# Noise in miniature microphones[a)]

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The internal noise spectrum in miniature electret microphones of the type used in the manufacture of hearing aids is measured. An analogous circuit model of the microphone is empirically fit to the measured data and used to determine the important sources of noise within the microphone. The dominant noise source is found to depend on the frequency. Below 40 Hz and above 9 kHz, the dominant source is electrical noise from the amplifier circuit needed to buffer the electrical signal from the microphone diaphragm. Between approximately 40 Hz and 1 kHz, the dominant source is thermal noise originating in the acoustic flow resistance of the small hole pierced in the diaphragm to equalize barometric pressure. Between approximately 1 kHz and 9 kHz, the noise originates in the acoustic flow resistances of sound entering the microphone and propagating to the diaphragm. To further reduce the microphone internal noise in the audio band requires attacking these sources. A prototype microphone having reduced acoustical noise is measured and discussed. © *2002 Acoustical Society of America.* [DOI: 10.1121/1.1436072]

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## I. INTRODUCTION

Noise that is present in the electrical outputs of a microphone may originate as an acoustical noise in the environment or as a noise generated within the microphone. This paper deals with the estimation and measurement of the internal noise in miniature microphones. The particular microphones used in this study are a type that is normally used in the manufacture of hearing aids. The internal noise may be generated in the electrical circuits of the microphone, in the mechanical motion of the microphone diaphragm, or in the acoustical propagation paths within the structure of the microphone. This study will measure the total internal noise of the microphone in its normal operating state, and separately measure the microphone noise in a vacuum, where the acoustical noise sources are eliminated. An empirical model of the noise and its separate electrical, mechanical, and acoustical components will be presented. Finally, a modified microphone configuration having lower internal noise will be shown.

The methods of measurement and analysis used in this study have all been previously described and used, although apparently not all for the same microphone. Olsen[1] made a similar study of the noise in a ribbon microphone, including a vacuum measurement that eliminates all sources of acoustical noise leaving only the electrical noise and mechanical noise. Bevan *et al*.[2] describe an analogous circuit noise model for an electret condenser microphone. Gabrielson[3] has presented a comprehensive review of thermal noise sources in acoustic and vibration sensors, and another paper[4] with particular application to micromachined microphones. Zuckerwar and Ngo[5] measured the total internal nose and the purely electrical noise in separate experiments to determine the frequency dependence of the remaining acoustical and mechanical noise.

The present study was undertaken to understand the design features of the microphone that effect its internal noise level with the hope of identifying design changes that would provide a practical microphone with reduced internal noise.

## II. THE MICROPHONE

The microphone used in this study is the model EM-3346 microphone from Knowles Electronics, shown in Fig. 1. The EM-3346 is similar to all microphones presently used in the manufacture of modern hearing aids, and is among the lowest in internal noise. Figure 2 is a cross sectional view showing its internal structure. Acoustic pressure from the environment enters the microphone through the sound coupling tube, and then passes through a thin slit in the outer microphone case into a small cavity called the microphone front volume. The use of a sound coupling tube has been desirable for hearing aid microphones because it allows the microphone to be mounted with its smallest area side toward the hearing aid case. In many hearing aid designs, the tube is a convenient feature to attach the microphone to the aid. The data of this study show, however, that this feature contributes to the internal noise of the microphones.

Referring again to Fig. 1, the inner wall of the front volume is a thin polymer diaphragm that is driven into motion by the acoustic pressure in the front volume. Not shown in the figure is a small hole pierced in the diaphragm to equalize the back volume with barometric pressure. Without this equalization, barometric pressure changes would cause very large displacements of the diaphragm that would degrade or damage the microphone.

