A Century of Microphones*

B. B. BAUER

CBS Laboratories, Stamford, CT 06905, USA

Of the various manifestations of a sound wave, the action of pressure on a diaphragm still is the universal means for detecting the presence of sound. The diaphragm actuates a transducer converting its motions into equivalent electrical waves. Innumerable transducers have been tried, but five are preeminent: 1) carbon, 2) condenser, 3) piezoelectric, 4) moving conductor, 5) moving armature.

Important microphone improvements during the late twenties and thirties have come about as a result of the application of equivalent circuit analysis to acoustical structures. The principle of pressure microphones, pressure-gradient microphones, combination microphones, and phase-shift microphones are described. Each of these has found an important niche in modern microphone applications.

A small number of important applications require superdirectional microphones. Here three approaches are used: 1) reflectors, refractors, and diffractors, 2) line microphones, and 3) higher order combination microphones.

In the future, improvements in the design of directional microphones will continue. Wireless microphones are bound to increase in popularity. New methods of transduction based on solid-state technology appear to be imminent. Unconventional methods of sound pickup may find wide use in space communication.

0 INTRODUCTION

As a sensor which transforms sound into an energy form suitable for amplification and transmission, a microphone is among the most common and useful technological servants of mankind. At this writing, a century of effort has been devoted to inventing and perfecting the microphone. This paper is intended to provide a record of the basic contributions made during that time as well as to survey the engineering principles employed in the present-day microphones. A brief look into the future will also be attempted.

1 PLAN OF THIS PAPER

From the scientific point of view a microphone may be designed to sense any of the manifestations of the sound wave and to convey it to a transducer which will transform it into electrical energy. A sound wave is accompanied by the presence of an alternating excess pressure called the sound pressure p; the particles of air are subject to a to-and-fro motion which may be described by their velocity u, and since the medium follows the adiabatic law, there exists an alternating change in temperature as well as corresponding changes in density, dielectric constant, magnetic susceptibility, and index of refraction. This paper is confined to those microphones in which the sound pressure or sound-pressure gradient are transformed into a force F by use of a diaphragm which, together with an associated electromechanical transducer, is set into motion resulting in generation of electricity. This is the method employed in earliest microphones, and it is virtually

the universal method for microphone operation today. Because of their importance to a proper understanding of microphones, brief descriptions of typical diaphragms and their interaction with the medium have been included in this paper.

Some of the other functions of a sound wave that have found significant but limited application in microphones are 1) the combined action of the particle velocity and the alternating temperature upon a heated fine wire[1] and 2) the combined action of pressure and particle velocity upon a cloud of ions.[2,3] Other possibilities have been considered: the change in dielectric constant or magnetic susceptibility of the air could be used to modulate the frequency of an oscillator;[4] the varying refractive index may be caused to modulate a light beam,[5] for example. Some of these functions may hold a key to microphone developments of the future.

Every conceivable means of electromechanical transduction has been combined with the vibrating diaphragm in an effort to produce "new and better" microphones. In this paper five basic transducers are described, any one of which will be found in virtually all of the present-day microphones: 1) loose contact (carbon), 2) electrostatic (condenser), 3) piezoelectric (Rochelle Salt and ceramic), 4) moving conductor (moving coil dynamic and ribbon), 5) moving armature (magnetic or reluctance). Many other means of transduction have been studied, tested, and patented, such as variable fluid contact,[6] movable vacuum tube elements,[7] piezoresistivity,[8] point-contact transistors,[9] and so on. To this date, these have not been widely adopted, but again these and newer methods of transduction may become important in future microphones.

Among the scientific tools of radio engineering, none has contributed as much to microphone development as the application of electrical circuit analysis to electroacoustical structures.[10] In employing the principles of this analysis, the operation of microphones is better understood and the groundwork is laid for future developments. It will be seen, for example, that some of the foregoing transducers are *displacement responsive* and others are *velocity responsive* (these terms arising

from the generated voltage being dependent on the amplitude of displacement or the velocity of the diaphragm). Equivalent circuit analysis shows how to proportion microphone structures best to utilize these characteristics.

2 DIAPHRAGMS

Earliest among microphone diaphragms—perhaps because of its similarity to the eardrum—was a stretched flat membrane (actually a sausage skin) used by Reis[11] to actuate a loose metal-to-metal contact. A stretched flat membrane [Fig. 1(a)] made of metal or very thin metallized plastic is used in present-day electrostatic microphones. The diaphragm is typically clamped at its periphery by a ring 1.1 and stretched to any desired tension by a threaded ring 1.2.

The cross-sectional shape as a function of radius r taken on by a circular membrane of radius a made of nonrigid material uniformly stretched with tension T and loaded with a uniformly distributed pressure P is a paraboloid of revolution described by the equation

$$y = (Pa^2/4T)(1 - r^2/a^2) = y_{max}(1 - r^2/a^2) \quad (1)$$

where y_{max} is the central, or maximum, displacement.[12] This equation is of interest since a stretched diaphragm used with condenser microphones commonly is subjected to uniform force of electrostatic attraction.

A flat diaphragm clamped between rings 1.3 and 1.4, or the like, is illustrated in Fig. 1(b). Used in

[9] R. L. Hanson, "Transistor Microphone," U.S. Patent 2,497,770 (1950).
[10] For an excellent treatise see H. F. Olson, *Dynamical Analogies* (Van Nostrand, New York, 1943). Also F. A. Firestone, "Twixt Earth and Sky with Rod and Tube; the Mobility and Classical Impedance Analogies," *J. Acoust. Soc. Am.*, vol. 28, pp. 1117–1153 (1956 Nov.).
[11] J. P. Reis, "Über Telephon durch den galvanischen Strom," *Jahresber. d. Physikal. Vereins zu Frankfurt am Main* (Germany), pp. 57–64 (1860–1861).
[12] I. B. Crandall, *Theory of Vibrating Systems and Sound* (Van Nostrand, New York, 1927), p. 20.

