Electrode surface profile and the performance of condenser microphones

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Condenser microphones of all types are traditionally made with a planar electrode parallel to an electrically conducting diaphragm, additional diaphragm stiffness at acoustic frequencies being provided by the air enclosed in a cavity behind the diaphragm. In all designs, the motion of the diaphragm in response to an acoustic signal is greatest near its center and reduces to zero at its edges. Analysis shows that this construction leads to less than optimal sensitivity and to harmonic distortion at high sound levels when the diaphragm motion is appreciable compared with its spacing from the electrode. Microphones of this design are also subject to acoustic collapse of the diaphragm under the influence of pressure pulses such as might be produced by wind. A new design is proposed in which the electrode is shaped as a shallow dish, and it is shown that this construction increases the sensitivity by about 4.5 dB, and also completely eliminates harmonic distortion originating in the cartridge. © *2002 Acoustical Society of America.* [DOI: 10.1121/1.1515971]

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I. INTRODUCTION

Condenser microphones of various designs are central to the whole of audio engineering practice and to scientific research in acoustics. At one end of the range we find relatively simple high quality omnidirectional microphones with diameters ranging from 3 to 25 mm for use with sound level meters and other types of precision measuring equipment,[1] while at the other end there are much more complicated studio microphones with adjustable directional patterns.[2] Alongside these there are simple, rugged, and inexpensive electret microphones for a whole variety of less demanding uses.

In all cases the basic principle of operation is the same—a thin conducting diaphragm is held under tension a very small distance away from a planar conducting electrode, and matching charges are induced on the diaphragm and electrode by a voltage applied between the two through a very high resistance. (In the case of an electret microphone, the charge is generated by electret polarization so that an external bias is not required.) Motion of the diaphragm then causes a corresponding change in the potential between the diaphragm and the electrode, and this voltage signal is amplified through a device with very high input impedance to provide the output signal. Of course, many refinements are involved in order to ensure a flat response over a wide frequency range and, in the case of studio microphones, to provide control over directional response. These refinements will not be of concern in the present paper.

The purpose of the present discussion is to analyze certain aspects of this basic microphone design and to propose that a significant improvement in performance can be achieved by modifying the plane electrode to an appropriately specified dished shape. It is difficult, in retrospect, to believe that such a modification has not been suggested, and perhaps implemented, during the past 80 or more years of microphone technology, but the possibility is not mentioned in classic papers on microphone design[1–3] or in two comprehensive modern texts on the subject,[4,5] and no reference to it has been found in the course of a search of published scientific or patent literature.

II. ANALYSIS OF THE PLANAR-ELECTRODE DESIGN

A. Microphone types

For the purposes of the present discussion, we identify two main classes of condenser microphone. The first class, designated here as type I and shown schematically in Fig. 1(a), is typical of measurement microphones. The diaphragm is of thin metal under high tension so that its natural frequency is typically in the range 10–150 kHz, depending on diaphragm diameter. This tension then provides the main restoring force for any displacement of the diaphragm. In the second class, characteristic of inexpensive electrets as well as of many studio microphones, and here designated as type II, the diaphragm is of metal-coated polymer material under only moderate tension so that its resonance frequency is only 1–2 kHz. In this case the air volume enclosed within the microphone capsule must be relied upon to raise the resonance frequency to a value of around 15 kHz, and this air volume provides most of the dynamic restoring force upon the diaphragm. The cavity is necessarily vented through a very small opening for static pressure equalization, however, so that the diaphragm tension must provide the restoring force against static electrical stress.

Two subclasses of type II microphones can be distinguished. In a type IIA microphone, the structure of which is

