# A Wideband Miniature Microphone*

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Microphones intended for speech communication systems have traditionally had a response which was purposely limited to the speech frequencies. Although such a response may maximize speech perception under adverse conditions, it does not sound "natural". A new microphone small and rugged enough to be used in headworn hearing aids has been designed with a smooth response from 50 Hz to 8 kHz.

**INTRODUCTION** By the end of World War II several studies had been made of the frequency response required of a communication channel in order to obtain high intelligibility under various conditions. These studies showed that with normal listeners a frequency passband of a few hundred to 3000 Hz was adequate for high-intelligibility voice transmission under good listening conditions, and that under adverse conditions (e.g., power-limited transmissions, system distortion, noise, etc.) such a response gave better speech intelligibility than either narrower or wider passbands. This had a strong influence on telephone system design, and the modern telephone has a frequency response extending from approximately 300 Hz to 3.5 kHz. Near the end of World War II, with a large number of servicemen returning with hearing impairments caused by injury or infection, both the United States and the British governments instituted independent studies to determine what the electroacoustical characteristics of a hearing-aid speech communication system should be. The results of these studies became known as the Harvard Report [1] and the Medical Research Council Report [2]. In both studies intelligibility tests with and without background noise, system overloads, etc., were made using hard-of-hearing subjects. Both studies found that a frequency response which was flat or rising at 6 dB per octave between 300 Hz (750 Hz in the British study) and 4000 Hz, with sharp cutoffs above and below this range, produced as good or better intelligibility than any other response for nearly all of the hard-of-hearing subjects. (Thus one concludes that hearing-impaired subjects and normal subjects both need essentially similar speech communication systems.)

For the person who cannot understand unaided speech, the most important criterion for judging a hearing aid is whether or not it improves speech intelligibility. Until such a large improvement is achieved that understanding speech becomes relatively easy, that continues to be the dominant criterion. Unfortunately, such a large improvement is not universal, and thus hearing aids have generally been designed with electroacoustical characteristics aimed at achieving a maximum improvement in speech intelligibility under adverse conditions.

There are some hearing-aid users, however, who simply need amplification. Given adequate amplification, they have no difficulty in understanding speech. The "pure conductive" loss is an example of this type of impairment. Such things as naturalness, comfort, talker recognition, etc., can thus become important factors in judging a hearing aid. For such individuals a hearing aid which had an appreciably wider frequency response and did not cut off sharply at the band edges would probably be more desirable. Although such frequency responses have

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been available in body aids where microphone size is not critical, they have not been available in the headworn hearing aids which would generally be more attractive to such individuals.

Thus there appeared to be a need for a microphone which had a wider and smoother frequency response, and yet was small enough and rugged enough to be used in a headworn hearing aid. A ceramic microphone which meets these requirements has been designed. The purpose of this paper is to describe some of the design decisions:

a) the choice of a ceramic transducer;
b) the selection of a particular frequency response;
c) the inclusion of a preamplifier;
d) the mechanical construction.

Some of the advantages and limitations of this new microphone when compared to the miniature microphones available in the past are, in particular,

a) its improved ruggedness;
b) its vibration characteristics;
c) its higher self-noise level.

## MAGNETIC VERSUS CERAMIC MICROPHONE

The highly efficient balanced-armature magnetic microphone has enjoyed a substantial edge over the piezoelectric ceramic microphone for hearing-aid applications where the desired frequency response is a few hundred to a few thousand hertz. One reason is that the balanced armature magnetic transducer can be made with nearly an 80% coupling coefficient, while the coupling coefficient of the piezoelectric ceramic transducers suitable for a hearing-aid microphone is about 6%, less than one tenth that of the magnetic transducer. In addition, the intrinsic shape of the frequency response of the magnetic microphone (rising at 6 dB per octave below and falling at 6 dB per octave above the passband), combined with the effect of the Thuras tube and small-cavity resonances commonly used to square up the corners of the passband [3], produces a "band-pass" characteristic usually desired for communications microphones. In contrast, the ceramic microphone has a frequency characteristic which is intrinsically flat from very low frequencies up to near resonance, falling at 12 dB per octave at frequencies well above resonance. Thus where extended low-frequency response is required, the ceramic microphone has an advantage.