[1] G. Forbes, "A Thermal Telephone Transmitter," *Proc. R. Soc. (London) A*, vol. 42, pp. 141–142 (1889 Feb. 24).
[2] Early experiments are described in a paper by W. Duddel, "Rapid Variations in the Current through the Direct-Current Arc," *The Electrician*, p. 271 (1900 Dec. 14). Duddel credits the discovery to Simon whose experiments are recorded in *Ann. der Phys.*, vol. LXIV, no. 2, pp. 233–239 (1898). Also see L. de Forest, British Patent 5258 (1906).
[3] S. Klein's ionophone described by J. C. Axtell, "Ionic Loudspeakers," *IRE Trans. Audio*, vol. AU-8, pp. 21–27 (1952 July).
[4] This possibility has come to the author's attention from time to time but it does not appear to have been explored.
[5] L. de Forest, U.S. Patent 1,726,299 (1924).
[6] A. G. Bell, 1876 Mar. 10. See H. A. Frederick, "The Development of the Microphone," *J. Acoust. Soc. Am.*, vol. 3, pt. 2, p. 5 (1931 July).
[7] H. F. Olson, "Mechani-Electronic Transducers," *J. Acoust. Soc. Am.*, vol. 19, pp. 307–319 (1947 Mar.).
[8] F. P. Burns, "Piezoresistive Semiconductor Microphone," *J. Acoust. Soc. Am.*, vol. 29, pp. 248–253 (1957 Feb.).
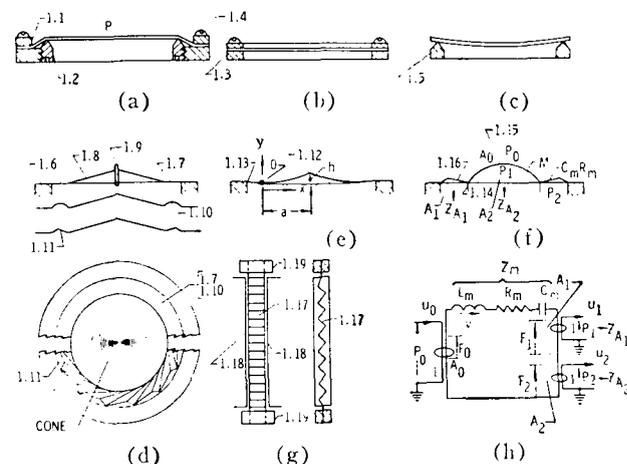

Fig. 1. Various types of diaphragms used in microphones.

early telephone receivers, this type of diaphragm is desirable where a great unbalanced pressure must be supported, but it also may be found in a modern electrostatic microphone.[13]

A more common arrangement for a flat-plate diaphragm is shown in Fig. 1(c), where the diaphragm is held against a circular support edge 1.5 by a steady-state force, such as magnetic attraction of a transducer in a telephone receiver.

The previously described diaphragms are best adapted to drive a distributed acoustical load. When it becomes necessary to actuate a mechanical system from a point or a line, the diaphragm usually takes on a different shape so as to present an adequate *driving-point impedance* to the load.

Very commonly used for a point drive is a cone diaphragm shown in three versions in Fig. 1(d). The edge of the diaphragm is effectively clamped or cemented against some support 1.6, leaving an annular portion 1.7 to flex in response to motions of the conical portion 1.8. The latter actuates a transducer through a drive rod 1.9. The flat annulus gives way to a formed or corrugated annulus 1.10 when linearity of motion and freedom from spurious resonances at high frequency are required. A major advance in annulus design was achieved by Harrison[14] who invented a tangentially corrugated annulus 1.11, shown at the bottom of Fig. 1(d), and which is used at present in many moving-coil microphones and horn loudspeaker drivers.

A "curvilinear" diaphragm developed by the author for use with piezoelectric microphones a quarter of a century ago is now widely used with various point drives. The goal is to provide a "nonbuckling" shape, that is, one that normally would be assumed by a pie-slice segment of a diaphragm supported at its apex and the circumferential edge and subjected to uniform pressure at one side. The desired shape may be defined approximately by the following equation:

$$y/h = \tfrac{3}{2}(x/a)^2 - \tfrac{1}{2}(x/a)^3 \qquad (2)$$

where the lowest point of the draw is at the origin O and h is the height at the apex 1.12. The contour may rise both toward the apex and toward the edge of support 1.13.

A "piston" diaphragm shown in Fig. 1(f) is, practically universally used with moving-coil microphones and other transducers where force is transmitted at the circular line around the rim to a coil 1.14. The central portion of the "piston" 1.15 is of spherical shape. The annulus 1.16 commonly is tangentially corrugated after Harrison.

A ribbon diaphragm which also is a transducer was invented by Gerlach.[15] As used in a pressure-gradient microphone invented by Olson,[16] this transducer is made of corrugated aluminum ribbon 1.17 less than 0.0001 inch thick, which either floats freely or is slightly stretched between two pole pieces 1.18. Electrical connections are made at the supports 1.19 to a high-turns-ratio transformer.

From an equivalent circuit point of view, the action of a diaphragm may be represented by Fig. 1(h).[17] The mechanical elements of the diaphragm, that is, mass M, compliance C_m, and internal damping resistance R_m, appear in the circuit as equivalent electrical elements to which forces derived from acoustical pressures are coupled by means of ideal $1:A$ transformers. The relationships between the pressure p and the force F developed upon an area A, and the volume velocity u and the linear velocity V resulting therefrom are correctly portrayed by the use of a transformer coupler, as may readily be verified from transformer equations. Normally the net areas on both sides of the diaphragm are equal, so that only two transformers (one for each side of the diaphragm) will be required. In the case of moving-coil microphones the two subareas of the diaphragm in Fig. 1(f) separated by the coil from 1.14 are subjected to different pressures and are confronted by different acoustical impedances. In this case each independently acting area must be represented by its own coupling transformer. These transformers are merely aids to correct circuit analysis representation. Usually they can be deleted in the actual experimental circuit work.

3 LOOSE-CONTACT TRANSDUCERS

Among the earliest devices intended for converting vibration into electrical impulses was Reis' loose-metal-contact transducer[11] which is reported to have transmitted tones of different frequencies, but not intelligible speech. This latter event seems first to have been achieved by Bell, using a magnetic microphone, on 1875 June 3.[18] However, Bell's microphone proved not to be sufficiently sensitive for telephone work, and the experiments of Berliner,[19] Edison,[20] Hughes,[21] and others soon thereafter introduced a long era of dominance for the loose-contact carbon transducer. To Edison goes the credit of being the first to design a transducer using granules of carbonized hard coal,[22] still used in

[13] J. K. Hilliard, "Miniature Condenser Microphone," *J. Soc. Mot. Pic. Telev. Eng.*, vol. 54, pp. 303–314 (1950 Mar.).
[14] J. P. Maxfield and H. C. Harrison, "Methods of High Quality Recording and Reproduction of Music and Speech Based on Telephone Research." *Trans. AIEE (Commun. and Electron.)*, vol. 45, pp. 334–348 (1926 Feb.).

