A Subminiature Electret-Condenser Microphone* of New Design

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The electret technology has been applied to the design of subminiature condenser microphones in an unusual manner. The use of a nontensioned diaphragm and the separation of diaphragm and electret functions permit the charge storage function, the frequency response, and the temperature coefficient to be independently optimized. The resulting microphones are characterized by an unusually low vibration sensitivity, noise level, and temperature coefficient, combined with a high degree of reliability. The range of selectable parameters permits the ready attainment of flat extended range devices for research purposes or tailored frequency response devices for use in hearing aids.

INTRODUCTION: Back in the mid 1960s it became increasingly apparent that there were several needs which were not met by the magnetic hearing-aid microphones. One of these was a need for a wider and smoother microphone frequency response. More and more people were buying hearing aids simply to make hearing easier. Given a little amplification, they had no difficulty in understanding speech. For them, such things as enjoyment of music, comfort in wearing, naturalness of sound, and the ability to easily identify who was talking all became important. The miniature microphones available for hearing aids, however, had all been designed with a narrow bandpass frequency response which was aimed at maximizing speech intelligibility under adverse conditions, and did not sound natural. The need for a wideband frequency response in a microphone small and rugged enough to be used in a headworn hearing aid was quite clear.

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A second problem was that of shock resistance. Although the magnetic microphones had been designed to be extremely rugged, routinely surviving several thousand *g*'s of shock without damage, the continuing pressures to reduce the size of headworn hearing aids meant that less and less space could be allowed for the shock absorption material needed to completely protect the microphones. In a study on the shock exposure seen by microphones in actual hearing aids [1] we found that microphones in some of the smaller hearing aids were being exposed to shocks of 5000 to 10 000 *g* or more. Thus transducer failure due to shock had understandably become the single biggest cause of field failures in some of the smaller hearing aids.

A third problem was that of vibration feedback between the microphones and receiver. With the amount of air-to-air gain required in many headworn hearing aids, and the reduced clearances allowed as they were made smaller and smaller, it became difficult to get enough vibration isolation between the microphone and receiver to avoid "whistling" due to mechanical feedback. Thus a reduced vibration sensitivity was a third need.

Wideband Ceramic Microphone

There appeared to be two technologies which could answer these needs: the piezoelectric-ceramic transducer and the electret-condenser transducer. It was soon clear that a FET preamplifier would have to be included in whichever microphone was used. Because the ceramic microphone technology was well advanced, with a high degree of reliability established in nearly two decades of actual field exposure, while the reliability of the electret was, and still is, for that matter, less certain, the ceramic approach was selected for the first design. The resulting ceramic microphone [2] produced a smooth wideband frequency response, extending the low end by two to three octaves and the high end by nearly an octave compared to previously available magnetic microphones. By using a special lightweight diaphragm, it was also possible to achieve a 5–10-dB reduction in midband vibration sensitivity, and nearly an order of magnitude improvement in shock resistance over previous magnetic designs.

This ceramic microphone gained wide acceptance, but it soon became clear that we had really answered only two of the three needs: the smooth tailored response removed the microphone frequency response barrier, and the ruggedness of the ceramic microphone had reduced shock-induced microphone field failures to nearly zero, but a vibration problem remained.

Vibration Problem

Although the midband vibration sensitivity of the ceramic microphone was substantially lower than that of the magnetic, the magnetic microphone vibration response falls off at approximately 6 dB per octave with decreasing frequencies while the vibration response of the ceramic is essentially flat to very low frequencies. Unfortunately, the Homo Sapiens head and neck complex seems to resonate at about 20 cycles, so that the shock excitation of heavy walking can produce up to 1 *g* (980 cm/s^2) of vibration on a behind-the-ear hearing aid [3]. Now 1 *g* of vibration at 20 cycles will produce more voltage out of the ceramic microphone than a 1-kHz sound pressure level of 100 dB.[1] If the ceramic microphone is mounted with its diaphragm parallel to the ground and with no isolation from the hearing-aid case, this 1 *g* of acceleration will be transferred unattenuated to the microphone diaphragm and the resulting output voltage can easily overload even a moderate-gain hearing aid. Thus the designers of high-gain hearing aids using the new ceramic microphone found they had to pay careful attention to the orientation and mechanical isolation of the microphone, and perhaps add an extra stage of RC rolloff in the amplifier to avoid an audible "thump" in the hearing aid every time the wearer took a heavy step. These precautions solved the problem, but they also added to the cost of the hearing-aid manufacturer.

