SOUND PRESSURE IN INSERT EARPHONE COUPLERS AND REAL EARS

M. D. BURKHARD *and* R. M. SACHS

Industrial Research Products, Inc., Elk Grove Village, Illinois

It is known that sound pressure, measured in couplers via a probe-tube microphone, often shows a pressure vs frequency response that drops sharply at a single frequency. In this study sound pressure was theoretically determined at various locations within a hard-walled cylindrical cavity, driven by a constant-volume velocity source with circular symmetry. At each location in the volume, a transfer impedance was defined as the ratio of pressure to inlet-volume velocity. In the region around the inlet, the transfer impedance passes through zero as it changes from negative to positive reactance with increasing frequency. Two hard-walled cavity examples were examined in detail (1) the main cavity of a 2-cm^3 HA-2 coupler, and (2) a cavity having dimensions approximately equal to the occluded ear canal between an earmold tip and the eardrum. Contours of constant minimum sound pressure vs frequency are given for these two cylindrical volumes with experimental verification. Implications for probe microphone calibration and measurement of sound pressure in ears are discussed.

In the course of an investigation of insert earphone calibration procedures, we became concerned with the discrepancy between pressure in real ears vs pressure in earphone couplers when either type of cavity was excited by the same (hearing aid type) insert earphone. Many experimenters have been concerned with the problem, notably, the groups of Nichols et al. (1945), Ewertsen, Ipsen, and Nielsen (1957), van Eysbergen and Groen (1959), Studebaker and Zachman (1970), and McDonald and Studebaker 1970).

Because of the different approaches and somewhat conflicting results of earlier studies, we undertook our own experimental comparison using probe-tube microphones. Almost immediately it became clear that some experimental artifacts were confounding the results. In the 2-cm^3 HA-2 coupler, for example, placing a microphone probe-tube near the 3-mm diameter inlet tube yielded pressure-response measurements that differed from pressure measurements of the 2.5-cm diameter microphone at the bottom of the coupler cavity. That is, one measurement could not be predicted from the other on the basis of the simple plane wave or lumped parameter acoustics usually assumed for the coupler. Might not a similar result occur in real-ear measurement, in which probe-tube measurements would not then correspond to the eardrum pressure?

Figure 1 illustrates the coupler discrepancy for a particular source. When a probe tube was placed to measure pressure near the inlet tube, the result was Curve B, but when the probe-tube tip was placed at the upper side wall of the

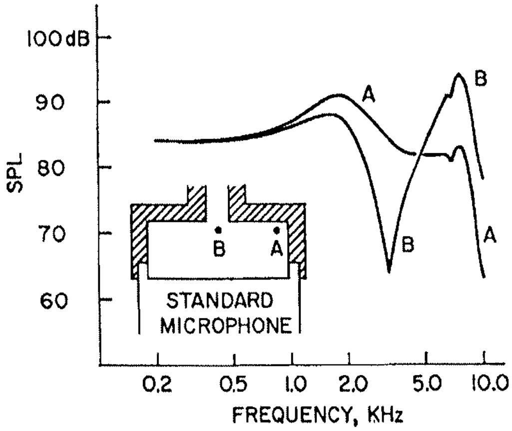

FIGURE 1. Probe-tube response curves for a 2-cm^3 coupler driven by a small earphone. The inserted figure is a scale cross-section drawing of the experimental conditions. A and B are probe locations.

coupler, away from the inlet, the result was Curve A. It can be shown theoretically that the sound pressure at Region A is the same as the sound pressure averaged over a standard 2.5-cm microphone at the bottom of the cavity (for frequencies up to at least 18 kHz). For Curve B, a sharp drop in pressure is observed around 3.2 kHz and a greater pressure above 5 kHz is seen than in Curve A. The 3.2 kHz dip is not the result of a simple longitudinal standing wave because a quarter wavelength equals the coupler length at approximately 12 kHz. Similarly, the minimum cannot be related to any radially or circumferentially excited modes, the lowest of which would also have a pressure minimum at 12 kHz or higher. The Curve A-B in Figure 2