[15] E. Gerlach, German Patent 421,038 (1925).
[16] H. F. Olson, U.S. Patent 1,885,001 (1932).
[17] B. B. Bauer, "Transformer Analogs of Diaphragms," *J. Acoust. Soc. Am.*, vol. 23, pp. 680–683 (1951 Nov.).
[18] See, for example, H. A. Frederick, "The Development of the Microphone," *J. Acoust. Soc. Am.*, vol. 3, pt. 2, p. 3 (1931 July). Also, A. G. Bell, U.S. Patent 174,465 (1876).
[19] E. Berliner, Caveat filed in U.S. Patent Off. 1877 Apr. 14.
[20] T. A. Edison, U.S. Patent 474,230; filed 1877 Apr. 27. Also U.S Patents 474-231-2.
[21] D. E. Hughes, "On the Action of Sonorous Vibrations in Varying the Force of an Electric Current." *Proc. R. Soc. (London) A*, vol. 27, pp. 362–369 (1878 May 9).
[22] T. A. Edison, U.S. Patent 406,567 (1889 July 19).

present-day microphones.

The carbon granules are made of deep-black "anthraxylon" coal ground to pass a 60–80 mesh, treated chemically, and roasted in several stages under a stream of hydrogen. This drives out volatile matter, washes out extraneous compounds, and carbonizes the coal. The last step of the process is magnetic and air-stream screening to eliminate iron-bearing and flat-shaped particles.[23]

Referring to Fig. 2(a), the modern carbon-granules transducer[24] is comprised of gold-plated metallic cups 2.1 and 2.2 attached to a diaphragm (not shown) and to a stationary back plate 2.11, respectively. A fabric washer 2.3 encloses the carbon cavity which is filled with granules 2.4 through an aperture 2.5 capped with a contact 2.6. Leads 2.7 and 2.8 complete the circuit with a polarizing source of current 2.9 and a load impedance 2.10. Frequently, the load impedance is a primary winding of a step-up transformer. Variations of transducer resistance stemming from displacement D modulate the current I in the circuit. The incremental

voltage developed across the load is proportional to displacement D.

The carbon-granules transducer not only has the distinction of being most widely used in microphones — every telephone in the world has one — but also of constituting its own amplifier of some 40- to 60-dB gain. Its disadvantages are a relatively high noise level and distortion, instability caused by variation of the contact resistance of the granules with position and degree of packing, and a loss of sensitivity or "aging" under action of vibration. With the advent of economical and efficient solid-state amplifiers, the importance of the carbon transducer is bound eventually to diminish.

A brief mention should be made of a stretched-diaphragm push–pull dual-button carbon transducer used in the early days of broadcasting because of its distortion-canceling properties.[25] This microphone became outmoded during the early thirties as a result of advances in other types of microphones aided by electronic amplification.

4 MOVING-ARMATURE TRANSDUCER

While claiming a record of first successful use for intelligible voice transmission, the "magnetic" trans-

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[23] Production of carbon granules appears to a degree to be a "trade secret" but see, for example, J. R. Fisher, "Coal for Transmitters," *Bell Labs. Rec.*, vol. 10, pp. 150–154 (1932 Jan.). See also W. E. Orvis, "Coal Talks," *Bell Labs. Rec.*, vol. 10, pp. 200–204 (1932 Feb.).
[24] W. C. Jones "Instruments for the New Telephone Sets," *Trans. AIEE (Commun. and Electron.)*, vol. 57, pp. 559–564 (1938 Oct.).

[25] W. C. Jones, "Condenser- and Carbon Microphones — Their Construction and Use," *Bell Sys. Tech. J.*, vol. 10, pp. 46–62 (1931 Jan.).
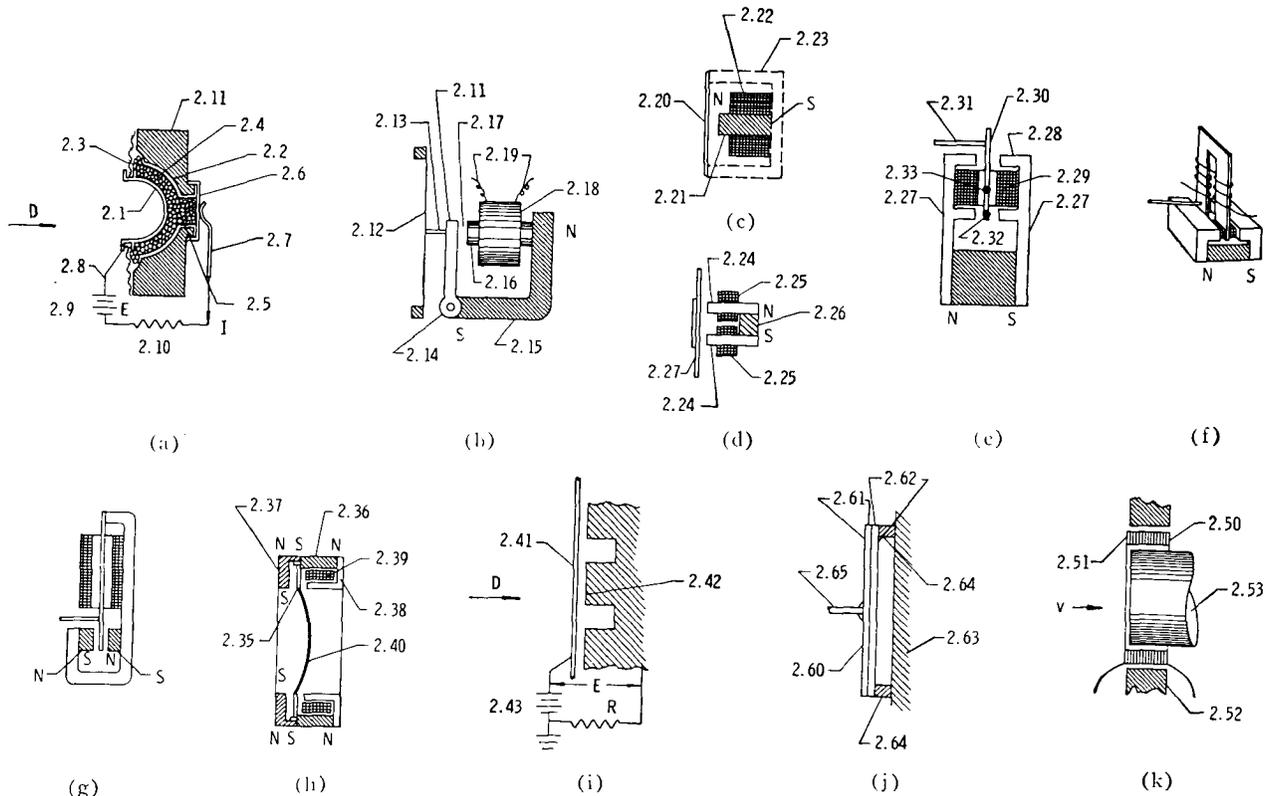