Now as far as microphones for headworn hearing aids were concerned, the entire discussion was mostly academic until recently. The low input impedance of bipolar transistors made the high impedance of ceramic microphones quite unattractive, and the few field effect transistors (FETs) that were available were expensive, noisy, and generally unsuitable for use with 1.5-volt batteries. The fact that this is no longer true has made a useful miniature ceramic microphone possible.

## CHOICE OF FREQUENCY RESPONSE

Before the final frequency response was chosen, we did extensive digital computer modeling and electrical analog simulation of possible microphone constructions, and satisfied ourselves that the flat frequency response characteristic shown in Fig. 1 was feasible for a miniature ceramic microphone. The performance of an experimental model verified these results. It was clear that available frequency response, especially at the lower frequencies, was not going to be a limitation with this new device for this application. Thus the question became, what was the best frequency response compromise for the new microphone.

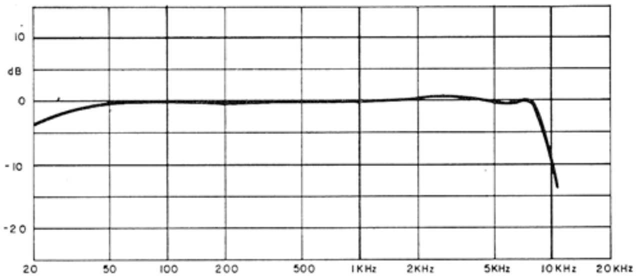

Fig. 1. Frequency response possible, with reasonable sensitivity, in a miniature ceramic microphone.

Clearly there would be little point in duplicating the intentionally sharp low-frequency roll-off already available in miniature magnetic microphones. On the other hand, some low-frequency roll-off seemed desirable to prevent overload from high-intensity low-frequency noises. The new microphone is intended to be used in a system which has appreciable acoustical gain and limited maximum sound pressure output; noises, particularly from industrial and traffic noise sources, tend to have high amplitude low frequencies and can cause premature amplifier overload with a microphone having a flat low-frequency response. Early user listener tests verified the desirability of some low-frequency attenuation, and the compromise we chose placed the "3-dB point" at approximately 250 Hz.

There is, also, a need for an increased response in the 3-kHz region if the microphone is to be used in a hearing aid. The ear canal plus concha plus pinna form a resonator–diffractor. The effect is shown in Fig. 2.

Figure 2, from Knowles [4], shows the difference between normal sound pressure at the ear drum and the sound pressure available at the entrance to a blocked ear canal. An in-the-ear hearing aid with that frequency response (as normally measured [5]) would be "flat" for the average male left ear: the boost in its frequency response would just be making up for the loss in acoustical amplification caused by blocking the ear canal. Subjective listening tests (simulating actual hearing aid usage) with a choice of microphone responses indicated that 4–5 dB of this 3-kHz boost should be included in the microphone response.

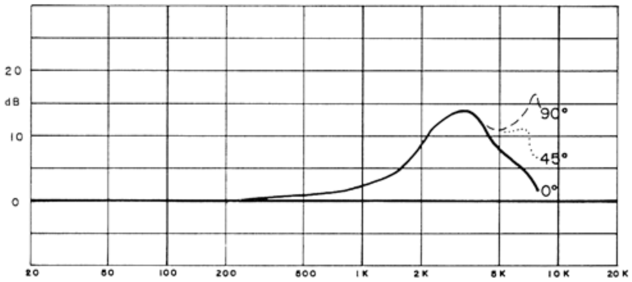

Fig. 2. Difference between normal eardrum pressure and pressure available to microphone of in-the-ear hearing aid.

