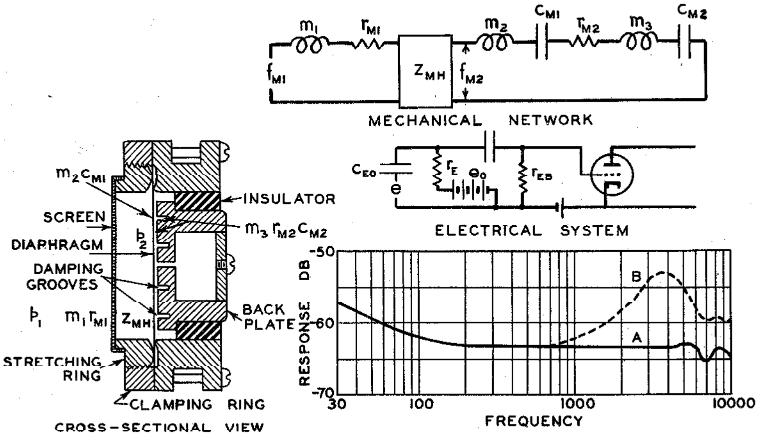

FIG. 8.5. Cross-sectional view, electrical system, and mechanical circuit of a condenser microphone. In the electrical system: e_0 = the polarizing voltage. r_E = the polarizing electrical resistance, r_{EB} = the bias electrical resistance. C_{E0} = the electrical capacitance of the microphone. In the mechanical circuit, m_1 and r_{M1} = the mass and mechanical resistance of the air load. z_{MH} = the mechanical quadripole representing the cylindrical cavity or pipe. m_2 and C_{M1} = the mass and compliance of the diaphragm. r_{M2}, m_3, and C_{M2} = the mass, mechanical resistance, and compliance of the air film. f_M = the driving force. $f_M = pA$. A = the area of the diaphragm. p = the sound pressure. The graph shows the open-circuit voltage response frequency characteristics. A. Response for constant sound pressure on the diaphragm. B. Response for constant sound pressure in free space.

B. *Condenser Microphone* (*Electrostatic Microphone*).—A condenser microphone, also termed an electrostatic microphone, is a microphone which depends for its operation on variations in electrical capacitance. The typical condenser microphone[4] consists of a thin stretched plate separated from a parallel rigid plate (Fig. 8.5). The electrical system of this microphone is shown in Fig. 8.5.

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[4] Wente, E. C., *Phys. Rev.*, Vol. 10, No. 1, p. 39, 1917.

The electrical capacitance, in statfarads, at any instant is given by

$$C_E = C_{E0} + C_{E1} \sin \omega t \tag{8.6}$$

where C_{E0} = electrical capacitance in the absence of an applied pressure, in statfarads,

C_{E1} = maximum change in the electrical capacitance due to the external applied sinusoidal pressure, in statfarads,

$\omega = 2\pi f$, and

f = frequency, in cycles per second.

From the electrical circuit

$$e_0 - r_E i = \frac{1}{C_E}\int i\, dt \tag{8.7}$$

where e_0 = polarizing voltage, in statvolts,

r_E = electrical resistance of the polarizing resistor, in statohms,

i = current, in statamperes, and

t = time, in seconds.

Equation 8.7 assumes that the bias resistor, r_{EB}, and the input electrical impedance of the vacuum tube is very large compared with r_E. Then e_0 may be considered to be in series with C_{E0} and r_E. Substituting the value of C_E from equation 8.7 in equation 8.6 and differentiating

$$(C_{E0} + C_{E1} \sin \omega t) r_E \frac{di}{dt} + (1 + r_E C_{E1}\omega \cos \omega t) i - e_0 C_{E1} \omega \cos \omega t = 0 \tag{8.8}$$

The solution of equation 8.8 is

$$\begin{aligned} i = {} & \frac{e_0 C_{E1}}{C_{E0}\sqrt{(1/C_{E0}\omega)^2 + r_E^2}} \sin (\omega t + \phi_1) \\ & - \frac{e_0 C_{E1} r_E}{C_{E0}^2 \sqrt{[(1/C_{E0}\omega)^2 + 4r_E^2]\,[(1/C_{E0}\omega)^2 + r_E^2]}} \sin (2\omega t + \phi_1 - \phi_2) \\ & + \text{terms of higher order} \end{aligned} \tag{8.9}$$

where $\phi_1 = \tan^{-1} 1/C_{E0}\omega r_E$ and $\phi_2 = \tan^{-1} 1/2C_{E0}\omega r_E$.