The diaphragm is metalized on one surface, and this metalization is electrically connected to the metal parts of the case. The diaphragm moves near a metal backplate whose

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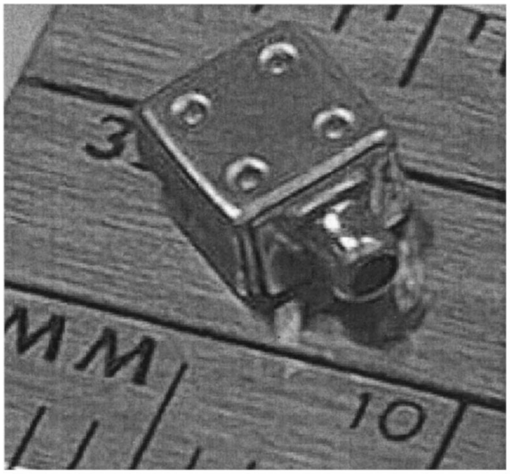


FIG. 1. The Knowles microphone model EM-3346 is an example of the miniature microphone discussed in this paper. This microphone is commonly used as the acoustic sensor in hearing aids.

surface is coated with an electrically charged electret material. The diaphragm and the backplate form a parallel plate capacitor that is charged to a relatively high voltage by the static charge stored in the electret. As the diaphragm moves, a small voltage is induced on the backplate, which is electrically isolated from the case. A wire connects between the backplate and the gate of a FET that buffers the high electrical impedance of the backplate to provide a useful output signal.

A number of features of the microphone will later be seen to be important in understanding the internal noise. First, the acoustic flow path from the external environment to the front volume contains several sections. Sound travels through the coupling tube and enters the front volume through a thin slot in the side of the microphone case. It then spreads across the width of the front volume and along its length. The acoustic flow impedance for this path is partly

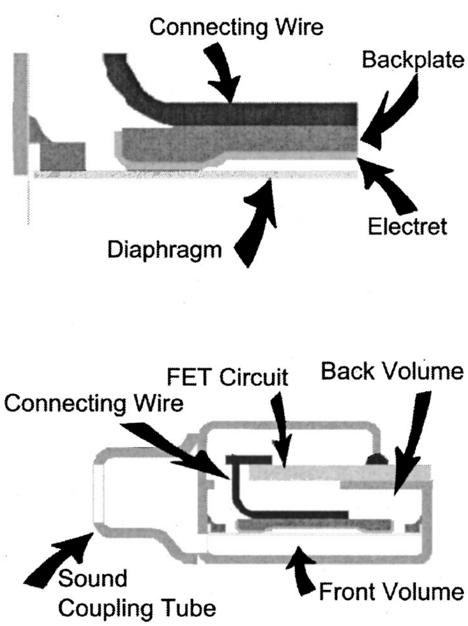


FIG. 2. Cross sectional view if the EM-3346 microphone showing its internal structure.

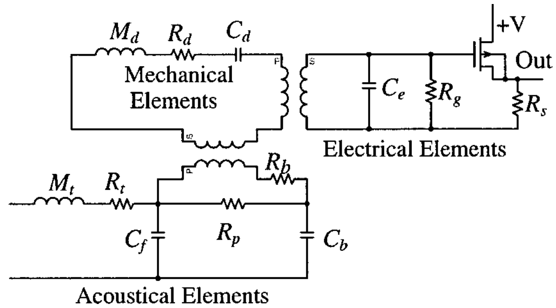


FIG. 3. Equivalent circuit of the electret microphone. The meaning of the circuit components is given in the text.

inertance (masslike impedance) and partly resistance. The motion of the diaphragm causes another acoustic flow of the air between the diaphragm and backplate into the larger part of the back volume. There is a significant acoustical resistance to this flow because of the smallness of the gap between the diaphragm and backplate. Often this resistance is reduced somewhat by "venting" the backplate with one or more small holes. There is also a significant acoustical resistance associated with flow through the barometric relief hole in the diaphragm. Altering the size of the hole can change the magnitude of this resistance.