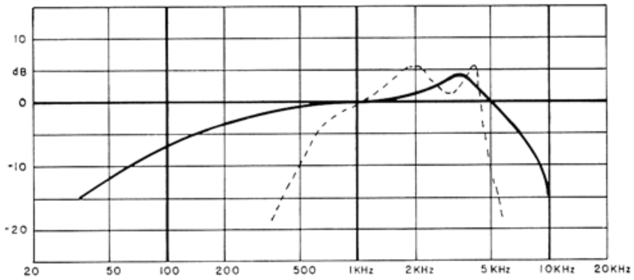

Fig. 3. Final frequency response chosen for the new ceramic microphone. Dashed curve is the frequency response of a widely used magnetic microphone. Both are the same size.

The final frequency response chosen for the new microphone is shown in Fig. 3. The frequency response of the smallest previously available magnetic unit is shown for comparison.

## NEED FOR AN INTERNAL PREAMPLIFIER

Having decided on a piezoelectric ceramic transducer, we were faced with a problem common to nearly all capacitive transducers (e.g., ceramic, condenser, electret). Their high impedance makes them extremely sensitive to noise pickup on their external leads. This can take two forms, electrostatic pickup of external ac fields and the condenser-microphone pickup which occurs whenever relative movement occurs between two conductors which have different dc potentials. The problem is usually solved by the use of shielded cable and/or by mounting a preamplifier right at the microphone. Shielded wire is not practical in a hearing aid because its inherent stiffness would mechanically bridge the vibration isolator in which the microphone is mounted. Although the exposed leads are usually short in a hearing aid, the gain is high. Thus we concluded that the prudent thing to do was to include a preamplifier inside the microphone so that *all* of the high-impedance circuitry would be completely shielded by the microphone case.

## DESIGN OF THE INTERNAL PREAMPLIFIER

Deciding a preamplifier is needed is not the same as having a practical circuit design. In headworn hearing aids the power supply is a single-cell silver or mercury battery. In the case of the mercury cell, the voltage has dropped to about 1.2 volts before 90% of the energy has been delivered (see Fig. 4), and some additional allowance must be made for the voltage drop across the decoupling network needed to keep voltage variations on the power supply from being fed back to the input. Thus the preamplifier must operate properly on a 1.1-volt supply. This limits the number of usable circuit configurations. Consider the typical amplifier circuit configuration shown in Fig. 5**a**, for example. For a FET to work in this circuit with a 1.1-volt supply, it would have to have a pinch-off voltage between roughly 0.3 to 0.5 volt. Since FETs are usually sold with a 2:1 or 3:1 spread in pinch-off voltage, the circuit shown in Fig. 5**a** is not attractive. In contrast, the source-follower circuit shown in Fig. 5**b** has the advantage that it will accept transistors with a wider range of pinch-off voltages, but has the disadvantage of a signal voltage loss instead of a gain. Fortunately, the circuit of Fig. 5**c** combines many of the advantages of Fig. 5**a** and **b**. It will work with FETs having a wide range of pinch-off voltages, yet it has a substantial voltage gain. This was the basic configuration we chose. In the final design, the load resistor is provided with taps, and the output lead of the microphone is internally soldered to that tap which produces the closest to nominal sensitivity specification.

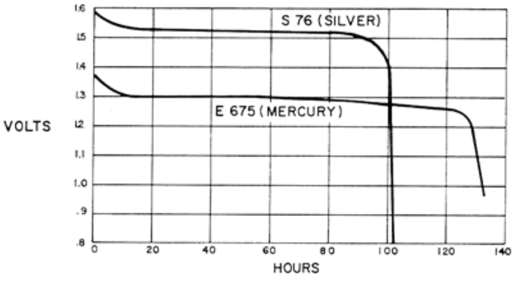

Fig. 4. Discharge of two popular hearing-aid batteries under 1.5-mA drain.

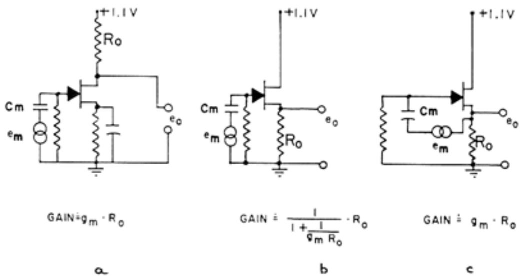

Fig. 5. Three possible preamplifier circuit configurations. $e_m$ and $C_m$ refer to the output voltage and capacitance, respectively, of the piezoelectric ceramic element.