Fig. 2. Various types of transducers used in microphones.

ducer also can point with pride to continued service since its inception, principally in telephone receivers, and more recently again in microphones. Many different magnetic transducers have been designed. The type described in Bell's first patent application[18] of 1876 is shown in Fig. 2(b). An armature 2.11 is connected to a diaphragm 2.12 by a drive pin 2.13. The armature is hinged at 2.14 to a yoke 2.15. The yoke bears a pole piece 2.16 forming an air gap 2.17 and carrying a coil 2.18 with terminals at 2.19. Bell's original idea was to interconnect two such transducers by means of a transmission line and a battery in the circuit which polarized the electromagnets of both transducers. The generated signal voltage is proportional to the armature velocity.

In 1877 Bell patented a notable improvement to the above structure in which he used a permanent magnet for purposes of polarization.[26]

The transducer of Bell is used to this day in telephone receivers in two modified forms shown here for reference. The one in Fig. 2(c) employs a combination diaphragm armature 2.20 and a permanent magnet pole piece 2.21 surrounded by a coil 2.22. A magnetic return cup 2.23 often is provided. A bipolar form in Fig. 2(d) employs two pole pieces 2.24, each provided with a coil 2.25 and a common permanent magnet 2.26. A Permindur pole shoe 2.27 helps to carry the steady-state flux of the magnet. The above units have not been successful as microphones because the moving member requires sufficient heft to carry unbalanced dc flux and to support the steady-state forces which it produces.

A magnetically balanced armature transducer, useful in microphones, was suggested by Siemens[27] and Watson,[28] but more definitely projected by Capps.[29] Shown in Fig. 2(e), an armature 2.30 within the coil carries the *differential flux only* stemming from motions imparted to it by the drive pin 2.31 connected to a diaphragm (not shown). The armature may be pivoted at a point 2.32, which results in a mechanically unbalanced structure, or at a point 2.33, which produces mechanical, as well as magnetic, balance.

In an attempt to dissociate as much as possible the steady-state and the ac flux paths, the magnetic structure and the armature may be deformed, topologically speaking, until a straight-line pole-piece structure and a U-shaped armature form have been obtained, with great economy of dimensions.[30] This structure, shown in Fig. 2(f), has found wide use in transistorized hearing aids in which miniaturization has become a most important virtue. A variation is shown in Fig. 2(g).

An improvement heretofore applied to a telephone receiver but with possible use in microphones is shown in Fig. 2(h).[31] In this arrangement, a ring armature

2.35 is maintained in an unsaturated condition by two ring magnets 2.36 and 2.37. The circuit comprising the alternating flux path includes a circular pole shoe 2.38 and a circular coil 2.39. This transducer is well adapted to being driven by a piston diaphragm 2.40.

Magnetic transducers are characterized by the presence of a negative force-displacement function at the air gaps which has the dynamic form of *negative stiffness*. The magnetization and saturation properties of the armature must be proportioned in such manner that the mechanical restoring stiffness of the armature and diaphragm are greater than the magnetic negative stiffness.[32]

5 Electrostatic Transducers

While Edison[33] and Dolbear[34] proposed the use of electrostatic transducers very early in the history of electroacoustics, it remained for Wente[35] to develop an electrostatic microphone that was truly a precision instrument. An electrostatic transducer is shown in schematic view in Fig. 2(i). A stretched flat conductive membrane 2.41 is arranged at a distance x from a back plate 2.42 defining an active area A. This produces a capacitor having a capacitance $C = kA/x$, where k is the dielectric constant of air. A polarizing potential difference E is provided from a source 2.43, connected to the electrodes through a very high resistance R. Thus a quasi-constant charge Q_0 is established on the capacitor, where $Q_0 = CE = kAE/x$. Solving for E,

$$E = (Q_0/kA)x \ . \tag{3}$$

Therefore the voltage across the condenser will vary linearly with the diaphragm displacement x. Because of the low-loss air dielectric, a capacitor transducer potentially is an extremely quiet, linear device.

In practice the spacing x is of the order of 0.001 inch, and the capacity of the microphone is around 25–50 pF. Therefore, a very high impedance preamplifier at the transducer is required. The electrostatic transducer is most often used where highest quality is sought regardless of cost and inconvenience caused by the integral preamplifiers, such as in recording and

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[31] E. E. Mott and R. C. Miner, "The Ring Armature Telephone Receiver," *Bell Sys. Tech. J.*, vol. 30, pp. 110–140 (1951 Jan.).

[32] For example, see B. B. Bauer, "A Miniature Microphone for Transistorized Amplifiers," *J. Acoust. Soc. Am.*, vol. 25, pp. 867–869 (1953 Sept.). In all transducers (other than loose-contact) any utilization of the generated electrical energy causes a reaction upon the transducer's mechanical impedance. In microphones, this effect is usually small, and is beyond the scope of this paper.

[33] Reported in G. B. Prescott, *The Speaking Telephone, Talking Phonograph and Other Novelties* (Appleton, New York, 1878).

[34] A. E. Dolbear, U.S. Patents 239,742 and 240,578 (1881).