A model of the microphone that includes these features is shown in the analogous circuit of Fig. 3. The components in this circuit are

| | |
|---|---|
| $M_t$ | inertance of the sound entry port |
| $R_t$ | resistance of the sound port |
| $R_p$ | resistance of barometric relief hole pierced in the diaphragm |
| $C_f$ | compliance of the front volume |
| $C_b$ | compliance of the back volume |
| $R_b$ | flow resistance between diaphragm and backplate |
| $M_d$ | effective mass of the diaphragm |
| $C_d$ | compliance of the diaphragm including the negative compliance from the attractive force between diaphragm and backplate |
| $R_d$ | mechanical resistance of the diaphragm |
| $C_e$ | capacitance of the diaphragm including stray capacitances in the microphone and circuit |
| $R_g$ | bias resistance at gate of FET |
| $R_s$ | FET source resistor |

The various impedances are of three types: acoustical, mechanical, and electrical. The variables in each domain have different units. The transformers in the equivalent circuit have transformation ratios that include the unit conversion factors. The transformation ratio from acoustical to mechanical variables is simply the effective area $S_d$ of the diaphragm. The transformation ratio from mechanical to electrical variables is $q/L$ where $q$ is the charge stored in the electret and $L$ is the equilibrium separation of the diaphragm and backplate.

## III. SOURCES OF NOISE

The three main noise mechanisms in any type of sensing device are *thermal noise*, *shot noise*, and *flicker noise*.[6,7] The measurements presented later in this paper show that thermal noise is the dominant noise mechanism in the miniature microphones at all frequencies between 20 Hz and at 10 kHz. Thus the investigation of thermal noise sources has been the primary interest in this study. Shot noise is associated with current flow across a potential barrier, and originates solely within the semiconductor device. In a FET device, shot noise is present only in the gate leakage current. This leakage and the associated noise are expected to be quite low in the CMOS FET. Flicker noise is a type of noise found in all active devices as well as some passive devices. It is associated with fluctuations in the resistance of circuit elements, and its value is related to the level of DC current in the element. It is often called $1/f$ noise because its power spectrum varies as $1/f^{\alpha}$ where $\alpha$ is approximately equal to unity. Observed values for $\alpha$ vary between 0.8 and 1.3 for most systems of interest.

Thermal noise in the microphone originates in the random motion of particles in the materials of the device. In the electrical elements. The random motion of electrons in the conductors generates noise. In the mechanical elements, it is the random motion of molecules in the solid lattice of the diaphragm material. In the acoustical elements, it is the random motion of the molecules in the air. In each case, the random flow generates a noise across any resistive element in the analogous circuit. The acoustical and mechanical noises generate motion of the diaphragm that is faithfully converted to electrical signals, just as any other signal is converted in the transducer.

The spectral density of thermal noise voltage is given by[8]

$$N=\sqrt{4kTR},$$

where $k$ is Boltzmann's constant, $T$ is the absolute temperature, and $R$ is the resistance. Thermal noise has a flat spectrum at the location where it is generated. However, each noise source is filtered by all successive analogous circuit elements before it appears at the output of the microphone. Since each noise source is filtered differently, it may be possible to empirically determine the dominant source of the noise in a particular frequency band from the shape of the noise spectrum.

## IV. NOISE MEASUREMENT EXPERIMENTS

When measuring the internal noise in a microphone, it is necessary to shield the microphone from all external sources of acoustical signals and noise to a level at least several decibels below that of the internal noise being measured. This must be done without changing the mechanical or acoustical properties of the microphone. In a microphone such as that shown in Fig. 1, it is *not* correct to block the sound entry port. While doing so might eliminate external acoustical noise from the measurement, it would also alter the reactive impedances in the acoustical part of the equivalent circuit. This, in turn, would change the filter function applied to some of the acoustical noise components and thus alter the spectrum of the noise being measured. The noise measurement must be done with the sound port open, while