## LAYOUT

Having decided on the circuit, the next problem was to put the transistor, two resistors, and a microphone in a 0.312- by 0.218- by 0.163-inch case, which was the design objective. The most economical solution appeared to be to use thick-film technology. We were able to solve the problem of electrically connecting the microphone to the thick-film substrate by building the microphone on the substrate. Figure 6 shows the construction in cross section. The hole in the thick-film substrate allows for a mechanical connection between the diaphragm and the ceramic element. The actual size of the completed microphone can be judged from Fig. 7, which shows the microphone next to a human ear.

## PERFORMANCE CHARACTERISTICS OF THE FINISHED MICROPHONE

Table I summarizes the typical specifications of the

Table I

| Characteristics | |
|---|---|
| Size | 0.310 by 0.218 by 0.160 inch |
| Sensitivity | —56 dB re 1 volt/microbar |
| Output impedance | 12,000 ohms |
| Battery drain | 0.025 mA |
| Noise level | 28 dB (see text) |
| Vibration sensitivity | —26 dB re 1 volt/*g* |

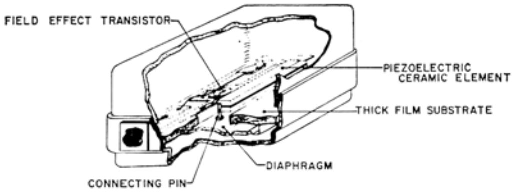

Fig. 6. Internal construction of the new ceramic microphone.

new microphone operated with a 1.3-volt power supply. Going down to 1.1 volts or up to 1.5 volts typically causes about 1 dB change in output. The ruggedness, noise level, and vibration sensitivity are discussed in more detail below.

## Ruggedness

Hearing aids are not meant to be dropped, but, like wrist watches, they are. Because of this, successful transducers for use in hearing aids have had to be extremely rugged: Well designed devices will survive shocks of the order of 1000–2000 *g* in the most damaging direction. Even so, analysis of transducers which have failed in the field has shown that the most common mode of transducer failure in actual hearing aids is shock [6]. By paying considerable attention during the design of this unit to keeping the mass of the moving elements small while keeping their strength high, we were able to produce a unit which is unusually rugged. Our laboratory shock tests indicate an improvement of better than 3:1 in shock resistance. The new unit will survive shocks of the order of 3000–6000 *g* in the most damaging direction, and samples of this construction have survived shocks calculated to be in excess of 20,000 *g*.

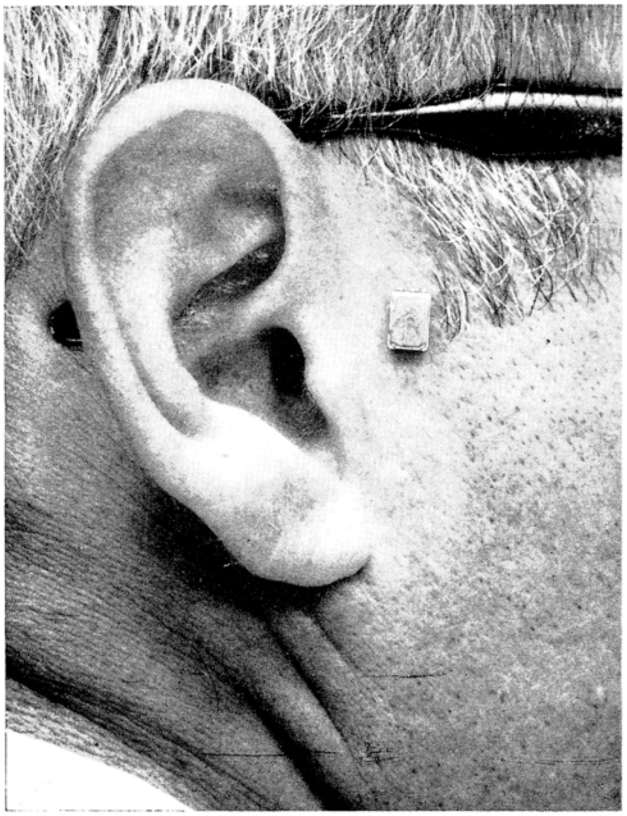

Fig. 7. Ceramic microphone shown next to a human ear.