Since the one clear advantage of the electret-condenser transducer was its inherently low vibration sensitivity, we decided to design a subminiature condenser microphone, duplicating, if possible, the tailored frequency response, the shock resistance, and the physical dimensions of our previous ceramic microphone design.

A NEW DESIGN

Although no two microphone designs are exactly the same, we made two design decisions which resulted in a construction noticeably different from that used in the conventional electret-condenser microphone, different enough to perhaps warrant the title, "A New Design." The first of these decisions was to separate the electret function from the diaphragm and combine it with the backplate. The second decision was to use a nontensioned diaphragm. In a nutshell, separating the diaphragm and electret functions makes it possible to get an unusually low vibration sensitivity, and the nontensioned diaphragm construction makes possible an unusually low temperature coefficient.

Separating the Electret and Diaphragm Functions

The idea of separating the electret function from the diaphragm function is hardly a new one; the original wax-electret condenser microphones designed back in the thirties used a separate diaphragm and combined the wax-electret with the backplate. But none of these microphones came to much practical importance. It wasn't until Sessler and West discovered that a stable "electret"[2] could be made out of thin plastic foils that the electret became much more than an academically interesting analog to the permanent magnet [4].

Along with the discovery that stable electrets could be made out of thin plastic foils, Sessler and West also found that this same precharged foil could be used as the diaphragm in a condenser microphone. Combining the electret with the diaphragm in this way substantially simplified the construction of electret-condenser microphones, and recent practice has been to follow the approach of Sessler and West and make the diaphragm out of a precharged fluorocarbon film which has been metallized on one side. Unfortunately, this approach also has a serious disadvantage, because a fluorocarbon film would probably not be the choice of any designer looking for a good diaphragm material. Mechanically speaking, the fluorocarbons have a high density, a low strength, notoriously poor creep resistance, and a large coefficient of thermal expansion.

Separating the charge storage or "electret" function makes it possible to select the electret material solely on the basis of its charge retention properties and the diaphragm material solely on the basis of its mechanical properties.

Having the freedom to choose a diaphragm film for its mechanical properties means that a high-strength film can

[1] The vibration sensitivity of the ceramic microphone is approximately equivalent to 100 dB sound pressure level at 1 *g*, i.e., an acceleration of 1 *g* at 1 kHz produces approximately the same electrical output as a 1-kHz sound pressure level of 100 dB re 0.0002 dyn/cm^2. The frequency dependence is shown elsewhere in this paper.

[2] The term "electret" was first coined by Heaviside in 1885; "another word that suggests itself is electret, against which there is nothing to be said except that it sounds strange" [5]. The term was later independently reinvented by Eguchi in 1920 [6]. Both authors reserved the term for a dielectric which had become permanently charged as a result of what is now called "internal dipole orientation." By common usage, however, the term has now come to mean any permanently charged dielectric, regardless of the charge storage mechanism [11].

be chosen, which in turn means that a very thin film can be used and still withstand the electrostatic stresses. If also a low-density film is chosen, the net result can be a large reduction in diaphragm mass. The resonant frequency of the microphone (and thus its frequency response) is related to the diaphragm mass and the diaphragm compliance. The diaphragm compliance is in turn related to the microphone sensitivity that can be obtained. Thus the lower the diaphragm mass, the higher the frequency response and sensitivity that can be obtained in a given case size.