For small diaphragm amplitudes, the generated voltage, in statvolts, is

$$e' = r_E i = \frac{e_0 C_{E1} r_0}{C_{E0}\sqrt{\dfrac{1}{C_{E0}^2\omega^2} + r_0^2}} \sin (\omega t + \phi_1) \tag{8.10}$$

Equation 8.10 shows that the condenser microphone[5] may be considered as a generator with an internal open circuit voltage of

$$e = e_0\left(\frac{C_{E1}}{C_{E0}}\right) \sin (\omega t + \phi_1), \text{ in statvolts,} \tag{8.11}$$

and an internal electrical impedance of $1/C_{E0}\omega$, in statohms.

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[5] Wente, E. C., *Phys. Rev.*, Vol. 19, No. 5, p. 498, 1922.

The mechanical network of the mechanical system of the condenser microphone is shown in Fig. 8.5. The performance of the vibrating system may be obtained from a consideration of the mechanical network. Equation 8.11 shows that the voltage is proportional to the amplitude. Therefore, to obtain a microphone in which the sensitivity is independent of the frequency, the amplitude, for a constant applied pressure, must be independent of the frequency. In the range below the resonant frequency the amplitude of a stretched membrane for a constant applied force is independent of the frequency (see Sec. 3.4). The addition of the back plate with very close spacing introduces mechanical resistance[6,7] due to the viscosity loss in the narrow slit (see Sec. 5.4). This mechanical resistance reduces the amplitude at the resonant frequency. The back plate also introduces stiffness due to the entrapped air. This stiffness can be reduced without reducing the mechanical resistance by cutting grooves in the back of the plate. If the damping is made sufficiently large the amplitude at the fundamental resonant frequency of the diaphragm can be made to correspond to that of the remainder of the range.

The amplitude of the diaphragm, in centimeters, is given by

$$x = \frac{f_{M2}}{\left[r_{M2} + j\omega(m_2 + m_3) + \frac{1}{j\omega}\left(\frac{1}{C_{M1}} + \frac{1}{C_{M2}}\right)\right] j\omega} \qquad 8.12$$

where f_{M2} = applied force, in dynes,

$f_{M2} = pA$,

p = sound pressure on the diaphragm, in dynes per square centimeter,

A = area of the diaphragm, in square centimeters,

r_{M2} = damping mechanical resistance of air film, in mechanical ohms,

m_2 = effective mass of the diaphragm, in grams,

C_{M1} = compliance due to stiffness of the diaphragm, in centimeters per dyne,

m_3 = mass of air film, in grams,

C_{M2} = compliance due to stiffness of the air film, in centimeters per dyne,

$\omega = 2\pi f$, and

f = frequency, in cycles per second.

Equation 8.12 shows that the sensitivity below the resonant frequency is inversely proportional to the stiffness and the mechanical resistance. For the same fundamental resonant frequency the stiffness can be reduced

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[6] Crandall, I. B., *Phys. Rev.*, Vol. 11, No. 6, p. 449, 1918.

[7] Crandall, "Vibrating Systems and Sound," D. Van Nostrand Company, Princeton, N.J., 1926.

by decreasing the mass. This procedure also reduces the amount of mechanical resistance required to damp the fundamental resonance and thereby obtain uniform response. Aluminum alloys, due to the low density and high tensile strength, are the logical materials for use in diaphragms. The minimum diaphragm thickness suitable for the manufacture of condenser microphones is about .001 inch. The electrical capacitance of a microphone with a diaphragm diameter of $1\frac{5}{8}$ inches and a spacing of from .001 to .002 inch is from 100 to 200 mmfds. Due to the high electrical impedance of this capacitance it is necessary to locate the microphone near the vacuum tube amplifier. The electrical capacitance of a long connecting cable reduces the sensitivity without frequency discrimination because the internal electrical impedance of the microphone is also an electrical capacitance. The response frequency characteristics of a condenser microphone for constant sound pressure on the diaphragm and for constant free wave sound pressure are shown in Fig. 8.5.