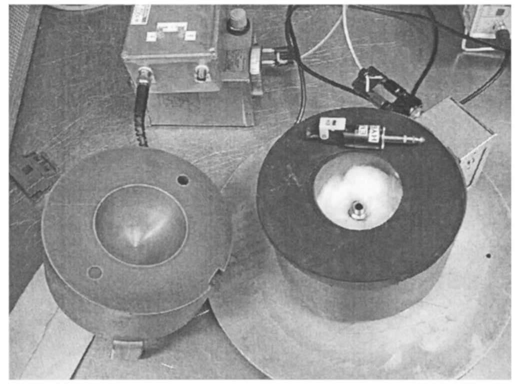

FIG. 4. Acoustical isolation housing for microphone noise measurement is a thick walled steel cylinder mounted on a small rubber bladder to shield from building vibrations as well as acoustical signals.

the unit is shielded from all environmental noise. The chamber used for the noise measurement reported here is shown in Fig. 4. It is composed of two steel cylinders each with a diameter of 6 in. and a length of approximately 3 in. Each cylinder is hollowed at one end to create a cavity with a diamter of 3 in. and a depth of approximately 2 in. The cylinders are placed together with the two cavities forming an internal volume of over 200 ml. This assures that the chamber will not affect the frequency response of the microphone. Visible in the bottom chamber section in Fig. 4 is a small amount of cotton wool that acts as acoustical damping. This eliminates the possibility that resonant modes of the otherwise hard-walled chamber might affect the measurement.

The two halves of the chamber are set together with a thin rubber gasket forming an acoustic seal. This stacked cylinder is set on a plate and a rubber air bladder to isolate the chamber from low frequency vibrations of the building and table. The entire chamber is electrically grounded, and shielded cables are run from the device under test to the measurement equipment to eliminate electromagnetic interference from the measurement. The electrical noise floor of the measurement system was quickly verified to be acceptable by connecting a 1 k$\Omega$ resistor across the measurement terminals. The A-weighted electrical noise in this case was well under 1 $\mu$V. This is equivalent to an input sound pressure level of approximately 5 dBA for the sensitivity of the microphone that is measured. This is at least 15 dB less than the measured microphone noise level.

The acoustical noise floor of the measurement chamber is not known in detail because it is not possible to fit micro-

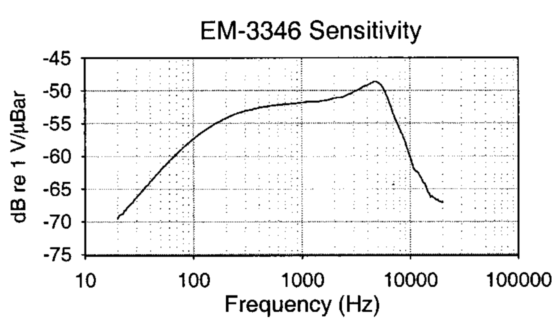


FIG. 5. Frequency response of the microphone sensitivity for the Knowles EM-3346 microphone.

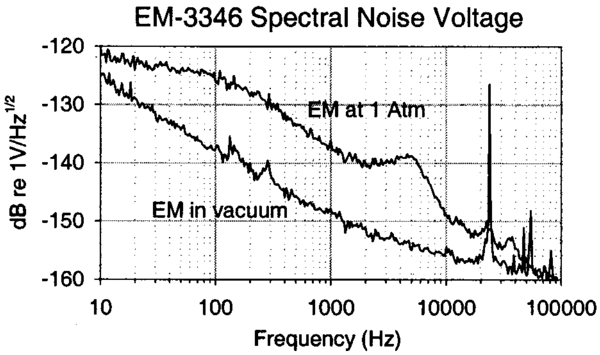


FIG. 6. Measured noise level of the EM-3346 microphone. The darker curve is the noise measured under normal operation at 1 atm. The lighter curve is the noise measured in a vacuum chamber where the acoustical noise sources have been eliminated.