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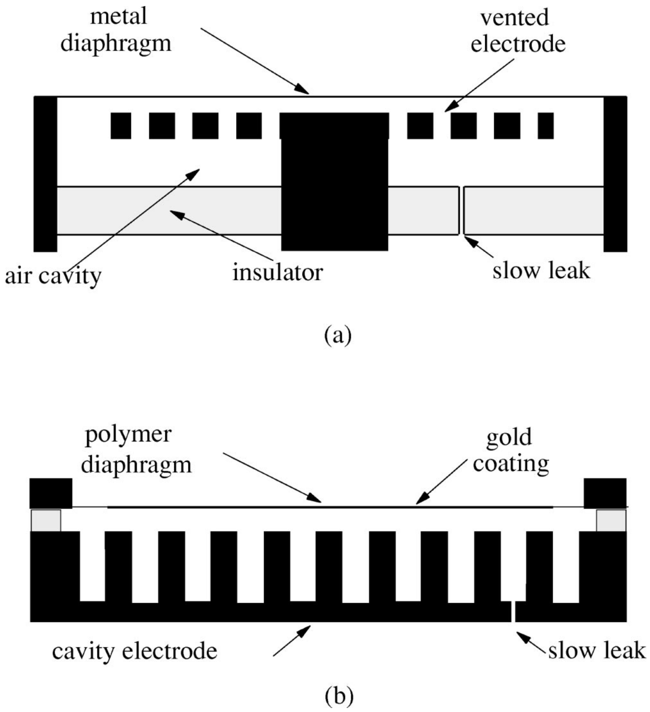

FIG. 1. Schematic of the main types of condenser microphone in current use. (a) Type I: a precision measurement microphone with a metal diaphragm under high tension. The directional pattern of such a microphone can be made cardioid by providing vents with appropriate acoustic resistance into the back of the cartridge from the environment. (b) Type II: a basic studio microphone with a metalized plastic diaphragm and restoring force provided by air enclosed in cavities in the thick electrode. A studio microphone consists essentially of two type II microphone cartridges mounted back-to-back and linked by a structure with high acoustic resistance. By varying the potentials on the two diaphragms, the response can be made omnidirectional, cardioid, or figure-eight.

otherwise similar to that shown in Fig. 1(a) for a type I microphone, there is a single air cavity behind the diaphragm and electrode. In microphones with cardioid directional characteristics this cavity is vented through an appropriate rear acoustic resistance. In a type IIB microphone, the air cavity is subdivided into a large number of small cells located in a rather thick metallic electrode, as shown in Fig. 1(b). In a microphone with variable directionality, two such capsules are placed back-to-back and acoustically coupled through a narrow intervening space and small holes in the electrodes.[2] The directional response can then be varied by changing the voltages applied to the two diaphragms. Simple electret microphones are generally of type IIA, while studio microphones are usually of type IIB.

Suppose that, for a microphone of either type I or II, the diaphragm tension is T and the reservoir volume is Δ_0. Then the local mechanical restoring force $F(r)$ per unit area on the diaphragm when it is displaced normally inwards by an amount $z(r)$, is

$$F(r) = -\frac{T}{r}\frac{\partial}{\partial r}\left(r\frac{\partial z}{\partial r}\right) + \frac{\rho c^2}{\Delta_0}\int_0^a 2\pi z r\, dr, \tag{1}$$

where a is the radius of the electrode. The form of the tension-dependent term assumes that only circularly symmetric displacements are considered,[6] while the second term on the right-hand side is simply the acoustic pressure developed in the air cavity by the diaphragm displacement $z(r)$. For a type I microphone T is very large, so that the first term is dominant and the second term can be neglected. For a type II microphone, however, the diaphragm tension is smaller by a factor of order 1000 and the second term is dominant in many features of the behavior. The first term, however, determines the behavior under electrostatic loading, since the reservoir is necessarily vented through a small opening and the pressure of the enclosed air quickly decays to atmospheric.

It might appear that the volume-dependent restoring term in Eq. (1) should have a different form in a type-IIB microphone, since the air cavity is distributed over the surface of the diaphragm in small cells that might be expected to provide a local rather than a global pressure response. The RC time-constant for the individual cells, where C is the acoustic compliance of the enclosed air and R the flow resistance of the thin air film between the electrode and the diaphragm, is however about equal to the inverse of the cavity-supported resonance frequency of the diaphragm, so that, at the frequencies well below this limit with which we are primarily concerned, the cavities are effectively interconnected and behave as one single cavity.

In what follows, the somewhat different but related behavior of these two microphone types under both static electrostatic forces and oscillatory acoustic pressures is considered. The design complications associated with studio microphones of variable directionality will not be of concern here, but only the behavior or the basic microphone cartridge.