[35] E. C. Wente, "A Condenser Transmitter as a Uniformly Sensitive Instrument for the Absolute Measurement of Sound Intensity," *Phys. Rev.*, vol. 10, pp. 39–63 (1917 July).

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[26] A. G. Bell, U.S. Patent 186,787 (1877).

[27] E. W. Siemans, German Patent 2355 (1878).

[28] T. A. Watson, U.S. Patent 266,567 (1882).

[29] F. L. Capps, U.S. Patent 441,396 (1890).

[30] B. B. Bauer, U.S. Patent 2,454,425 (1948).

calibration work. An electrostatic transducer also is characterized by the presence of negative stiffness.

6 MOVING-COIL TRANSDUCER

While the early efforts and concepts in connection with moving-coil transducers are associated with the names of Cuttriss and Redding[36] and Siemens,[37] the credit for developing a wide-range practical moving-coil microphone goes to Wente and Thuras.[38] Referring to Fig. 2(k), the moving coil is circular in shape and is attached at the rim 2.51 to a diaphragm (not shown) being supported and centered thereby in an air gap between pole pieces 2.52 and 2.53. If the length of the conductor in the air gap is l, the flux density is B, and the diaphragm velocity is v, the voltage generated in the coil is

$$E = Blv \tag{4}$$

and hence, a moving-coil transducer is a velocity-responsive device.

Wente and Thuras based the development of their microphone and receiver upon equivalent circuit analysis. It is interesting to note that the circuit developed by them for a moving-coil receiver (where the goal is constant diaphragm displacement as a function of input voltage) is identical with the circuit to be used for a displacement-responsive (e.g., ceramic) microphone.

A moving-coil transducer is sensitive, rugged, provides good frequency response and low noise, and at present is the "workhorse" among the microphones used for broadcasting and public address applications. The low coil impedance is suitable for operation with long cables, followed with a step-up transformer at the preamplifier, although in many microphones a built-in transformer provides the proper impedance transformation right at the microphone.

7 PIEZOELECTRIC TRANSDUCER

In 1820 Becquerel described and observed piezoelectric effects,[39] although a systematic study leading to modern understanding of these effects is credited to the Curies.[40] Nevertheless, piezoelectric microphones had not become practical until the invention of the "bimorph" Rochelle Salt transducer by Sawyer.[41] The bimorph ushered in a quarter of a century era of dominance for Rochelle Salt crystals in low-cost microphones, which (because of the relatively poor stability of Rochelle Salt in severe climates) subsequently was

to be challenged by polycrystalline barium titanate ceramics of Grey[42] and more recently by lead zirconium titanate ceramics of Jaffe.[43] The shapes taken on by these bodies is that of a sandwich designated 2.60 in Fig. 2(j), consisting of two slabs of piezoelectric material 2.61 and 2.62 which are joined into an integral unit with appropriate electrodes. The element is attached to a reference frame 2.63 by raised portions 2.64, and driven by means of a drive unit 2.65 which is connected to a diaphragm. The tension and compression in the beam combine with the polarization mode of the individual slabs to produce a potential difference in the electrodes as a function of displacement. Rochelle Salt bimorphs are available for actuation by torsion or bending stresses, while the ceramic units are usually of the latter variety.

8 MICROPHONE STRUCTURES

Hunt[44] refers to the 1870s as "vintage years for electroacoustics." The inventions of the telephone and phonograph together with innumerable transducers to implement them occurred during those years. In the same manner, the 1930s, having seen the development of many a modern microphone, may be thought of as vintage years for microphones.

In studying the historical development of microphones it becomes evident that control over their directional capabilities has become increasingly important with time. In the following sections, we describe 1) *pressure microphones*, which respond to sound pressure at one exposed surface of the diaphragm and (because sound travels around corners) are more or less equally sensitive from all directions; 2) *gradient* or *pressure-difference microphones*, in which the diaphragm is exposed for differential action by sound pressure equally at both surfaces to achieve a bidirectional operation; 3) *combination microphones*, which unite pressure and gradient concepts to achieve unidirectional action, and 4) *phase-shift microphones*, which achieve unidirectional action with a single transducer and acoustical phase-shift networks. Diaphragms and transducers in endless combinations have been brought together to produce a multitude of such microphones, but only a few basic examples can be given here.

9 PRESSURE MICROPHONES

The electrostatic microphone of Wente[35] is one of the simplest and, with modern refinements, one of the most effective of microphones. Its basic form is shown in Fig. 3(a). The microphone is composed of a flat

[36] C. Cuttriss and J. Redding, U.S. Patent 242,816 (1881).
[37] E. W. Siemens, German patent 2355 (1878).
[38] E. C. Wente and A. L. Thuras, "Moving Coil Telephone Receivers and Microphones," *J. Acoust. Soc. Am.*, vol. 3, pp. 44–55 (1931 July).
[39] A. C. Becquerel, *Bull. des Sciences* (Soc. Philomatique de Paris, France), vol. 7, pp. 149–155 (1820 Mar.).
[40] J. and P. Curie, *Bull. de la Société Minéralogique de France*, vol. 3, pp. 90–93 (1880 April).

[41] C. B. Sawyer, "The Use of Rochelle Salt Crystals for Electrical Reproducers and Microphones," *Proc. IRE*, vol. 19, pp. 2020–2029 (1931 Nov.).
[42] Grey, U.S. patent 2,486,560 (1949).
[43] Jaffe, U.S. Patent 2,708,244 (1955).
[44] F. V. Hunt, *Electroacoustics* (Harvard University Press, Cambridge, MA, 1954), p. 37.

stretched conductive diaphragm 3.1 attached to a box 3.2 so as to expose one surface to the external sounds. A stationary electrode 3.3 inside the box, placed close to the diaphragm, forms the electrostatic transducer.

The equivalent network analogy of the electrostatic microphone is shown in Fig. 3(b). Sound pressure acts upon the diaphragm through an air-load radiation impedance portrayed by an inductance L_a in parallel with a resistance R_a.[45] Thin films of air between the diaphragm and the electrode are squeezed in and out as the diaphragm vibrates to-and-fro resulting in damping action, the collective effect of which is represented by R_b and L_b. The fluid motion finds its way into the volume of the recesses 3.4 which, taken together, define an acoustical compliance C_b.