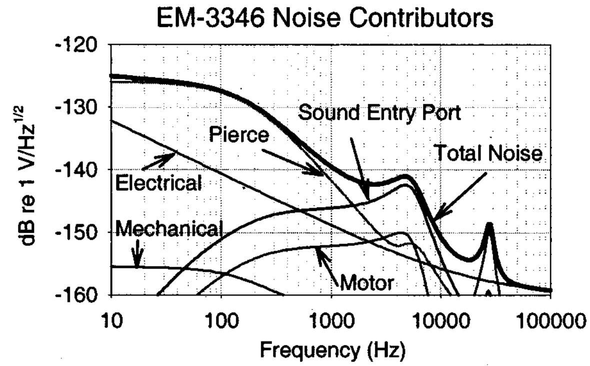


FIG. 8. The total noise at the output of the microphone is made up of several independent sources. Dominant sources are the resistance of the hole pierced in the diaphragm and the resistance of the flow in the sound entry port.

phones with lower internal noise into the chamber. As a qualitative check, it is known that speaking in a loud voice near the chamber with a microphone installed does not produce a detectable voice signal in the microphone output.

The microphones used for this test are Knowles model EM-3346 units, whose typical frequency response is shown in Fig. 5. Figure 6 shows the noise level of the microphone as measured under normal operating conditions in the chamber of Fig. 4. This noise peak at approximately 5 kHz is at the same frequency as the peak in the sensitivity. This is a hint that the noise, at least in this frequency region, is of acoustical origin, since acoustical noise is filtered by the transfer function of the sensitivity. To investigate this hypothesis, we can measure the microphone noise in a vacuum chamber. The vacuum measurement eliminates all acoustical noise sources, so the remaining noise is entirely of electrical and mechanical origin. Figure 7 shows a small vacuum chamber that is used to measure the vacuum noise of the microphone.

Figure 6 shows the noise of the microphone measured in a vacuum in comparison to the noise in normal operation. A number of features can be different from the shape of these curves.

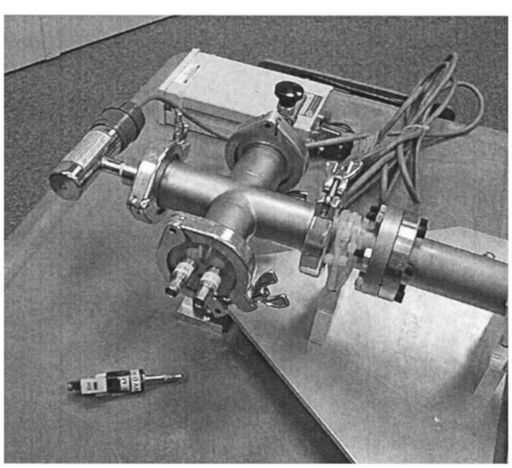

FIG. 7. Small vacuum chamber for the measurement of the electrical noise of the microphone. The microphone holding fixture at the lower left is placed into the chamber, and electrical connections emerge through the BNC connectors.

In the frequency range from 20 Hz to 10 kHz, the total microphone noise in normal operation is dominated by acoustical noise. By removing the acoustical noise in the vacuum measurement, the total noise level drops by more than 5 dB.

Electrical noise is not a significant part of the total internal noise except possibly at the extreme low and high frequencies in the figure. The spectrum of the electrical noise varies approximately as $1/f$ in the frequency range below 1 kHz.

The very tall peak in the vacuum noise near 25 kHz is the mechanical resonance of the diaphragm when the acoustical impedance of the air confined in the microphone does not load it.

## V. EMPIRICAL MODEL OF THE NOISE

The analogous circuit of Fig. 3 can also be used to model the noise of the microphone. In the work reported here, the PSPICE circuit analysis code was used to model both the sensitivity and the noise of the microphone. Thermal noise is modeled by placing a noise voltage generator with spectral density $\sqrt{4kTR}$ in series with each resistor, whether the resistor is in the electrical, the mechanical or the acoustical sections of the circuit. The semiconductor noise contributions are modeled using the Type 1 FET model of PSPICE[9] using parameter values that have been fit to the characteristics of the custom CMOS FET in the microphone. Figure 8 shows the model results for the total noise of the EM-3346 microphone. Both the shape of this curve and the level of the noise are a good match for the measurement shown in Fig. 6. By independently "turning on" the noise of the separate sources, it is possible to calculate the contribution of each source. This process was performed for each of the resistances in the analogous circuit of Fig. 3 to produce the noise contribution curves of Fig. 8. The curves are labeled as listed in Table I.