B. Electrostatic deflection

The behavior of all microphone types under electrostatic loading is formally the same, except for the magnitude of the diaphragm tension T. The analysis is well known[7] but is repeated here to make clear the subsequent developments. Suppose that the separation between the diaphragm and the plane electrode is h when no voltage is applied, and that the diaphragm is deflected a distance $z(r)$ toward the electrode by an applied voltage V. Then, by Eq. (1) with the enclosed volume term omitted,

$$\frac{T}{r}\frac{d}{dr}\left(r\frac{dz}{dr}\right) = -\frac{\epsilon_0 V^2}{(h-z)^2}, \tag{2}$$

where ϵ_0 is the permittivity of free space. If the electrode has a radius $b<a$, where a is the diaphragm radius, then Eq. (2) still applies provided we take $V=0$ for $b<r<a$.

This equation is easy to solve in the linearized limit $z \ll h$, in which case

$$z = \frac{\epsilon_0 V^2 b^2}{4Th^2}\left(1 - \frac{r^2}{b^2} - 2\log\frac{b}{a}\right), \quad r<b, \tag{3}$$

$$= -\frac{\epsilon_0 V^2 b^2}{2Th^2}\log\frac{r}{a}, \quad b<r<a. \tag{4}$$

In this limit the shape is a paraboloid of revolution for $r<b$ and a logarithmic surface of opposite curvature for $b<r<a$.

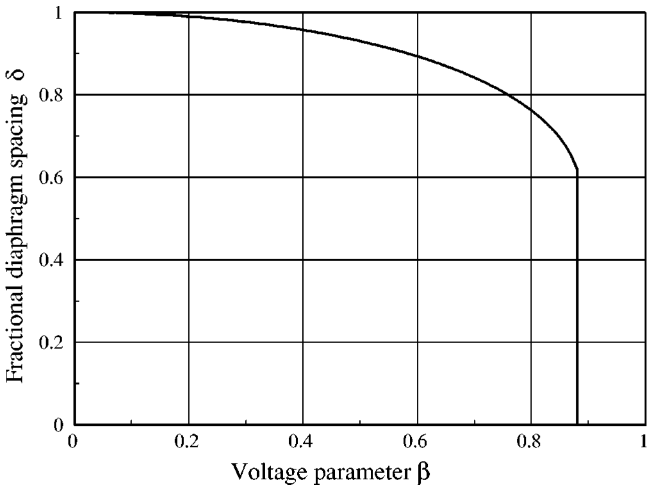

FIG. 2. Calculated variation of the normalized diaphragm spacing δ from the electrode as a function of the polarization voltage parameter $\beta = (\epsilon_0 b^2/4Th^2)^{1/2}V$. The diaphragm collapses onto the electrode when β exceeds 0.88.

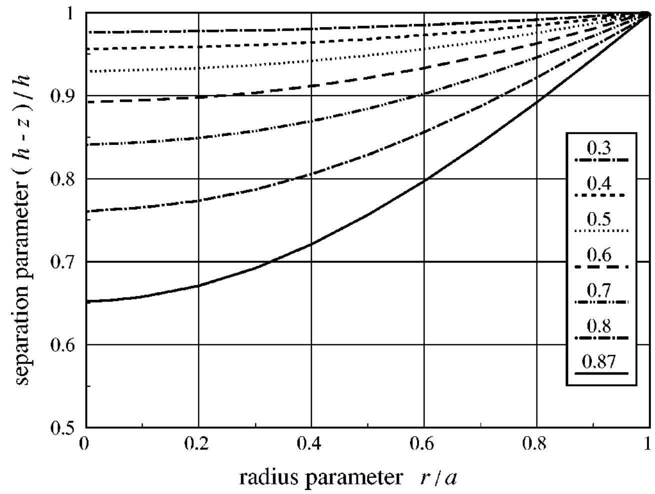

FIG. 3. Calculated normalized profiles of the diaphragm, as a function of the parameter β, for electrostatic loadings up to the point of collapse. All profiles are approximately parabolic.