A simplified equivalent circuit is obtained by dividing the mechanical impedance of the diaphragm by the square of the area A, which allows the elimination of ideal 1:A transformers [Fig. 3(c)]. The input voltage E_p replaces the sound pressure p. Since diaphragm displacement D is equivalent to the charge on a condenser $Q = CE$, it is a requirement in the equivalent circuit that the voltage E_0 remain invariant with frequency for constant E_p. This result is achieved if the combined series compliance of the diaphragm $(C_m A^2)$ and of the volume 3.4 (C_b) comprise the controlling circuit impedance. In the microphone of Wente this condition was obtained by stretching the diaphragm to a high-resonance frequency. A similar effect may come about by reducing the dimensions of C_b until the spring of the air becomes the controlling factor.[46] R_b and L_b are selected to damp the diaphragm resonance, to provide a "flat" response at high frequency.

A piezoelectric microphone[41] in Fig. 3(d) is very similar in its equivalent circuit to the electrostatic microphone, except that a damping screen defining an acoustical resistance R_s and inertance L_s is added in the structure. The volume C_s between the screen and the diaphragm forms a part of the equivalent circuit

mesh in Fig. 3(e) and (f). The mass, compliance, and resistance of the piezoelectric element and the diaphragm are lumped together and represented as L_m, C_m, and R_m, respectively. A damping element or screen may be placed behind as well as in front of the diaphragm.

A different approach is taken in designing pressure microphones which use *velocity-responsive* transducers. Among the most elegant is the pressure-microphone portion of a combination microphone described by Olson in 1932.[47] In schematic cross section this microphone is shown in Fig. 4(a), its equivalent electrical network in Fig. 4(b), and a simplified version in Fig. 4(c). Because it is a design objective to make the *velocity* of the transducer invariant with frequency (and the electrical circuit counterpart of velocity is the current I), the circuit must be resistance controlled. This is achieved by the expedient of making all the mechanical and acoustical impedances small compared with the termination resistance R_b. The latter is obtained with a pipe or labyrinth filled with tufts of felt.

A more modern version of this microphone was described by Olson and Preston in 1950.[48] In this unit a pickup probe in the form of a small horn was added to the microphone to enhance its high-frequency response.

A major advance in pressure microphone design was

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[45] Means of approximating air-load impedance with fixed elements is an important tool in the bag of tricks of the electroacoustician. For example, see B. B. Bauer, "Notes on Radiation Impedance," *J. Acoust. Soc. Am.*, vol. 15, pp. 223–224 (1944 Apr.); R. C. Jones, "A Fifty Horsepower Siren," *J. Acoust. Soc. Am.*, vol. 18, pp. 371–387 (1946 Oct.), F. B. Hunt, *op. cit.*, p. 158.

[46] The pressure-operated mode of the Von Braunmühl and Weber microphone to be described is probably air-stiffness controlled, but see also T. J. Schultz, "Air-Stiffness Controlled Condenser Microphone," *J. Acoust. Soc. Am.*, vol. 28, pp. 337–342 (1956 May).

[47] H. F. Olson, "A Unidirectional Ribbon Micropone" (abstract only), *J. Acoust. Soc. Am.*, vol. 3, p. 315 (1932 Jan.).

[48] H. F. Olson and J. Preston, "Unobtrusive Pressure Microphone," *Audio Eng.*, vol. 34, pp. 18–20 (1950 July).
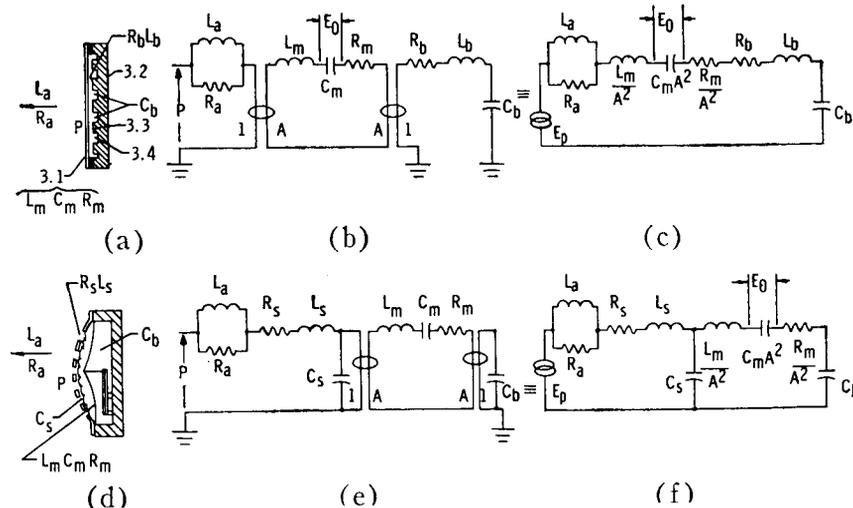

Fig. 3. Pressure microphone with displacement-responsive transducer.

achieved by Wente and Thuras[38] with the invention of a moving-coil microphone shown in Fig. 4(d). The equivalent circuit is given in Fig. 4(e), and a simplified circuit in Fig. 4(f). It should be noted that the acoustical compliances C_1 and C_2 confronting the two portions of the diaphragm are interconnected by the acoustic impedances R_{1b}, L_{1b}, R_{2b}, L_{2b} defined by the circular slits between the coil and the magnetic structure, which form a resonant circuit capable of producing spurious response. Wente and Thuras encountered this problem and solved it by addition of a separate internal circuit mesh. However, by choosing the acoustical constants in accordance with equations at the bottom of Fig. 4(f),[17] the spurious resonance is prevented, and the simplified circuit of Fig. 4(f) then correctly portrays the operation of the microphone.

10 GRADIENT MICROPHONES

A number of illustrations and patent drawings of early microphones show diaphragms open on both sides for access to the sound waves, and in the early part of the century Pridham and Jensen[49] and Meissner[50] invented noise-canceling microphones in which access at both sides of the diaphragm was provided for entry of noise, with preferential access on one side for speech sounds. Notwithstanding, the invention of a pressure-gradient ribbon microphone ("ribbon velocity microphone") by Olson[16] was an outstanding contribution to the art. This microphone is shown in schematic el-

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[49] Personal communication from the late P. Jensen.