Reduced Vibration Sensitivity

When it comes to vibration sensitivity, the relationship is direct: the heavier the diaphragm, the higher the vibration sensitivity. By using the separate diaphragm approach, we were able to achieve a 4–7-fold reduction in vibration sensitivity over what we could have obtained using the combined approach. Fig. 1 shows a vibration sensitivity comparison between magnetic, ceramic, and condenser microphones. The top dashed curve is for a magnetic microphone, the next dotted curve is the ceramic and the bottom, solid curve, the new condenser microphone. These three microphones have about the same dimensions; the only distinction is in the 0.090-inch (0.25 cm) thickness of the ceramic and condenser compared to the 0.163-inch (0.41 cm) thickness of the magnetic. Note that the vibration sensitivity of the ceramic microphone is 5–10 dB lower than that of the magnetic microphone in the speech band of frequencies, but at very low frequencies it is quite a bit higher. An RC rolloff starting at about 250 Hz

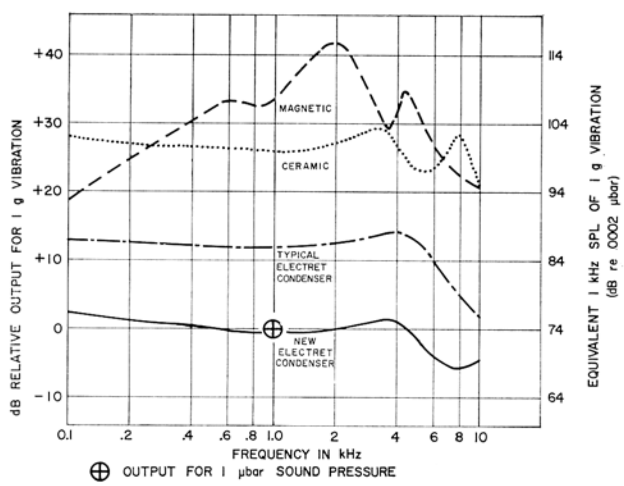

Fig. 1. Vibration sensitivity comparison between magnetic, ceramic, and electret-condenser microphones.

will bring them into line, but such a circuit represents an additional cost to the designer and still leaves him with only a slight improvement over the magnetic in receiver-to-microphone isolation. The 25–30-dB improvement provided by the new electret-condenser design noticeably eases the stringent requirements on vibration isolation.

Nontensioned Diaphragm

While discussing the diaphragm construction, it is useful to have in mind a rough idea of the finished product. This is shown in cross section in Fig. 2. The multiple diaphragm support points are formed into a metal backplate which is coated with a polymer film to provide an electret integral with the backplate. (The height of the diaphragm supports in Fig. 2 has been exaggerated for clarity.) The idea of building condenser transducers with multiple diaphragm supports and an intervening dielectric layer is not a new one, incidentally, having been patented nearly 50 years ago [7].

What is novel in the new design is the diaphragm construction [8]. Note that the diaphragm in Fig. 2 consists of a flat portion surrounded by a flexible annulus formed on the edge of the diaphragm. The flexible surround is designed to assure that no tension is applied to the diaphragm plate. Thus the flat portion of the diaphragm

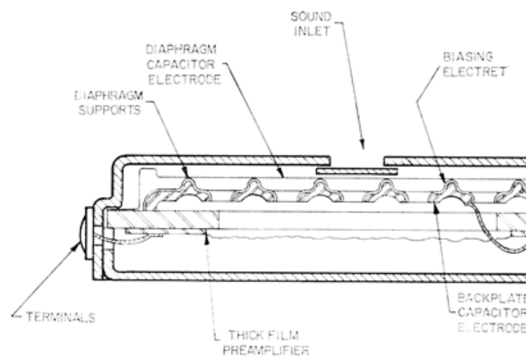

Fig. 2. Cross section of completed subminiature condenser microphone.

operates as a multiply supported plate held down by the electrostatic forces produced by the charged electret. The analysis of such a multiply supported plate is a mathematician's delight, by the way, involving infinite series of infinite series and a wonderful amount of computer time.