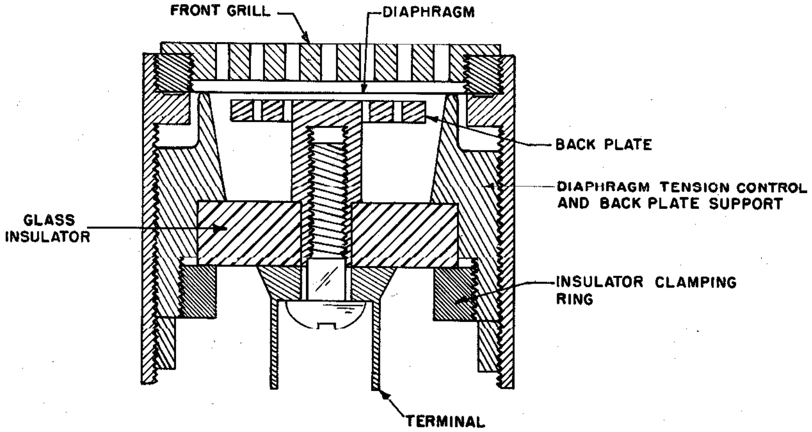

FIG. 8.6. Cross-sectional view of a miniature condenser microphone with a stretched membrane-type diaphragm.

The condenser microphone[8,9] shown in Fig. 8.5 employs a diaphragm with a diameter of $1\frac{5}{8}$ inches. The over-all diameter of the condenser microphone unit is about 3 inches. These microphones were developed about twenty-five years ago and were employed in the early days of sound reproduction. The condenser microphone was replaced by the electrodynamic (voice coil and ribbon) and piezoelectric microphone. During the past decade, smaller condenser microphones have been developed. A miniaturized version of the microphone shown in Fig. 8.5 is shown in Fig. 8.6. The over-all diameter of the microphone unit is a little less than 1 inch. The fundamental resonant frequency of the diaphragm is about 9000 cycles. The system is highly damped so that uniform response is maintained to over 15,000 cycles. The

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[8] Harrison and Flanders, *Bell Syst. Tech. Jour.*, Vol. 11, No. 3, p. 451, 1932.

[9] Veneklasen, Paul S., *Jour. Acous. Soc. Amer.*, Vol. 20, No. 6, p. 807, 1948.

deviations in response are smooth and can be easily compensated by electrical means to obtain a response frequency characteristic which is independent of frequency. The amplifier which may be used with this microphone is shown in Fig. 8.7. The cathode follower type of operation provides a system having a high input electrical impedance. This is necessary for the small condenser microphones in which the capacitance is only about 50 mmfds in order to maintain the response in the low-frequency region. See equation 8.11. The condenser microphone shown in Fig. 8.6 is used as a standard microphone in pressure calibration of laboratory standard microphones. See Sec. 10.2A1d.

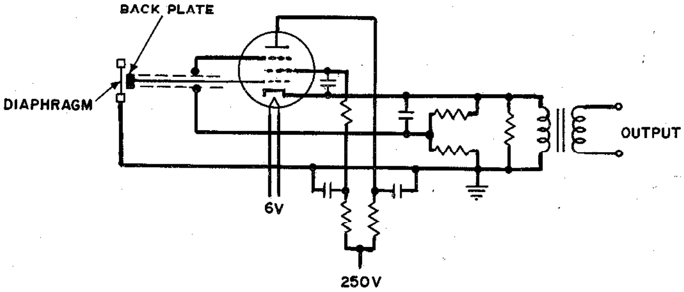

FIG. 8.7. Circuit diagram of a vacuum tube amplifier with a very large input electrical impedance.

Another miniature condenser microphone[10] is shown in Fig. 8.8. This microphone employs a plate instead of a stretched diaphragm. See Sec. 3.5. The over-all diameter of the microphone unit is about $\frac{3}{4}$ inch. The amplifier used with these microphones is of the type shown in Fig. 8.7.

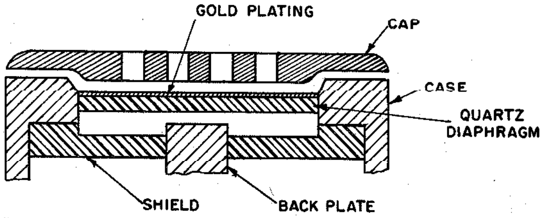

FIG. 8.8. Cross-sectional view of a miniature condenser microphone with plate-type diaphragm.

C. *Piezoelectric (Crystal) Microphones.*[11,12,13]—A piezoelectric microphone is a microphone which depends upon the generation of an electromotive force by the deformation of a crystal having piezoelectric properties.

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[10] Hilliard, J. K., and Noble, J. J., *Trans. IRE*, Prof. Group on Audio, Vol. AU-2, No. 6, p. 168, 1954.

[11] Sawyer, C. B., *Proc. Inst. Rad. Eng.*, Vol. 19, No. 11, p. 2020, 1931.

[12] Williams, A. L., *Jour. Soc. Mot. Pic. Eng.*, Vol. 18, No. 4, p. 196, 1934.

[13] Nicolson, U.S. Patent 1,495,429.