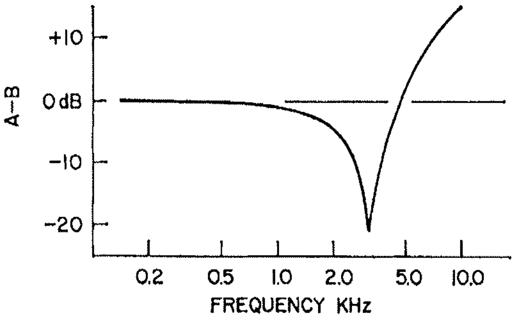

FIGURE 2. The pressure difference between sound pressure for a probe at the sound inlet hole, position B shown in Figure 1, and the sound pressure recorded with the standard microphone. The inset drawing in Figure 1 applies.

represents the difference between the probe-tube pressure at the inlet-tube entrance, and pressure measured over the bottom surface by a standard 2-cm^3 coupler microphone.

SOLUTION

The errors of pressure measurement in cavities are due to pressure distributions that do not follow acoustic plane wave or lumped parameter assumptions. They have been treated in various contexts, for example, Dalsgaard (1959, 1962), Cox (1947), Mawardi (1949), Delaney (1969). For our purposes, Ingard (1948) provided enough theory to solve the problem at hand, namely, "What is the pressure distribution inside the 2-cm^3 cavity when the sound enters through a small hole at one end?" Figure 3 shows the geometry being considered. Assume a source of volume velocity U (constant with frequency) feeding the cavity through the symmetrically placed inlet tube at the top. All of the cavity walls are hard. We are interested in the pressure in some region a distance Y from the top and a radius R from the central axis. Ingard's formula (1948, p. 673) has the following general format:

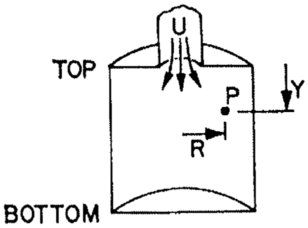

FIGURE 3. The general hard-wall, closed cyclindrical cavity for which the sound pressure distribution is analyzed. The point P is located distance Y from the sound inlet surface, and R from the axis of symmetry .

$$\text{Acoustic Transfer Impedance} = \frac{P}{U} = \text{Plane Wave Solution} + \sum_{1}^{\infty} \begin{matrix}\text{Radial}\\ \text{Wave}\\ \text{Terms}\end{matrix} \qquad (1)$$

This acoustic transfer impedance P/U is entirely reactive and is in the form of an infinite sum. The zero-order term is simply the plane wave solution. For low enough frequencies, this term is a negative reactance or compliance, the same as predicted by the more familiar plane wave analysis. The rest of the terms in the sum may, therefore, be called the contribution due to radial wave motion of the sound spreading from the inlet into a larger diameter space. This sum term contributes a positive reactance or inertance at locations near the inlet tube. This inertance reacts with the cavity compliance to form a series resonance so that at some frequency, f_o, the total transfer reactance will be zero. That is, the pressure measured by a probe tube at this location will be zero at f_o.

The plane wave solution term depends on the frequency, length of the cavity, and cross-sectional area of the cavity. The radial wave terms depend on distance from the center axis, radially, in addition to frequency, length of the cavity, and cross-sectional area of the cavity.

Thus, the null frequency f_o will vary with location in the cavity. A 2-cm^3 HA-2 coupler cavity, for example, has a 3-mm diameter inlet tube in which we observed f_o to equal 3.2 kHz at location B, Figure 1. The inertance that reacts with the compliance of a 2-cm^3 volume to produce the null at 3.2 kHz is 1.8 gm/cm^4. (In electrical analog units, this corresponds to 1.4 microfarad capacitance and 1.8 millihenries.) The calculated end correction for a tube in an infinite baffle that has no obstruction near it is 2.1 gm/cm^4 (Beranek, 1954), which is reasonably close. It turns out that when one computes the inertance term using the series shown in Equation 1, which takes into account the surrounding cavity walls, the actual computed value is 1.8 gm/cm^4, showing excellent agreement between the measurement and theory. As the point at which pressure is measured in the cavity is moved away from the inlet tube, f_0 increases.

The mathematical series is convergent, thus only the first 20 terms of the series were needed to evaluate the transfer impedance to any point in a cylindrical cavity from an arbitrary source in one end, with an error of less than 0.1%. A computer program was written for this purpose.