In addition to ensuring that there is essentially zero tension in the diaphragm, the flexible surround also provides a compliant region which minimizes the effect of any dimensional changes of the diaphragm relative to the backplate, regardless of whether they are due to temperature, humidity, or aging of the materials themselves. In particular, the compliant surround allows for the expansion and contraction of the plate portion of the diaphragm without regard to the temperature coefficient of the material to which the flange of the diaphragm is mounted.

Tensioned-Diaphragm Construction

To understand the advantages of this construction over the customary construction, recall that the common method of making a condenser or electret-condenser microphone is to fasten a tensioned foil to a support structure which has to be precisely positioned relative to the plane of the backplate. The diaphragm operates as a simple membrane (or in the case of the multiply supported diaphragm as a multiply supported membrane), with the membrane tension providing the restoring force to balance the electrostatic attraction between the diaphragm and the backplate.

The main difficulty with this construction is the problem of maintaining a diaphragm tension, and thus microphone sensitivity, which is independent of temperature. In the case of metal diaphragms, this problem can be solved by making the support ring out of the same alloy as the diaphragm foil. This produces the same temperature coefficient of linear expansion for both the diaphragm and the support ring. Since the modulus of elasticity is nearly independent of temperature (an assumption generally valid for metal alloys), the result is a diaphragm tension independent of temperature.

This is only a partial solution in the case of the fluorocarbons, however, because their modulus of elasticity is also a function of temperature; in particular, the tension decreases with increasing temperature even when the film is maintained under a constant strain. This means that even when exactly the same material is used for the diaphragm and the support, the diaphragm tension and thus the microphone sensitivity will still be a function of temperature.

Another problem worth mentioning is one that is intrinsic to a tensioned diaphragm approach. The problem comes about because the diaphragm foil is normally very thin while the supporting structure is, of necessity, fairly bulky. After a sudden change in temperature, therefore, the diaphragm will reach the new equilibrium temperature long before the supporting structure. The result can be a temporary change in microphone sensitivity by as much as 1 or 2 dB (or even more after an extreme change in temperature), even though the published temperature coefficient of the microphone is close to zero. As an example, great caution is required in calibrating even the laboratory standard 640AA condenser microphone, because the thin diaphragm foil will reach a new temperature within a minute or so but the thick mounting ring and case take much longer.[3]

A similar time-dependent phenomenon can occur when plastic materials are used for the diaphragm and the supporting structure. All plastics, including the fluorocarbons, change dimension slightly as their moisture content changes. Unlike the relatively short time constants for temperature, however, the time constant for dimensional changes due to water absorption can be a fraction of an hour for a thin diaphragm and may be literally days for the supporting structure. We have witnessed a gradual sensitivity change of 3–4 dB, stretched out over a period of two weeks at room temperature, on a commercially available tensioned diaphragm electret-condenser microphone, following a few days exposures to extreme temperatures and humidities (63°C and 95% relative humidity).

Reduced Temperature Coefficient

As a design approach we felt that perhaps all of the problems of maintaining constant diaphragm tension could be avoided by simply not tensioning the diaphragm in the first place. This reasoning led to the nontensioned diaphragm discussed above. The success of this approach is shown by the curves in Fig. 3. This shows the typical change in 1-kHz sensitivity for three commercially available electret-condenser microphones which were measured at −17°C, room temperature, and 63°C, i.e., at 40°C above and below room temperature. Fig. 3**a** shows the variation in sensitivity measured on a type of miniature microphone which uses a tensioned diaphragm. The shaded areas represent the range of sensitivities measured on 15 of the 18 samples tested. (Data on three samples were discarded as being not typical of the group.) Fig. 3**b** represents a microphone intended for measurement applications. It, too, uses a tensioned diaphragm. Fig. 3**c** shows the measurements on the present microphone which uses a nontensioned diaphragm. Note that with this construction, a change of 40°C in either direction from room temperature typically causes only a few tenths of decibels change in sensitivity, even though the plastic diaphragm material, the thick film ceramic mounting plate, and the metal backplate all have substantially different coefficients of expansion.