A general solution for larger deflections is necessarily numerical, since the equation is nonlinear. Such a solution is most usefully parametrized in terms of the quantities

$$\beta = \left(\frac{\epsilon_0 b^2}{4Th^2} \right)^{1/2} V, \quad \delta = \frac{h-z}{h}, \tag{5}$$

which represent, respectively, the normalized polarizing voltage and the fractional value of the separation between the diaphragm and the electrode. The calculated result is shown in Fig. 2. As the potential on the diaphragm (the parameter β) is increased, the diaphragm moves steadily toward the electrode until suddenly, at about $\beta = 0.88$, it collapses onto the electrode. Just before the collapse, the separation between the diaphragm and the electrode has been reduced to about 0.63 of its unpolarized value. The physical reason for the collapse is that the maintenance of diaphragm potential at the center of the diaphragm requires an inflow of charge from the supply to the center of the diaphragm, thus increasing the electrostatic force and further reducing the separation, which in turn requires more charge to maintain the diaphragm potential. This electrostatic force, which increases about as $(h-z)^{-2}$, ultimately overbalances the elastic restoring force, which increases only linearly with z.

When values for the relevant physical parameters are inserted into the parameter β, it is found that for a typical type I microphone $\beta < 0.01$, while for a type II microphone $\beta \sim 0.3$. This means that the electrostatic displacement of the diaphragm is almost negligibly small for a type I microphone, while a type II microphone has a significant static displacement and may be close to the condition for collapse if excess voltage is applied. Computed profiles of the diaphragm for various values of the parameter β are shown in Fig. 3. It can be seen that the profile is approximately parabolic right up to the value of β giving collapse.

C. Acoustic deflection

Suppose that there is an extra inward diaphragm deflection $\psi(r)$ in a uniform acoustic pressure field $p(\omega)$, and for simplicity let $b = a$ so that the whole diaphragm is electrically active. Since the diaphragm (or the electrode, depending on the microphone design) is essentially electrically isolated at acoustic frequencies, the total charge Q upon it remains fixed at the value

$$Q = 2\pi\epsilon_0 V_0 \int_0^a \frac{r\,dr}{h - z(r)}, \tag{6}$$

where V_0 is the steady supply voltage, h is the initial diaphragm separation from the electrode, and $z(r)$ is the electrostatic displacement of the diaphragm. The diaphragm potential V under the influence of the additional acoustic displacement $\psi(r)$ is then

$$V = V_0 \int_0^a \frac{r\,dr}{h - z(r)} \Bigg/ \int_0^a \frac{r\,dr}{h - z(r) - \psi(r)}, \tag{7}$$

and the time-varying part of this potential constitutes the electrical signal from the microphone.

The behavior of $\psi(r)$ is given by

$$\rho \frac{\partial^2 \psi}{\partial t^2} = -F(\psi, r) + G(\psi, r) + p, \tag{8}$$

where ρ is the mass of the diaphragm per unit area, $F(\psi, r)$ is the additional elastic restoring force as given by Eq. (1) with $z(r)$ replaced by $\psi(r)$, and $G(r)$ is the additional electrostatic force, given by Eq. (7) as

$$G(r) = \frac{\epsilon_0 V^2}{(h - z + \psi)^2} - \frac{\epsilon_0 V_0^2}{(h-z)^2}. \tag{9}$$

The second term on the right-hand side of Eq. (1) simply contributes a constant times the average magnitude of ψ across the diaphragm and so is proportional to p. Since at high sound levels the acoustic vibration amplitude $\psi(r)$ of the diaphragm may be not much less than the diaphragm spacing $h-z$, the nonlinear terms in Eq. (9) are significant, so that the electrical signal V will suffer an appreciable amount of harmonic distortion, as will be discussed in Sec. III.

At low acoustic levels $\psi(r)$ is everywhere much less than the diaphragm spacing $h-z(r)$ so that, from Eq. (9), $G(r)$ is approximately zero and $F(r)$ is simply proportional to ψ. It is then simple to solve the linearized version of Eq. (8). For very low frequencies, the left-hand side of Eq. (8) can be neglected, leading to $F(\psi,r)=p$ and hence, if we take $b=a$ for simplicity, to the result

$$\psi(r)=Ap\left(1-\frac{r^2}{a^2}\right), \tag{10}$$

where A is a constant. For frequencies approaching that of the cavity-supported diaphragm resonance, the left-hand side of Eq. (8) cannot be neglected, and the solution has the well-known form[6]

$$\psi(r)=BpJ_0(2.4r/a), \tag{11}$$

where J_0 is a Bessel function of order zero and B is another constant. The profile shapes given by Eqs. (10) and (11) are very similar.

