coupled by way of a horn and a number of lumped acoustic circuit elements to a ½-in. Brüel and Kjer condenser microphone. The response is substantially flat and smooth up to about 10 kcps and the sensitivity (about -80 dB re 1 V·dyn·cm⁻²) is highly stable. The orifice impedance (5 to 10×10⁸ dyn·sec·cm⁻²) is large, compared with the earcanal impedance, except at very low frequencies. (Muirhead probe microphone type H112 is almost identical with the NRC Mk VI design.)

As shown in Fig. 1, for this type of experiment, the stainless-steel probe tube is divided into two portions,

II. RESULTS

Individual curves for each of the ten subjects at six angles of incidence are given in Fig. 3. As in previous work, the results are presented as the ratio, expressed in decibels, of sound pressure at the earcanal entrance to the free-field pressure in the empty chamber at the center head position. In practice, each curve has been prepared by graphical subtraction of two level recordings with a small amount of visual smoothing. The

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first three angles of incidence, 0°, 45°, and 90°, are believed to cover the azimuthal region which is of greatest interest in connection with earphone calibration. How ever, 180°, 270° and 315° have also been included as a matter of general interest. In the shadow zone (270° and 315°), the data above 8 kcps and below −15 dB are considered to be unreliable and have, therefore, been omitted. The author regrets that time did not permit measurements to be made at more angles of incidence.

Three of the ten subjects were measured at more than one sitting and the average deviation of repeated curves taken at 45°, 90°, and 180° was found to be about 0.3−0.5 dB in the 2-kcps region and about 1−2 dB in the 8-kcps region, with occasional fluctuations to 5 dB. At 0°, the average deviations increased to 1 and 3 dB in the 2- and 8-kcps regions, respectively. In the shadow zone, the deviations became somewhat larger and decidedly irregular. In view of Nordlund’s findings with an artificial head, most of these deviations can be ascribed to minor uncertainties in the orientation of the subject’s head. (It should be noted that no jig was used to position the head so that deviations of a few degrees from the nominal angle could not be precluded.) In any event, the intersubject differences are clearly much more significant than the uncertainty in any individual curve.

In Fig. 4, average curves for Subjects 1−9 are presented. The reason for omitting Subject No. 10 is given later. For comparison, Wiener’s curves⁸ are shown by the broken lines. With minor exceptions, the agreement is as good as the statistical differences between the two groups would allow.

If one subtracts the earcanal-pressure-level curve at 0° from each of the remaining five curves of Fig. 4 in turn, one should obtain a measure of the variation of acoustic stimulus with azimuthal angle averaged over nine subjects. Such data may then be compared with the available minimum-audible-field (MAF) threshold data. (A somewhat different method of comparison has been used by Wiener in Ref. 7.) Such a comparison has been made in Table I. The threshold data have been read from Fig. 5 of Sivian and White.⁹ The curves of MAF versus azimuthal angle presented in that classical paper are not averages but rather estimated curves representative of the data obtained with the three subjects measured. The mean deviation between the data for Sivian and White and those from the present study is only 2.4 dB.

### III. DISCUSSION

In Fig. 5, the average curves of Fig. 4 have been brought together for better comparison in two groups with the 90° curve included in each group. Generally speaking, where all six curves follow decidedly parallel paths, one would expect that the individual shape (and, of course, the average shape) would be indicative of the frequency response of a part of the system having a substantial measure of azimuthal independence. One can identify at least four such features: (1) a peak at about 2.4 kcps, (2) a minimum between 3.8 and 4.1 kcps some 12 dB lower than the preceding peak, (3) a rather sharp minimum at 10 kcps, and (4) a broad peak around 13 kcps. The 2.4-kcps peak is clearly associated with the over-all fundamental resonance of the external ear. It coincides exactly with the mental resonance frequency calculated by von Békésy, and is only slightly lower in frequency than the peak in eardrum/free-field pressure ratio measured by Wiener and Ross. It is, however, decidedly lower in frequency than the eardrum versus free-field peak reported by Jahn.¹⁰ The minimum near

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### Table I. Decibel differences between (A) earcanal-pressure levels at azimuthal angle θ and azimuthal angle 0° from Fig. 4, and (B) minimum-audible-field (MAF) threshold differences from Sivian and White for same values of azimuthal angle.