It is seen in Fig. 8 that two sources of noise dominate within the audio band. At frequencies below 1 kHz, the dominant source is thermal noise from the resistance of the hole pierced in the diaphragm. Between 1 kHz and 10 kHz, the dominant source is the acoustical resistance in the flow through the sound entry tube and port. The electrical noise from the FET and the electrical resistances is an important

TABLE I. Correspondence between labels on curves in Figs. 11 and 12 and the microphone resistance that causes the noise.

| Curve label | Circuit resistance | Description |
|---|---|---|
| Pierce | $R_p$ | Flow resistance of diaphragm pierce hole |
| Sound entry port | $R_t$ | Flow resistance through sound entry port and across diaphragm |
| Motor | $R_b$ | Flow resistance between diaphragm and backplate |
| Mechanical | $R_d$ | Mechanical resistance to motion of the diaphragm |
| Electrical | $R_s$ ,FET | FET bias and source resistors, semiconductor noise |

contributor to the total noise only above 10 kHz, and at *very* low frequencies (below 10 Hz which is not shown in the figure).

## VI. INTERNAL NOISE REDUCTION

Because the dominant noise in much of the frequency spectrum is acoustical noise, changes to the acoustical design of the microphone are necessary to further reduce its internal noise. The preceding section shows that the major sources of acoustical resistance in the microphone are as follows:

(1) Flow through the sound inlet tube and then through the small slot in the outside case that allows sound entry from the tube into the front volume.
(2) Flow within the confined space of the front volume.
(3) Flow through the hole pierced in the diaphragm to allow barometric pressure relief.
(4) Flow between the diaphragm and backplate within the back volume of the microphone.

Reductions in any of these flow resistances will affect both the internal noise level and the shape of the microphone sensitivity. As an experiment, the authors attempted to remove as much as possible of the acoustic flow resistance in the microphone without changing the dimensions or design

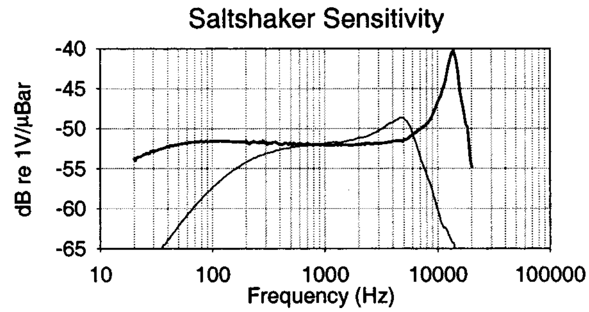


FIG. 10. Frequency response of the sensitivity for the microphone shown on the right-hand side of Fig. 9. The lighter curve is the response of the EM-3346 for comparison.

of the microphone motor. An attempt was made to reduce the first three sources of acoustical noise listed above. This involved removing the sound tube and opening the front volume of the microphone directly to the external acoustic field, and also decreasing the diameter of the barometric relief hole pierced in the diaphragm. With reference to the circuit analog of Fig. 3, the changes attempt to eliminate $R_f$ and $M_f$ , and to increase the value of $R_p$ .