When the diaphragm displacement is no longer negligibly small compared with the diaphragm separation h, then the redistribution of charge on the deflected diaphragm must be taken into account by including the force term $G(r)$ from Eq. (9) with V given by Eq. (7). This clearly introduces more nonlinear terms and so more harmonic distortion of the electrical output signal δV. This will not be pursued further here.

III. DISTORTION AND SENSITIVITY

To examine the effect of electrode shape on sensitivity and distortion, it is simplest to consider first an idealized type I microphone with no electrostatic distortion of the diaphragm. Suppose that the diaphragm radius is a and that its equilibrium spacing from the electrode is h. As derived previously in Eq. (10), the acoustic displacement has the form

$$z(r)=\psi_0\left(1-\frac{r^2}{a^2}\right)\cos\omega t, \tag{12}$$

where ψ_0 is the acoustic displacement at the center of the diaphragm. If it is assumed for simplicity that the electrode extends to the edge of the diaphragm, then the microphone capacitance is

$$C=2\pi\epsilon_0\int_0^a\frac{r\,dr}{h-\psi_0(1-r^2/a^2)\cos\omega t}, \tag{13}$$

$$=\frac{\pi a^2\epsilon_0}{\psi_0\cos\omega t}\log\left(\frac{h}{h-\psi_0\cos\omega t}\right). \tag{14}$$

If $Q=C_0V_0$ is the charge on the electrode when the polarizing voltage is V_0 and $C_0=\pi a^2\epsilon_0/h$ is the capacitance when the acoustic displacement amplitude $\psi_0=0$, then the potential V of the electrode in the presence of acoustic displacement is

$$V=\frac{Q}{C}=-\frac{V_0(\psi_0\cos\omega t/h)}{\log[1-(\psi_0/h)\cos\omega t]}. \tag{15}$$

Expansion of this expression as a power series in $\cos\omega t$ and conversion to a series in $\cos n\omega t$ involves tedious algebra, but the first few terms are given approximately by

$$V\approx V_0\left[1-0.56\frac{\psi_0}{h}\cos\omega t-0.06\left(\frac{\psi_0}{h}\right)^2\cos 2\omega t -0.03\left(\frac{\psi_0}{h}\right)^3\cos 3\omega t+\cdots\right]. \tag{16}$$

This means that the relative amplitude of second-harmonic distortion is about $0.11\psi_0/h$ and of third-harmonic distortion about $0.05(\psi_0/h)^2$. Converting to distortion levels shows that, when $\psi_0=0.1h$ so that the amplitude of the electrical signal is $0.06V_0$, second-harmonic distortion is about -40 dB relative to the fundamental, and third-harmonic distortion is about -66 dB. The electrostatic modification of the acoustic deflection function, referred to briefly earlier, will add further distortion terms. These figures require some modification when the fact that the electrically active part of the diaphragm does not extend to its full diameter is taken into account. Formally, this is done by changing the upper limit of the integral in Eq. (13) from a to b, which significantly complicates the algebra. The result is a reduction in both the electrical output and also the distortion.

From a practical point of view it must be pointed out, however, that the acoustic level required to achieve a diaphragm displacement of $0.1h$ is much larger than would normally be contemplated for a microphone. Indeed the output signal amplitude would then be about one-tenth of the polarizing voltage, so that the preamplifier would be forced into severe clipping. The consequent distortion would completely obscure the microphone distortion.

There is one other feature of the planar-electrode design that is worthy of comment, and that is the possibility of what might be termed acoustic collapse. If the acoustic signal has a large positive pressure, then this will bring the center of the diaphragm close to the electrode and the migration of charge will cause it to collapse into contact, thus short-circuiting the microphone and rendering it inoperative for perhaps several seconds until the charge has been restored through the very high supply resistance. This phenomenon can be investigated in the quasi-static limit by adding an acoustic pressure term p, independent of r, to the right-hand side of Eq. (2).