[50] B. F. Meissner, U.S. Patent 1,507,081 (1924), filed 1919 Mar. 12. In a recent personal communication, Meissner recounts attempts at intercommunication in open cockpit planes in 1916–1917, leading to removal of the back case from a Baldwin earphone (used as microphone) to provide equal noise access to both sides of the diaphragm.

evation in Fig. 5(a) and in plan cross section in Fig. 5(b). Olson designed the pole pieces 5.1 and 5.2 to form a small baffle with an effective front-to-back air path d equal to one half the shortest wavelength of sound to be received. A ribbon transducer 5.3 was installed for free motion therebetween. The resulting action is shown by the phasor diagram in Fig. 5(e). The front and back pressures, designated as P_1 and P_2, are displaced in phase by an angle $(\omega d/c)$ cos θ.

The equivalent circuit of the ribbon microphone is shown in Fig. 5(c), and a simplified circuit in Fig. 5(d). It is noted that by making the mechanical compliance of the ribbon sufficiently large, and the damping resistance sufficiently small, the inductive (mass) elements will become controlling. Lumping these elements into a single constant L, the acoustic impedance of the transducer may be expressed as $j\omega L$. Therefore, the velocity v (and consequently the output voltage E_0) is expressed by

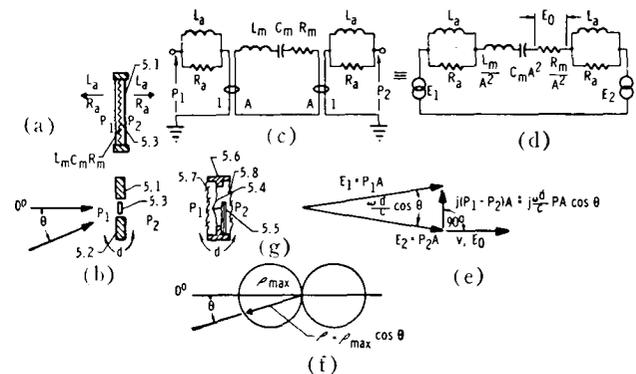$$v = j(\omega d/c)PA \cos \theta / j\omega L$$

$$= (d/cL)PA \cos \theta . \qquad (5)$$

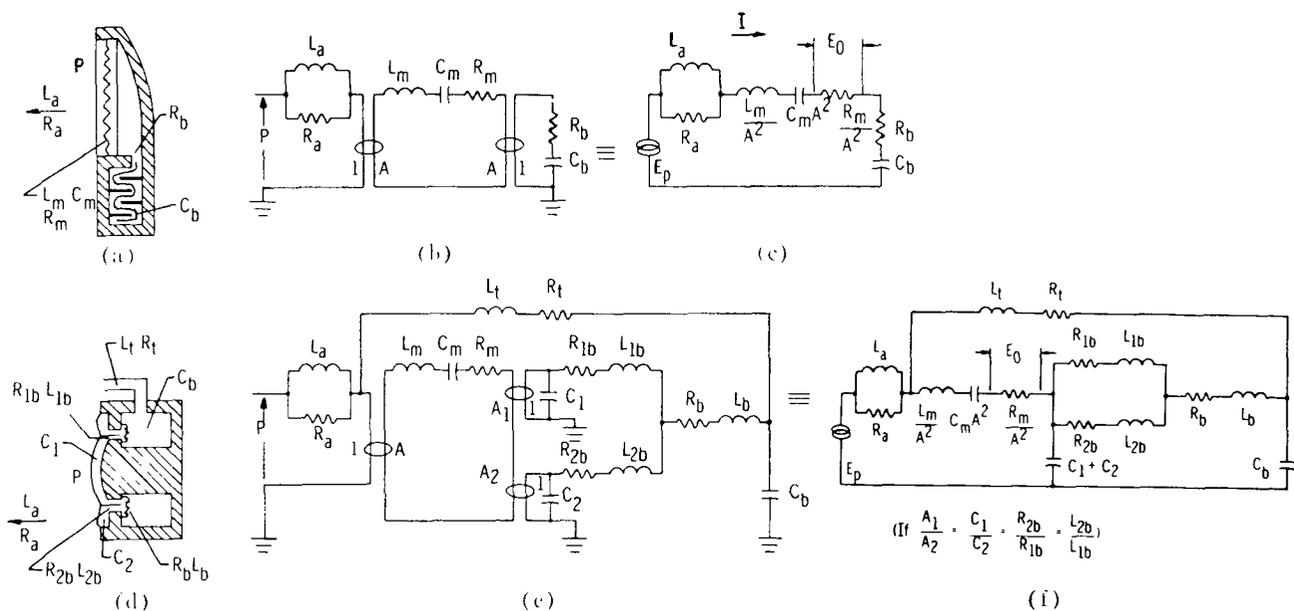Fig. 5. Pressure-gradient microphones.

Fig. 4. Pressure microphone with velocity-responsive transducer.

The output of a ribbon microphone, therefore, is in phase with the sound pressure, invariant with frequency, and proportional to the cosine of the angle of sound incidence. The polar response is the "cosine" pattern $\rho = \rho_{max} \cos \theta$ shown in Fig. 5(f). The power response to random sounds for this pattern is one third the response of an omnidirectional (circular) pattern exhibited by pressure microphones.

A piezoelectric pressure-gradient microphone also can be constructed[51] as shown in schematic cross section in Fig. 5(g). A diaphragm 5.4 and a transducer 5.5 are housed in a round casing 5.6 with access to the atmosphere through damping screens 5.7 and 5.8. While this microphone had little commercial importance, it served as a stepping stone in the discovery of phase-shift microphones, to be described.

11 COMBINATION MICROPHONES

The invention of the ribbon gradient microphone provided the necessary tool for the creation of a unidirectional microphone.[47,52] Such a microphone is shown in schematic cross section in Fig. 6(a). Two ribbons are provided with a common supporting frame 6.1. The ribbon 6.2 is freely accessible on both sides to form a pressure-gradient element with directional pattern expressed by the equation $\rho = \cos \theta$. The ribbon 6.3 is terminated by a damped pipe to form a nondirectional pressure microphone with directional pattern expressed by the equation $\rho = 1$. Adding the two in equal half-and-half proportions produces a polar pattern $\rho = 0.5 + 0.5 \cos \theta$, which is a heart-shaped pattern or "cardioid." [The latter is a special case of the more general limaçon pattern $\rho = (1 - k) + k \cos \theta$.] The resulting directional characteristics are shown in Fig. 6(b).