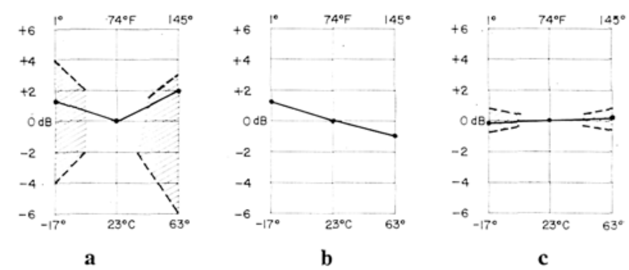

Fig. 3. Typical change in 1-kHz sensitivity for three commercially available electret-condenser microphones measured at −17°C and +63°C. **a.** Miniature microphone, stretched diaphragm construction. **b.** Measurement microphone, stretched diaphragm construction. **c.** Present microphone, nontensioned diaphragm construction.

Despite its many advantages, it should be noted that the nontensioned diaphragm construction does not represent an automatic cure-all to the problems of condenser microphone stability. The compliant annulus and the redundancy of the many diaphragm supports provide a degree of stability very adequate for hearing-aid and related applications. Predictable stability for quality instrumentation applications, however, is yet to be established.

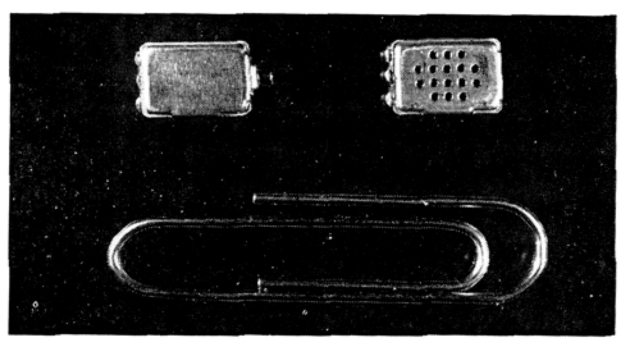

Fig. 4. Two versions of the new condenser microphone. **a.** Frequency response specifically tailored for use in headworn hearing aids. **b.** Relatively flat response over the audio band.

CHARACTERISTICS OF THE FINISHED DESIGN

Maximum Reliability Construction

In keeping with the design goal, the complete microphone was assembled into the same size case [(0.312 by

[3] An additional pitfall can arise if the preamplifier is not isothermal. The center contact pin on some vacuum tube preamplifiers can run a degree or two hotter than the outer shell, for example. The resulting temperature gradient induced in the condenser microphone can cause a few tenths of decibels shift in sensitivity, with a time constant of several minutes, a shift that can take a frustrating amount of time to track down the first time it is encountered.

0.218 by 0.090 inch) (0.79 by 0.55 by 0.25 cm)] previously used for the "thin" version of the ceramic microphone. This metal case provides the required electrostatic shielding for the high-impedance internal circuitry. An idea of the size of these microphones can be obtained from Fig. 4, showing two versions next to a paper clip.

A cross section of the finished microphone construction was shown in Fig. 2. As in the ceramic microphone, we built the condenser microphone on the back of a thick-film preamplifier substrate. This construction lends an interesting contribution to the reliability of the finished design, because it allows a permanent welded and encapsulated connection to be made between the backplate and the circuit. Avoiding a nonsliding, dry circuit connection is no small advantage in the hearing-aid environment, where the combination of salts, acids, and moisture contained in perspiration routinely work havoc, even with sliding contacts where the contact surface is regularly renewed.

As might be expected, the construction of the preamplifier itself also has a bearing on the ultimate reliability of the overall microphone. Although much has been written about the problem of producing a stable electret, much less has been written about the equally difficult problem of obtaining a high degree of reliability in the ultrahigh-impedance preamplifier which must be included in the microphone case. As was recently observed, it is not difficult to achieve an electret lifetime far exceeding that of a typical high-impedance preamplifier when both are subjected to abusive environments [4, p. 1591].