IV. IMPROVED ELECTRODE DESIGN

Referring back to Eq. (7), it is immediately apparent that, if the electrode is curved so that the static diaphragm separation $h-z(r)$ is made everywhere proportional to the acoustic displacement $\psi(r)$ so that $[h-z(r)]=\gamma\psi(r,t)/p(t)$, where $p(t)$ is the acoustic pressure signal and γ is a constant, then Eq. (7) simplifies to the form

$$V=V_0[1+\gamma^{-1}p(t)], \tag{17}$$

and the electrical output mirrors the acoustic input without distortion. In physical terms, this means that the diaphragm motion does not cause any redistribution of charge, so that the electrostatic force on all parts of the diaphragm remains constant, thus ensuring that the displacement ψ, and thus the reciprocal of the microphone capacitance, faithfully follows the acoustic pressure signal p.

These observations are the basis of the proposed improved microphone design. The electrode profile that will

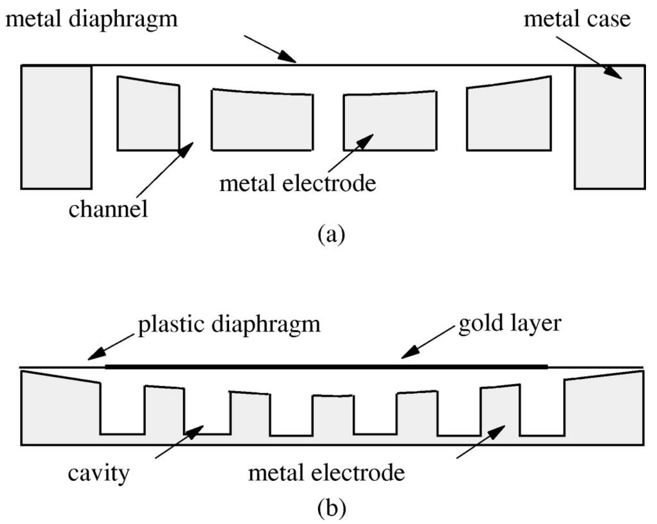

FIG. 4. Optimal electrode profile. (a) In practice the electrode will terminate a small distance from the edge of the diaphragm in a type I microphone; (b) in a type II microphone the diaphragm metallization should terminate at 0.9 times the diaphragm radius.

give optimal performance does not differ greatly between type I and type II microphones, though there are significant quantitative variations associated with the extent to which the diaphragm is deflected by electrostatic forces.

A. Type I microphones

As discussed previously, the tension in the diaphragm of a type I microphone is so high that the static deflection is only of order 10^{-3} of the electrode spacing. This means that the diaphragm can be treated as essentially planar, and this assumption forms the basis for an initial evaluation of optimal electrode profile. It has already been shown that the vibration amplitude of the diaphragm has a parabolic profile at low frequencies and a rather similar Bessel-function profile near the major resonance, in each case vanishing at the circumference. An optimum electrode shape should therefore follow a similar profile, vanishing at the edge of the diaphragm, and with a central displacement chosen to optimize other features of the design, as shown in Fig. 4(a).

Suppose that the radius of the diaphragm is a and that of the electrode b and that the central diaphragm spacing is h_0. Then the electrode shape is $h(r)=h_0[1-(r/a)^2]$ and the low-frequency acoustic displacement has the similar form $\psi(r)=\psi_0[1-(r/a)^2]$. The electrical capacitance has the value

$$C=\epsilon_0\int_0^b \frac{2\pi r\,dr}{h(r)}=\frac{\epsilon_0\pi b^2}{h_0}\log\left(\frac{a^2}{a^2-b^2}\right). \tag{18}$$

To avoid a short circuit at the edge of the diaphragm, b must be significantly less than a, and a choice of $b=0.9a$ will later be shown to be optimal, giving a capacitance of $1.7\epsilon_0\pi b^2/h_0$. The diaphragm spacing at the edge of the electrode will be 0.2 times that at the center.

The electrical output under a polarizing voltage V_0 when the central acoustic displacement is ψ_0 is given by Eq. (7) with the upper limit of both integrals taken as b rather than a. The result is

$$\delta V=\frac{V_0\psi_0}{h_0}, \tag{19}$$

and there are no higher terms, so that harmonic distortion is identically zero.