Figure 9 show the comparison of the standard microphone with the microphone as modified to open the front volume directly to the external acoustic field. This is called a ''saltshaker'' configuration because of the appearance of the several small holes in the wall of the front volume. Figure 10 shows the sensitivity of this microphone. Notice that the acoustical resistance plays an important part in determining the frequency response of the system. The design changes removed a significant amount of both flow resistance and inertance (masslike impedance), which causes the primary resonance to increase in frequency and to be significantly less damped. The change in the resistance of the barometric relief hole causes the frequency response to remain flat to a lower frequency. Figure 11 shows the noise spectrum for the saltshaker microphone. The spectral shape has changed along with the changes in the sensitivity, and the spectral level of the noise has decreased by approximately 6–8 dB over much of the audio frequency band. The noise measured in a vacuum is also shown. The vacuum noise is composed of the electrical and mechanical noise components, with no contribution from the acoustical noise. More insights of this kind

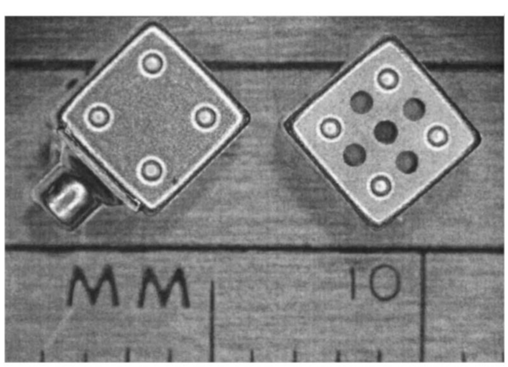


FIG. 9. Left: Standard EM-3346. Right: ''Saltshaker'' configuration that is modified for lower acoustic flow resistances between the far field and the diaphragm.

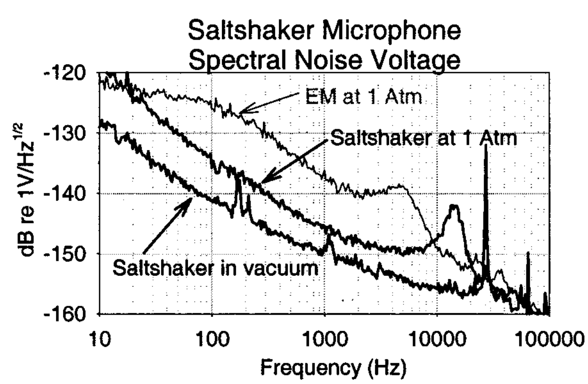


FIG. 11. Spectral nose of the ''Saltshaker'' microphone, compared to the standard EM-3346. Also shown is the vacuum noise of the saltshaker microphone.

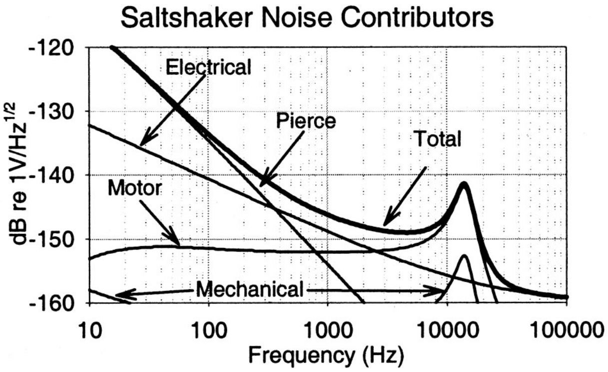


FIG. 12. The saltshaker configuration eliminates noise from the sound entry port and reduces the pierce noise above 50 Hz. The dominant sources are pierce noise below 300 Hz, motor noise from 3 kHz to 25 kHz, and electrical noise at other frequencies.

can come from a model of the noise components.

The noise contribution curves for the saltshaker microphone are shown in Fig. 12. The saltshaker design has eliminated the sound tube and enlarged the sound entry ports to the point that the flow impedance is negligible compared to the remaining flow resistance. Thus the noise contribution from the sound entry port is not present in Fig. 12.

The other modification in the saltshaker microphone from the standard EM-3346 is a reduced size for the barometric relief hole pierced in the diaphragm. This significantly increases the resistance $R_p$ of the hole. It is, perhaps, not intuitively clear that *increasing* a thermal resistance should result in a noise reduction at the microphone output. In fact, at low frequencies, it does not. At frequencies below about 40 Hz, the thermal noise from the larger resistance of the pierce hole causes increased noise at the output. Above 40 Hz, the noise from the pierce resistance is shunted by the acoustical compliance of the back volume, $C_b$, and is greatly reduced in the output. The total noise of the saltshaker microphone remains below that of the standard microphone from 40 Hz to about 9 kHz, where the diaphragm resonance causes the flow resistance of the motor to dominate.