COUPLER EVALUATION

Figure 4 shows a particular kind of evaluation for the 2-cm^3 cavity. The abscissa is frequency in kHz; the ordinate is acoustic-transfer reactance in dyne sec/cm^5 (10^5 Pa sec/m^3). The ordinate may also be considered as the pressure at various regions in the cavity due to a 1-cm^3/sec volume velocity source. The

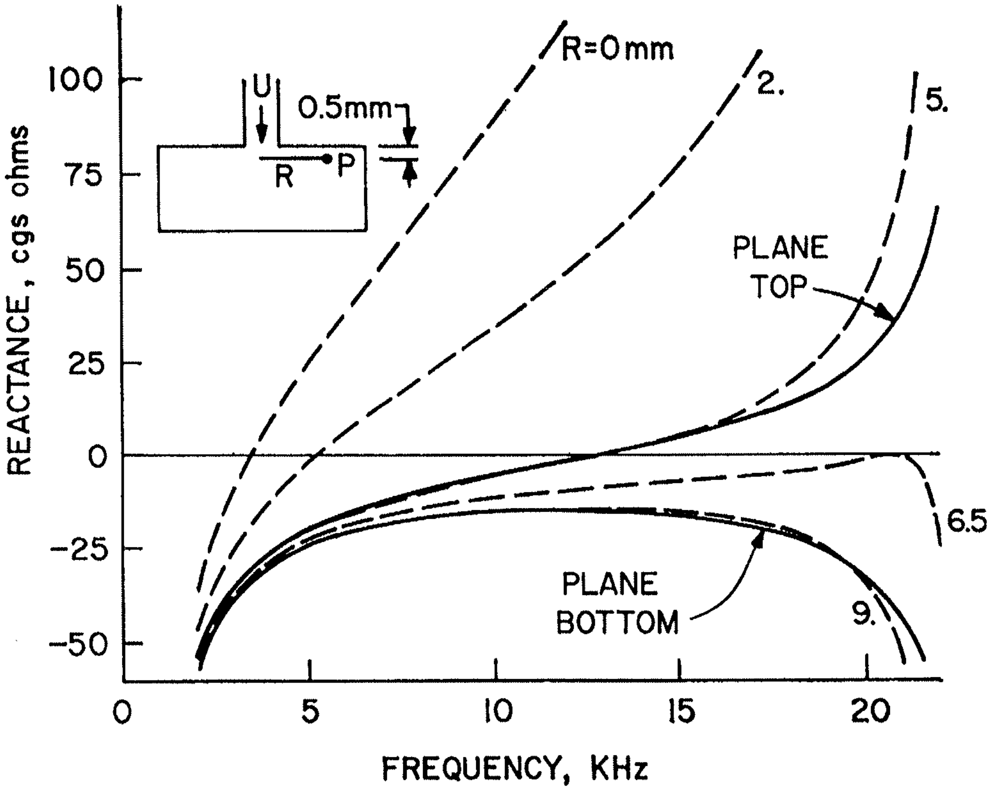

FIGURE 4. Reactance versus frequency at a position Y = one-half mm for various radial positions. The cavity is a 2-cm^3 coupler of the type described in ANSI, 1973, and used for hearing aid output measurements.

parameter is the radius R in mm at which pressure is measured by a hypothetical probe tube very close to the top of the cylinder ($Y = 0.5$ mm). This particular 2-cm^3 coupler cavity has a length of 7.35 mm and radius of 9.3 mm. Consider the curve marked plane top. This curve describes the pressure one would record near the top of the cavity if only longitudinal plane waves were present, that is, the source tube diameter equals the cavity diameter. The f_o for this curve is 12.7 kHz, corresponding to approximately a quarter wavelength plane-standing-wave in the cavity. With a 3-mm diameter hole, it is seen that as R increases from 0 to about 5 mm, the probe-tube curve approaches the plane-wave curve. In fact, below 14 kHz the plane wave top and $R = 5$ mm curves essentially superimpose. The curve labeled plane bottom describes the pressure recorded on the bottom of the cavity when only plane waves are present. In fact, this is the pressure that is typically recorded by a 2-cm^3 coupler standard 2.5-cm diameter microphone. Because pressure is measured over the entire bottom surface, it can be shown that the effect is as if only plane waves existed in the cavity. As R increases beyond 5 mm, the probe-tube pressure suddenly bends downward at high frequencies, and approaches the pressure measured by the 2.5-cm diameter standard microphone.