This should be compared with a microphone with a planar electrode with the same values of a and b, and a constant electrode spacing $h(r)=h_0$. The electrical capacitance is $\epsilon_0\pi b^2/h_0$, which, for the case $b=0.9a$, is about half that of the curved electrode design. Evaluation of the modified integrals in Eq. (7) for this case shows that, to first order,

$$\delta V=\frac{V_0\psi_0}{h_0}\left(1-\frac{b^2}{2a^2}\right). \tag{20}$$

If $b=0.9a$, then the voltage signal is smaller than that for the curved-electrode design by a factor of about 0.6, which is about 4.5 dB. As discussed previously, there are also higher terms of all orders that contribute harmonic distortion.

It can be concluded that the curved-electrode design offers significant advantages in terms of increased sensitivity (about 4.5 dB), increased capacitance (factor about 1.7), and freedom from distortion, compared with the corresponding planar electrode design. Some practical issues will be discussed in a later section.

B. Type II microphones

The major difference between a type I and a type II microphone in the present context is the fact that the diaphragm of the type II microphone suffers appreciable curvature under the influence of electrostatic forces, the separation at the diaphragm center being reduced by perhaps a factor 0.7 in a normal plane-electrode design. These microphones also usually employ a greater electrode separation from the diaphragm, typically about 40 μm, partly for this reason. An optimal electrode design will therefore be dished to about 50 μm at its center and come close to the level of the diaphragm mount at the circumference as in Fig. 4(b).

Because of the appreciable electrostatic deflection of the diaphragm, however, it must be questioned whether the paraboloidal or near-spherical electrode shape is still appropriate. The form of the electrostatic deflection is once again given by Eq. (2), but now with the electrode separation varying with radius r. If we define the shape of the electrode by the curve $h(r)$ as in Fig. 5 and the shape of the diaphragm under electrostatic deflection by $f(r)$, then minimum distortion and maximum sensitivity is achieved if $h(r)-f(r)$ is proportional to the acoustic deflection of the diaphragm which, as has been shown previously, is approximately parabolic at low frequencies. The equation for the electrostatic deflection $f(r)$ is then

$$\frac{T}{r}\frac{d}{dr}\left(r\frac{df}{dr}\right)=-\frac{\epsilon_0 V^2}{[h(r)-f(r)]^2}. \tag{21}$$

The problem then is to choose an electrode profile $h(r)$ so that $h(r)-f(r)$ is parabolic.

If the paraboloidal-electrode design is appropriate, then we can assume that $h(r)=h_0[1-(r/a)^2]$, where a is the radius of the diaphragm. Substituting this into Eq. (21) gives

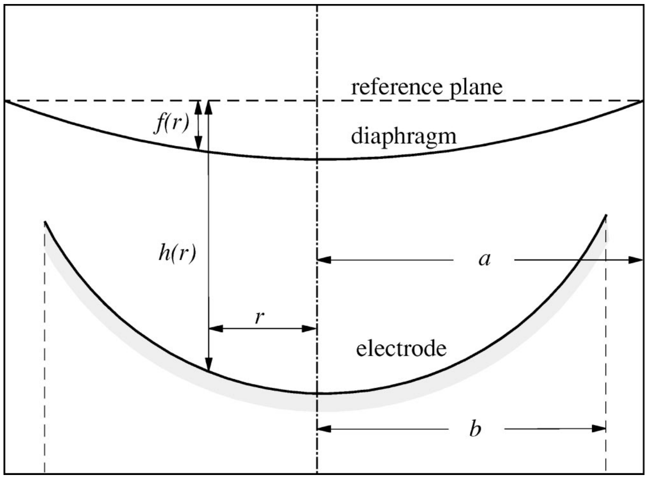

FIG. 5. Definition of the curves $h(r)$ specifying the shape of the electrode relative to the undisplaced diaphragm plane, and $f(r)$ specifying the shape of the diaphragm under electrostatic deflection.

a nonlinear equation that must be solved numerically, though the solution has a quite general form when the boundary condition that $z=0$ at $r=a$ is inserted. The electrostatic force per unit area, however, is greater at the edge of the diaphragm than at its center, because of the smaller separation there, and this leads to a displaced diaphragm shape that is approximately that of one half of a very oblate spheroid, the slope of the diaphragm being very steep at its edges, if the metalization is assumed to cover the entire diaphragm.