## VII. CONCLUSIONS

The miniature microphones discussed in this paper are a type that is customarily used as a component in hearing aids. The internal noise in these microphones is predominantly the thermal noise associated with acoustic flow resistances in the small passages within the microphone. Testing of the microphone noise in a vacuum, which eliminates the noise sources of acoustical origin, verifies that the purely electrical noise is a small contributor to the total noise at all frequencies in the audible range.

An empirical model using an electrical circuit analog has been used to identify the noise contribution from the various acoustic flow resistances. In the EM-3346 microphone, the resistance associated with flow into the microphone port is the dominant source for audible frequencies above about 1 kHz. Below 1 kHz, the dominant source is the resistance associated with the flow through the hole pierced in the microphone diaphragm to equalize barometric pressure.

An experimental microphone was built and tested that reduced the noise from both of these sources. The sound tube and sound entry port were replaced by several larger holes in the front volume. This essentially eliminates the flow resistance from the sound entry path, and gives the microphone the characteristic appearance that gives it the name "saltshaker." The hole pierced in the diaphragm was also reduced in size to change the frequency response of the noise from that resistance. Together these two changes result in a microphone having lower noise than the standard configuration from approximately 40 Hz to 9 kHz. The dominant sources of noise remaining in the saltshaker microphone are the flow resistance between the diaphragm and backplate at frequencies above 2.5 kHz, noise from the diaphragm pierce resistance for frequencies below 300 Hz, and electrical noise between 300 Hz and 3.5 kHz. Further significant reduction in microphone internal noise must deal with all three of these sources.

The removal of the sound coupling tube to achieve lower internal noise may be a difficult change to accommodate in the manufacture of hearing aids. Current hearing and manufacturing practice is to mount the microphone by its coupling tube with the smallest side of the microphone in contact with the inside of the case. Effective use of the salt shaker microphone would require that the largest side of the microphone be in contact with the case wall. It may be difficult to accommodate this change in hearing aid design. However, it is clear that microphone design changes of the type discussed in this paper are necessary to reduce the dominant sources of internal noise in this type of miniature microphone.

[1] H. F. Olsen, "Microphone thermal agitation noise," J. Acoust. Soc. Am. **51**, 425–432 (1972).
[2] W. R. Bevan, R. B. Schulein, and C. E. Seeler, "Design of a studio-quality condenser microphone using electret technology," J. Audio Eng. Soc. **26**, 947–957 (1978).
[3] T. B. Gabrielson, "Fundamental noise limits for miniature acoustic and vibration sensors," ASME J. Vibr. Acoust. **117**, 405–410 (1995).
[4] T. B. Gabrielson, "Mechanical-thermal noise in micromachined acoustic and vibration sensors," IEEE Trans. Electron Devices **40**, 903–909 (1993).
[5] A. J. Zuckerwar and K. C. Ngo, "Measured $1/f$ noise in the membrane motion of condenser microphones," J. Acoust. Soc. Am. **95**, 1419–1425 (1994).
[6] C. D. Motchenbacher and F. C. Fitchen, *Low Noise Electronic Design* (Wiley, New York, 1973), pp. 9–21.
[7] P. Horowitz and W. Hill, *The Art of Electronics,* 2nd ed. (Cambridge University Press, New York, 1989), p. 432.
[8] Leo L. Beranek, *Acoustical Measurements* (American Institute of Physics, New York, 1993), p. 190.
[9] *PSpice Reference Guide*, 2nd online ed. (a part of the online documentation for the Orcad PSpice Version 9.2 software), Cadence Design Systems, Inc., Palo Alto.