Some idea of the expenditure required to adequately isolate and control all the potential microphone failure mechanisms may be of interest. In the course of our development program, we accumulated more than 14 000 000 device-hours of environmental testing, most of them at 50°C or 63°C and 95% relative humidity. These figures do not include the millions of device-hours subsequently accumulated in a continuing production monitoring program nor the millions of device-hours previously accumulated in designing the high-reliability thick-film preamplifier used first in the ceramic microphone and then adapted for use in the condenser microphone.

The combination of the new design approach and the extensive reliability program took their toll in time and energy, but paid off in a microphone whose stability has been unequaled, either in accelerated testing or actual hearing-aid usage, by any known commercially available miniature condenser microphone. Although the ceramic microphone will always be inherently more reliable, the actual field reliability of the new condenser microphone appears to be adequate even for the rigors of hearing-aid usage.

Since a high degree of shock resistance was one of the design goals, it should also be mentioned here. A comparison between the shock resistance of the ceramic and the condenser microphone designs results in a standoff. We routinely test production samples of both types at shocks in excess of 20 000 g, and a failure in either type is a rare occurrence.

Frequency Response

The question of proper frequency response shaping for a wideband hearing-aid microphone is a subject in itself

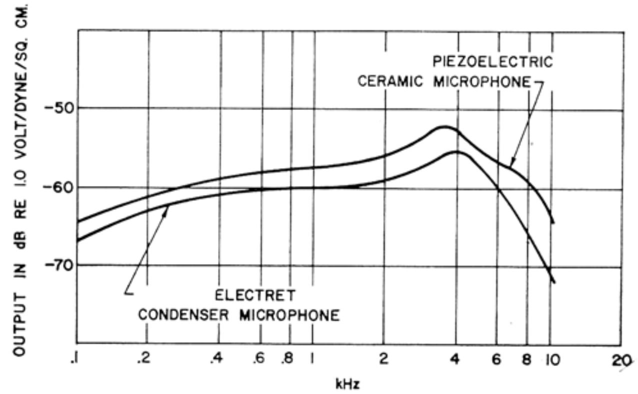

Fig. 5. Frequency response of the condenser and ceramic microphones designed for headworn hearing aids.

because of head and ear diffraction effects, and in fact has been the subject of papers given at previous AES meetings [9]. The responses shown in Fig. 5 were tailored with such effects in mind. Fig. 5 shows the response of the new condenser microphone compared to the previously designed ceramic microphone. As mentioned in the Introduction, the goal in the condenser microphone design was to duplicate the response of the previously designed ceramic one. The increase in peak frequency from about 3500 Hz in the ceramic to 4000 Hz in the condenser was deliberate, however, and was done in response to suggestions of hearing-aid designers that we increase the peak frequency slightly. In most hearing aids, an additional section of tubing between the microphone and the opening in the hearing aid case tends to lower the peak frequency below that of the microphone itself.

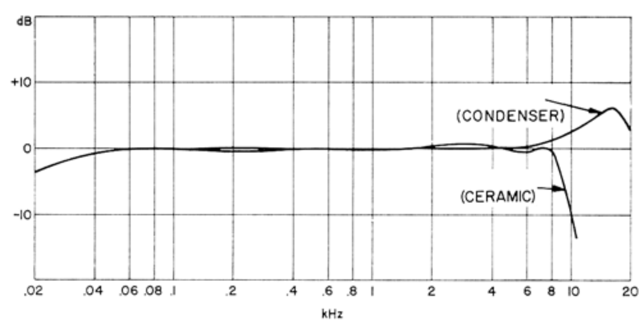

Fig. 6. Normalized frequency response of condenser and ceramic microphones adapted for extended range.

Both the ceramic and the electret microphones have been adapted to a relatively flat frequency response version as shown in Fig. 6.