One can show the pressure distribution in a 2-cm^3 coupler with the locus of equal f_o. In Figure 5, any point on a contour curve is a pressure node at its designated frequency. For f_o between 4 and 14 kHz, these contours are approximately spherical surfaces surrounding the inlet tube. A pressure probe tube would have to be located outside an f_o contour if one desires a useful microphone band width approaching f_o Hz. Above 14 kHz, the surfaces be-

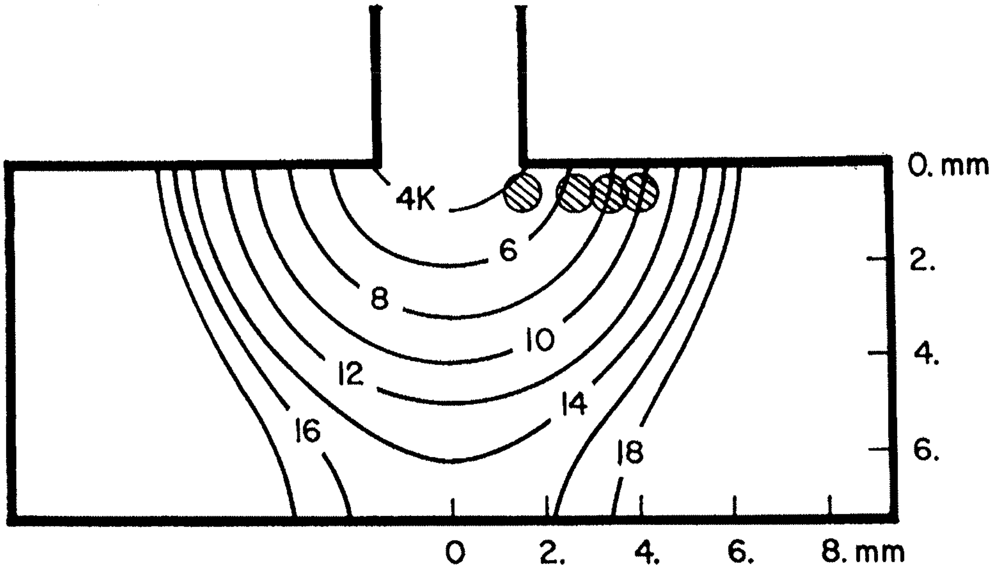

FIGURE 5. Surfaces of pressure minima are indicated in this scaled cross-section drawing of an HA-2, 2-cm^3 coupler volume. The numbers on each of the lines are frequencies, kHz, at which the pressure minima occur.

come truncated as the f_0 contours extend from top to bottom of the cavity. If the probe tube were located about one-half mm or more outside of the 18 kHz contour, pressure would never become zero. It just reaches a minimum before becoming large again as frequency increases.

Experimental verification is also shown in this figure. A probe tube of about 1-mm inside diameter was moved around the inlet tube until a pressure null was observed at 4, 6, 8, and 10 kHz, respectively. The locations of nulls are indicated by circles nearest the respective contours. The 4 and 6 kHz experimental locations are displaced 0.4 and 0.3 mm from the predicted respective f_0 contours. This discrepancy can be explained at least in part by the spreading inertance of the probe tube itself.

The most important parameters that determine the position of the f_0 contours are (1) the diameter ratio (inlet tube to cavity diameter) and (2) the diameter-to-length ratio of the cavity. Figure 6 shows a simulated hard-walled ear-canal coupler having a total volume of 0.57 cm^3 representing the portion of the ear canal remaining between an earmold and the eardrum. Length is 1.27 cm (0.5 in.) and diameter is 0.75 cm (0.3 in.). The length is a half wavelength at 13.6 kHz. In this case, the contours form spherical surfaces at frequencies between 5 and 7 kHz, but above 7 kHz the surfaces begin to flatten out, eventually becoming planes parallel to the top and bottom face above 10 kHz. This calculation implies that spreading of sound from the source is essentially complete at locations greater than 4 mm from the top face. The pressure recorded by a probe microphone in this region is independent of the radial position of the probe-tube tip. One never does see the transition to this plane wave condition in the 2-cm^3 coupler because there is a much smaller ratio of cavity length to diameter as well as a smaller ratio of inlet tube to cavity diameter.