## Noise Level

As might be expected, a price had to be paid for the extended bandwidth obtained in the ceramic microphone, and it was an increase in the noise level. Although the sound level meter *A*-weighting characteristic is commonly used to give an equivalent sound-pressure-level rating to microphones, it is somewhat hard to apply this single-number rating to a communications system whose response is limited to between a few hundred and a few thousand hertz. What we have done for many years is to measure the electrical output of the microphone noise in the 300-Hz to 4-kHz speech band and compare that to the electrical output of the microphone in a 1-kHz sound field. On that basis, the new ceramic microphone has an equivalent noise pressure (ENP) of 26 dB re 0.0002 microbar ($2 \times 10^{-5}$ N/m$^2$). This is 5 dB higher than the similarly derived 21-dB ENP of the comparable size *BJ* series magnetic microphones. The *A*-weighted noise rating of the new microphone is typically 28 dB re 0.0002 microbar.

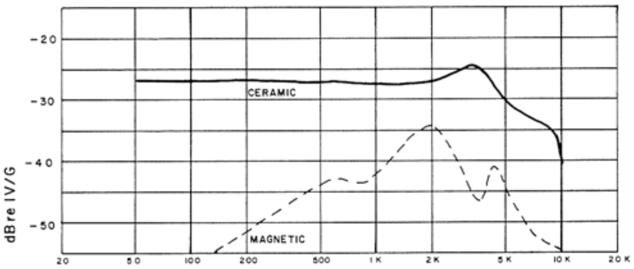

Fig. 8. Absolute vibration sensitivity of two microphones.

## Vibration Sensitivity

The absolute vibration sensitivity of the new microphone is shown in Fig. 8, along with that of the previously shown magnetic microphone (dotted curve). The comparison in Fig. 8 is somewhat misleading, however, since it makes no allowance for the difference in acoustical sensitivities. In Fig. 9 the two curves have been normalized. This was done on the basis of the average acoustical sensitivities of the two microphones at 500, 1000, and 2000 Hz.

Although the new microphone has a generally lower relative vibration sensitivity than previously available miniature microphones, its extended low-frequency accelerometer response means the low-frequency response of the hearing aid amplifier may need to be rolled off in

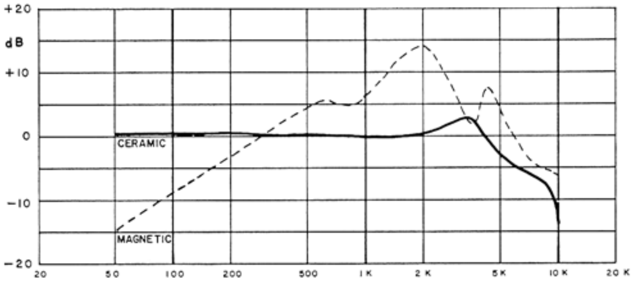

Fig. 9. Normalized vibration sensitivity of two microphones.

order to avoid vibration-induced low-frequency overload.

## CONCLUSION

With the availability of a truly miniature wideband microphone, the microphone no longer becomes the limiting factor in determining the frequency response of the hearing aid, and it should be possible to reevaluate the question of optimum frequency response for the head-worn aid.

## ACKNOWLEDGMENT

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## THE AUTHORS

Mead C. Killion received an AB degree in mathematics from Wabash College in 1961. Mr. Killion is currently a senior engineer at Industrial Research Products, Inc. Since joining that firm in 1962, he has been involved in the design of electro-acoustical transducers and instrumentation. Two previous papers —one on a 7-watt Class D audio amplifier, and one on a low-noise preamplifier for the 640AA—have been presented before the CAAG and the AES.

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