The escape from this difficulty is, however, quite simple. If the diaphragm metallization radius b is assumed to be approximately $0.9a$, then numerical evaluation shows that the steep diaphragm slope at its edge is eliminated, and the shape of the diaphragm is quite closely parabolic for $0 \leqslant r \leqslant b$, thus following the shape of the electrode as desired. This is a quite adequate solution. The improvements to be expected in sensitivity are similar to those for a type I microphone, and harmonic distortion in the microphone cartridge itself should be eliminated.

C. Electrode venting

As shown in Figs. 1 and 4, the electrodes in all condenser microphone designs have vent holes to relieve the compressive pressure in the thin air layer between the diaphragm and the electrode. Flow to the vent holes in this air layer is impeded by air viscosity, and the flow resistance increases inversely as the cube of the separation between the diaphragm and the electrode. In current manufacturing, the design of each microphone is optimized so that the damping provided by this resistance reduces appropriately the peak in the response at the resonance frequency.

To achieve uniform response over the whole area of the diaphragm in accord with the design objectives set out earlier, it is necessary that the size and spacing of the vent holes through the electrode also be optimized. The decreased diaphragm spacing toward its edges leads to a great increase in flow resistance in the enclosed air layer, which varies as h^{-3}. While the local acoustic impedance of the diaphragm is also higher, it is necessary to change the size and spacing of the vent holes toward the edge of the diaphragm in order to achieve uniform damping behavior. The exact solution is outside the scope of the present paper.

D. Acoustic collapse

Another incidental advantage of the curved-electrode design is that such a microphone does not suffer from acoustically induced collapse of the diaphragm at very high sound pressure levels. In a planar-electrode design, particularly in a type II microphone, redistribution of charge on the diaphragm under very large acoustic deflection can cause collapse onto the electrode. No such charge redistribution occurs in the curved-electrode design, so the problem is not encountered.

E. Practical issues

The microphone designs discussed previously were idealized to a small extent. In the case of a type I microphone, for example, the electrostatic diaphragm deflection is not zero, though it is much smaller than for a type II microphone. As has been shown, however, the distorting effect on the diaphragm of this electrostatic displacement can be minimized if the electrode diameter is about 0.9 times the diaphragm diameter, and this is desirable for simple electrical reasons in any case. Electrical discharge between diaphragm and electrode should not be a problem, though a slightly curved edge to the electrode is probably desirable.

In practice it is also probably not reasonable to shape the electrode to a parabolic profile because of manufacturing difficulties. Because of the small curvature required, however, a spherical-dish shape is completely adequate. Indeed, almost any shallow dish shape should yield an improvement in microphone performance. To place the dimensions in context, the diaphragm spacing of a conventional 1 in. (25 mm) measuring microphone is typically about 20 μm, so the dished electrode, which is about 20 mm in diameter, will have a curvature radius of about 2.5 m. In the case of a conventional type II studio microphone cartridge, the unpolarized diaphragm separation is 40–50 μm, so that the curvature radius is about 1 m. Lapping tables to produce such curvatures in the electrodes are straightforward to produce since, in contrast with optical components, a surface accuracy of ± 1 μm is completely adequate. A lapping table with diameter 20 cm would typically require a central elevation of 2–5 mm, which is easily made and measured.

V. CONCLUSIONS

This analysis suggests that the behavior of all types of condenser microphones could be improved, both in relation to sensitivity and distortion, by using a shallowly dished electrode instead of the normal planar electrode design. While this adds minor manufacturing complications, it turns out that simple spherical dishing with a radius of curvature between about 1 and 2.5 m is adequate for most common microphone types, and this should not be difficult to implement. The appropriate electrode curvature depends on the type of microphone, the unpolarized diaphragm spacing and tension, and the operating voltage. The analysis presented here allows the optimal electrode design to be calculated in each case.

It is a matter for discussion whether or not these advantages are of sufficient practical benefit to justify the required modifications to current microphone designs. An improvement in sensitivity of 4.5 dB is certainly helpful, but the same result could have been achieved with a planar design by reducing the diaphragm spacing by a factor 0.6 or by increasing the polarizing voltage by a factor 1.7. Similarly, the actual distortion level in a conventional microphone design depends upon the preamplifier as well as the cartridge, and this must be taken into account. Nevertheless, these are all advantages of the proposed new design, and there may be special applications in which they become important.

ACKNOWLEDGMENTS

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