<table>
<thead>
<tr>
<th>Azimuthal angle θ</th>
<th>Expt.</th>
<th>0.3</th>
<th>0.5</th>
<th>1.1</th>
<th>2.2</th>
<th>3.2</th>
<th>4.2</th>
<th>5.0</th>
<th>6.4</th>
<th>7.5</th>
<th>10</th>
<th>12</th>
</tr>
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<tr>
<td>45°</td>
<td>A</td>
<td>1.0</td>
<td>4.0</td>
<td>4.7</td>
<td>0.8</td>
<td>4.1</td>
<td>3.1</td>
<td>4.1</td>
<td>7.1</td>
<td>5.0</td>
<td>3.8</td>
<td>1.7</td>
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<tr>
<td></td>
<td>B</td>
<td>−1.2</td>
<td>2.2</td>
<td>6.5</td>
<td>3.0</td>
<td>4.0</td>
<td>6.0</td>
<td>7.5</td>
<td>8.0</td>
<td>13.5</td>
<td>8.2</td>
<td>−0.8</td>
</tr>
<tr>
<td>90°</td>
<td>A</td>
<td>3.0</td>
<td>4.6</td>
<td>6.0</td>
<td>0.6</td>
<td>1.5</td>
<td>−1.5</td>
<td>2.5</td>
<td>9.5</td>
<td>12.0</td>
<td>6.0</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.2</td>
<td>4.2</td>
<td>4.5</td>
<td>4.2</td>
<td>2.0</td>
<td>1.8</td>
<td>6.2</td>
<td>11.0</td>
<td>16.2</td>
<td>11.0</td>
<td>9.0</td>
</tr>
<tr>
<td>180°</td>
<td>A</td>
<td>−1.0</td>
<td>−0.3</td>
<td>2.5</td>
<td>−4.8</td>
<td>−3.5</td>
<td>−4.4</td>
<td>−7.9</td>
<td>−6.6</td>
<td>−1.0</td>
<td>−3.4</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>−1.4</td>
<td>−2.2</td>
<td>3.0</td>
<td>0</td>
<td>−3.0</td>
<td>−0.8</td>
<td>4.0</td>
<td>5.0</td>
<td>3.5</td>
<td>−2.5</td>
<td>−2.5</td>
</tr>
<tr>
<td>270°</td>
<td>A</td>
<td>−2.5</td>
<td>−1.0</td>
<td>−0.3</td>
<td>−11.6</td>
<td>−10.0</td>
<td>−15.3</td>
<td>−16.6</td>
<td>12.8</td>
<td>−1.0</td>
<td>−10.0</td>
<td>−14.0</td>
</tr>
<tr>
<td>(−90°)</td>
<td>B</td>
<td>0.5</td>
<td>−3.0</td>
<td>−1.8</td>
<td>−9.5</td>
<td>−15.5</td>
<td>−12.5</td>
<td>−11.0</td>
<td>15.0</td>
<td>−4.5</td>
<td>−10.0</td>
<td>−13.2</td>
</tr>
<tr>
<td>315°</td>
<td>A</td>
<td>−1.6</td>
<td>−2.4</td>
<td>−6.3</td>
<td>−7.4</td>
<td>−6.1</td>
<td>−8.8</td>
<td>−10.2</td>
<td>−8.3</td>
<td>−7.8</td>
<td>−11.0</td>
<td>−7.0</td>
</tr>
<tr>
<td>(−45°)</td>
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<td>−5.2</td>
<td>−7.5</td>
<td>−3.8</td>
<td>−7.5</td>
<td>−8.5</td>
<td>−7.2</td>
<td>−11.8</td>
<td>−2.5</td>
<td>−10.5</td>
<td>−6.2</td>
</tr>
</tbody>
</table>

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*Ref. 8.
⁹ Estimated values from incomplete data.
FIG. 3. Ratio of sound pressure at the ear canal entrance to the free-field pressure at center head position (dB), as a function of frequency, for ten individual subjects, at six azimuthal angles of incidence. At \( \theta = 0^\circ \), subject is facing source. At \( \theta = 90^\circ \), source is normally incident at plane of left ear, in which probe tube is situated.
4 kcps coincides approximately with the frequency at which the effective length of the ear canal proper is $\lambda/4$ but may well be part of a more complex process. The 10-kcps minimum is probably associated with an effective canal length of $3\lambda/4$. It lies fairly close to the second peak of eardrum/ear canal-entrance pressure ratio in Jahn's Fig. 8 (Ref. 10).

Apart from the relationships revealed by the average curves, it is at once apparent that the relative positions of the individual curves in Fig. 3 are independent of angle of incidence, to a notable degree. This is particularly clear in the 2.5- to 5-kcps region, but a pattern can still be seen above 10 kcps. The curves for Subject No. 10 preserve the pattern but are clearly exceptional, particularly in the 3- to 5-kcps region. Otoscopic examination of the group showed all subjects to have normal external ears, with the exception of No. 10, whose canal was almost completely filled with wax.

A comparison between Figs. 3 and 4 shows that the averaging process produces a curve in which the maxima and minima are broader and weaker than those occurring in most individual curves. Perhaps more may be learned from individual curves than from group averages.

Of the six groups of curves in Fig. 3, the $90^\circ$ group appears to possess more order than any of the others.
It is as though the essential phenomena are brought into sharper focus when the sound beam has normal incidence at the ear. This is undoubtedly connected with the relatively simple head-diffraction pattern associated with normal incidence, but may also relate to the acoustics of the external ear. For example, diffraction from the rim of the pinna may make a significant contribution at certain other angles of incidence, as suggested by Wiener\textsuperscript{7} and Harris\textsuperscript{2}.

It would seem that a clear understanding of the acoustics of the auricle must await further work. In the meantime, it may be pointed out that the height, breadth, and depth of the concha (cavum plus cymba) are approximately 2.2, 2, and 1.2 cm, respectively—values which are by no means negligible, compared with the wavelength of sound above 3 kcps. From an extremely crude model, one would, in fact, expect to find three normal modes in the 6- to 10-kcps region. These would, of course, have high radiation damping with correspondingly broad bandwidths, and the excitation of one of the three would be highly dependent on the azimuthal angle of the incident beam. Perhaps this may give a clue to the very high pressure levels observed at 90° in the 7-kcps region and the angular dependence in this region.

\textsuperscript{11} J. D. Harris, "Sound Shadow Cast by Head and Ears," J. Acoust Soc. Am. 36, 1049(A) (1964).