Transient Response

It might be worthwhile to make just a remark or two about transient response. It is always an interesting subject, because it is nearly impossible to get agreement on what is meant by the term. It is of interest here because much has been said about the "inherently superb transient response" of condenser microphones due to their "infinitesmally light and freely responding diaphragms." By this line of reasoning, the new condenser microphone might be expected to have five times as good a transient response as previously available electret-condenser microphones, since it has a diaphragm which is roughly five times lighter.

All of the computer analyses, physical measurements, and listening tests we have done, however, leave us reasonably convinced that the laws of physics which apply to linear reciprocal systems also apply to microphones. The transient response of a device can be predicted from its (complete) frequency response as long as the device is operated within its linear region, regardless of the weight of the diaphragm. In particular, an electret-condenser microphone which has 10-dB peak at 4 kHz produces a noticeable high pitched ringing sound (as does a ceramic microphone with such a peak), regardless of how "infinitesmally light and freely responding" its diaphragm. Conversely, a ceramic microphone whose frequency response was made similar to the 640AA condenser microphone had a "sound" which was nearly impossible to distinguish from the 640AA in careful *A-B* tests once the microphone noise spectra were made similar.

This is not to say that different microphones do not have different "sounds" and different transient responses. Apparently similar microphones often have substantial differences in their near-field and far-field response, on-axis and off-axis response (even for nominally "nondirectional" microphones), noise spectra, overload characteristics, and complete frequency responses. None of those, however, has anything to do with the weight of the diaphragm.

The ceramic and condenser microphones whose responses are shown in Figs. 5 and 6 both have transient responses which are similarly clean and well damped, as would be expected from their frequency response curves.

Overload Sound Pressure Level

The actual condenser transducer used in the new microphone is linear up to approximately 140-dB sound pressure level (2000 dyn/cm^2). In a typical hearing aid circuit with 1.5-V supply, however, the restricted output voltage swing of the microphone preamplifier limits this to roughly 120-dB sound pressure level before nonlinearity sets in. This is of little practical importance in any hearing-aid application, of course, since even a moderate-gain hearing-aid amplifier will overload long before the microphone input reaches 120 dB. Where microphone operation at higher levels is required, it is possible to bias the internal preamplifier for linear operation up to 140-dB sound pressure level by adding two external resistors and using a 10-V supply.[4]

Noise Level

The *A*-weighted noise level of the new condenser microphone is typically equivalent to a 1-kHz sound pressure level of 26 dB. This is approximately 2 dB less than the 28-dB equivalent sound pressure level for the ceramic microphone in the same 0.090-inch (0.25-cm) case size. The spectrum shape of the new condenser microphone is also different from that of the ceramic, with more of the noise concentrated at low frequencies where the human ear is less sensitive. As a result, the subjective noise level of the new condenser microphone is typically 3–4 dB lower than that of the same size ceramic microphone.

SUMMARY

All of the original design goals were met. A new design approach which combined two old ideas (separating the electret from the diaphragm and the use of multiple diaphragm supports with intervening dielectric layer) with a novel diaphragm construction and a high-reliability preamplifier made possible a subminiature condenser microphone comparatively free of the disadvantages normally associated with such microphones. In addition, this approach made possible a 4–7-fold reduction in vibration sensitivity compared to previously available electret-condenser microphone designs.

Several versions of both the condenser and the ceramic microphones have been made available, including wideband frequency response versions, tailored frequency response versions, and directional response versions [10]. These microphones, along with recently introduced subminiature wideband receivers, have now opened up performance areas previously unavailable in headworn hearing aids.

ACKNOWLEDGMENT

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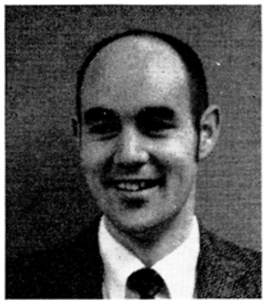
THE AUTHORS



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He has had 30 years experience in research, development, and production engineering of commercially produced electroacoustic transducers, including microphones, earphones, magnetic and disc recording heads, and phonograph cartridges. Mr. Carlson has had the principal responsibility for the development of miniature microphones and receivers (earphones) for the past 16 years at Industrial Research Products, Inc., where he is currently Manager of Development Engineering. He holds nearly 20 patents in the field.