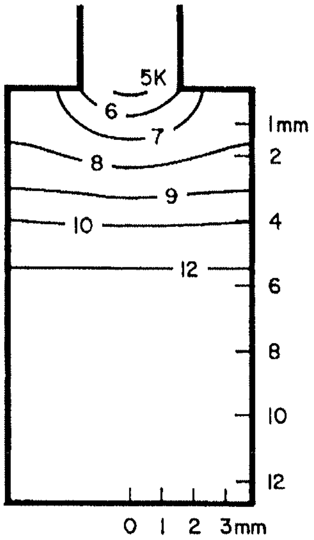

FIGURE 6. The lines represent surfaces of constant pressure minima at the indicated frequencies, kHz, for a hard-wall simulation of an average occluded ear canal.

APPLICATIONS

Probe Tube Calibration

One application of these results concerns the calibration of probe-tube microphones (see Delaney, 1969). For example, one manufacturer supplies a 2-cm^3 coupler for calibration in which the output of the probe-tube microphone is compared with the output of the reference microphone at the bottom of the cavity. An important assumption with this method of calibration is that the cavity pressure at the probe-tube tip is the same as that integrated over the bottom microphone surface. An insert earphone, supplied, allows calibration of the probe tube up to about 5 kHz, a low enough frequency so that radial waves are not too great a problem. Even here, however, the difference between probe-tube tip pressure on the center line of the coupler and the bottom 1.25-cm microphone pressure amounts to about 2 dB at 5 kHz. The real problem arises when the supplied 2-cm^3 coupler is used to calibrate probe tubes in the 7 to 20 kHz range. In this case, a 1.25-cm condenser microphone is used as a source; but our calculations show that the pressure in the coupler at the probe-tube tip will drop to zero in the region f_o equals 12 to 14 kHz, leading to an erroneous conclusion of attenuation caused by the probe tube. Even at 10 kHz the difference between probe-tube and bottom-microphone pressure is about 7 dB.

Measurement of SPL at Eardrum

Another application concerns either the measurement or control for hearing aid receiver sound pressure output in the ear canal. Admittedly, the ear canal is terminated with a compliant and lossy eardrum, so that pressure measured by the probe tube will not vary as widely as predicted for a hard-wall cavity. However, one can minimize possible adverse radial wave effects in the following ways: First, the source inlet tube should have as large a diameter as possible for the earmold in the ear canal, and second, the probe-tube tip should not be very close to the source inlet tube. In general, for a given f_o, there is an inverse relationship between inlet diameter and the minimum allowable proximity of the probe-tube tip to the inlet.

A typical situation concerns the recording of sound pressure in real ear canals for comparison with standard 2-cm^3 coupler pressure. A convenient procedure has been to pass the probe tube for the microphone through one hole in an earmold, while the sound is introduced via another hole in the earmold. For calibration, the earmold, with transducers attached, is placed on an HA-1 type 2-cm^3 coupler. Then the same earmold structure is inserted into the ear to be measured with the assumption that the calibration obtained for the probe on the coupler applies to the measurement condition in the ear. From the analysis and data shown here, it is evident that a real and incidental null occurs in the apparent calibration of the probe tube when placed on the coupler in the upper-middle frequency range of interest in most experiments. When the same system is placed in an ear, this incidental null is absent and an abnormally high sound pressure would be recorded because of the erroneous conclusion that the probe had a minimum of response because of the effects discussed. At higher frequencies of interest, a sound pressure null may be recorded erroneously because of the incidentally high pressure in the 2-cm^3 coupler calibration, and would not be part of the acoustic environment established in the ear.

The measurement of eardrum pressure is, of course, difficult; the only sure way is with a probe actually located next to the eardrum. While measurement of pressure at a point removed from the earmold tip, the order of 5 mm, minimizes the errors caused by sound spreading from the inlet, this pressure will be only indicative of the pressure at the tympanum at frequencies with wave length long compared to the occluded canal length, and when the acoustic impedance of the eardrum is high compared to the characteristic impedance of the ear canal. Distance from the measurement point to the tympanum and the complex impedance at the end of the ear canal that gives rise to standing waves must be known for more accurate estimates of sound pressure on the tympanum throughout the frequency range of interest in hearing research.

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