PROJECT NOTES / ENGINEERING BRIEFS

TRANSIENT INTERMODULATION DISTORTION IN COMMERCIAL AUDIO AMPLIFIERS*

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Seven popular commercial tuner–amplifiers have been investigated to measure their transient intermodulation distortion (TIM). Results indicate that most of them show a clear tendency to produce TIM, and severe TIM is present in some. In most cases the prevention of TIM would have been relatively simple.

INTRODUCTION: A new distortion mechanism, known as transient intermodulation distortion (TIM), has been described in a number of papers [1] - [6]. It is basically an overload phenomenon caused by the use of feedback in the amplifier. The audible sensation is equivalent to momentary crossover distortion occurring at loud high-frequency passages of the music.

The physical origin of this distortion is the feedback loop around the amplifier. Because of the feedback, the amplifier open-loop frequency response has been compensated to yield a -6 dB per octave rolloff in the Bode diagram. The -3 dB point of this compensation often lies around $1-5$ kHz in transistorized amplifiers and around $5-500$ Hz in operational amplifiers. When a transient signal is fed into the amplifier, there is a short interval during which no output signal, and therefore no feedback is present due to this "slowness." Consequently, the effective momentary input signal of the amplifier is very much larger than under steady-state conditions [1].

These inter-loop signal peaks are usually much higher than the overload margins of the amplifier input stages. They are therefore clipped, and the feedback mechanism [2], [6] then tends to lengthen up to a hundred times the natural cut-off time [6], thus producing $5-1000$ μs periods during which the amplifier is under slewing conditions. The result is equivalent to a momentary burst of intermodulation distortion or crossover distortion.

It is to be noted that this effect occurs already considerably below the usually specified amplifier slew rate [6], and that this form of distortion cannot be detected from the output signal of the amplifier visually or by using conventional steady-state distortion measurement methods.

In previous theoretical work [1], experimental measurements were carried out on a simulated audio amplifier. This approach was chosen because of the complexity of the real amplifier transfer functions, especially in the neighborhood of the unity gain point.

In the present work measurements on seven commercial amplifiers are presented. These amplifiers were chosen to represent some of the most popular medium-priced tuner–amplifiers on the European market. The amplifiers tested were Marantz 29, Körting 1000 L, B&O Beomaster 3000, Sony STR 222, Philips RH 702, Scan-Dyna 3000, and Pioneer SX 440. For the presentation of

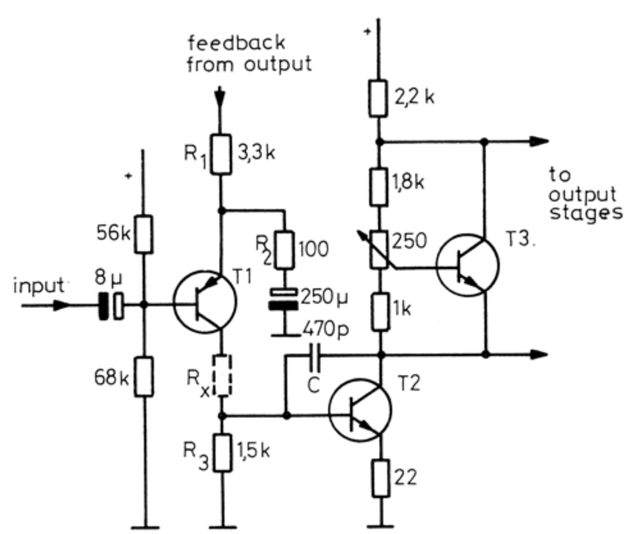

Fig. 1. Driver stages of amplifier 6.

* Presented March 27, 1974 at the 47th Convention of the Audio Engineering Society, Copenhagen.