A similar principle was employed by combining a piezoelectric pressure-gradient microphone with a piezoelectric pressure microphone to produce a cardioid pattern.[53] This latter unit incorporated a switch for selective choice of any of the three patterns. By combining a ribbon pressure-gradient with a moving-coil pressure microphone, Marshall and Harry produced a very superior unidirectional microphone and endowed it with six directional patterns.[54] It is to be noted that the pattern $\rho = 0.25 + 0.75 \cos \theta$, shown in Fig. 6(h), provides the lowest random energy pickup in the limaçon family: one fourth that of an omnidirectional pattern, while the pattern $\rho = 0.37 + 0.63 \cos \theta$ provides the greatest front-to-total random ratio of 93 percent.[55]

The above microphones suffer from axial dissymmetry

and production difficulty in the matching of two dissimilar units. In the newer designs they have been outmoded by simpler and more effective "phase-shift" microphones, to be described later.

A brilliant combination microphone based on the electrostatic principle was described by Von Braunmühl and Weber.[56] The principle of this microphone, according to the inventors, is as follows [Fig. 6(c)]: A brass circular body member b is provided with a series of holes a through the member and another series of holes e partway through. Two diaphragms c and d are fastened at the sides of the body, forming two electrostatic transducers. Assume first the condition of sound arriving at 90°. The sound pressure will merely push both membranes to-and-fro against the stiffness of the diaphragms and the air trapped within the body openings, by equal amounts denoted by the arrows S_1 and S_2 in Fig. 6(e). Now, let the sound arrive from the 0° direction; an additional pressure-gradient component will push both diaphragms and the air as a body (owing to the interconnection through the holes a) against the resistance of the film of air trapped between the diaphragm and the electrode faces. This latter effect is denoted by arrows s_1 and s_2. If the friction factor and the stiffness factors are suitably chosen, $S_1 = s_1$ and $S_2 = s_2$ and therefore only the front diaphragm c will move. By the same token, for sounds arriving from the 180° direction only the rear diaphragm will be set into motion, as shown in Fig. 6(f). The polar pattern exhibited by the front diaphragm, used by itself, will be a cardioid shown in solid lines in Fig. 6(g). If both diaphragms are connected in parallel, then the polar response of the combination will be omnidirectional or circular. While not so stated by the inventors, it is almost axiomatic that the rear diaphragm, by itself, will produce a reverse cardioid shown by the dotted line in Fig. 6(g); and if both diaphragms are oppositely polarized and their ac outputs summed, then a cosine pattern will emerge. The principle of Von Braunmühl and Weber is found to this day in electrostatic microphones used for recording and other high-quality applications.

While Von Braunmühl and Weber envisioned the operation of their microphone as a combination of pressure and pressure-gradient functions, another way of looking at it, within certain limitations, is as a special case of a phase-shift microphone to be described next.

12 PHASE-SHIFT MICROPHONES

In attempting to balance the two damping screens of the structure in Fig. 5(g), the author noted that certain conditions of screen unbalance produced a small but decided unidirectional effect. In analyzing this phe-

[51] B. Baumzweiger (Bauer), U.S. Patent 2,198,424 (1940); filed 1937 Nov. 4.

[52] T. Weinberger, H. F. Olson, and F. Massa, "A Unidirectional Ribbon Microphone," *J. Acoust. Soc. Am.*, vol. 5, pp. 139–147 (1933–1934 Oct.).

[53] B. Baumzweiger (Bauer), U.S. Patent 2,184,247 (1939); filed 1937 Dec. 20.

[54] W. R. Harry, "Six-Way Directional Microphone," *Bell Labs. Rec.*, vol. 19, pp. 10–14 (1940 Sept.).

[55] R. P. Glover, "A Review of Cardioid Type Unidirectional Microphones," *J. Acoust. Soc. Am.*, vol. 11, pp. 296–32 (1940 Jan.).

[56] Von Braunmühl and Weber, U.S. Patent 2,179,361 (1939); filed 1936 Mar. 30.

nomenon by means of equivalent circuit analysis it became apparent that acoustical phase shift introduced by the networks was responsible. Soon thereafter the conditions were formulated for producing any directional pattern in the limaçon family with any transducer and an appropriate phase-shift network.

The invention is described in a parent patent[57] and four continuations-in-part.[58] The former outlines three different phase-shift networks which are the basis of practically all phase-shift microphones currently in use, and which are summarized in Fig. 7.

A piezoelectric phase-shift microphone is shown in Fig. 7(a). The microphone consists of a circular mounting plate 7.1 upon which is fastened a diaphragm 7.2 and a piezoelectric transducer 7.3. In the simplified equivalent circuit of Fig. 7(b) these are shown as defining an impedance Z_{am}, which includes the air load. Sound waves for frontal (0°) incidence first impinge upon the diaphragm with a pressure P_1 traveling to the rear of the microphone through a distance d with a velocity c. The rear pressure P_2 lags behind P_1 by a phase angle $\phi = \omega d/c$. For any other angle of incidence θ, $\phi = (\omega d/c) \cos \theta$. Air flow into the volume 7.5 which defines an acoustical compliance C_2 is caused by pressure P_2 acting through the circumferential entry port 7.4 which defines a resistance R_2 and inertance L_2. It is shown in the parent patent that *regardless* of

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[57] B. B. Bauer, U.S. Patent 2,237,298 (1941); filed 1938 Sept. 29.
[58] B. B. Bauer, U.S. Patents 2,305,596 to 599 (1942); filed 1941 Apr. 8.

the magnitude of Z_{am}, a cardioid pattern will be obtained if the elements of the network R_2, L_2, and C_2 are proportioned as follows:

$$R_2 = d/cC_2 \tag{6}$$

$$L_2 = C_2 R_2^2/2 . \tag{7}$$

In the above proportions, the elements R_2, L_2, and C_2 form a phase-shift network whereby the pressure P_2 within the microphone is equal to P_2 but is shifted in phase by an angle $\phi' = \omega d/c$. ϕ' remains unaffected by direction of arrival of sound. Referring to Fig. 7(g), and letting P_2 and P_3 remain stationary, as the source of sound rotates from the front to the back of the microphone, the phasor P_1 will describe a path from $P_{1-0°}$, to $P_{1-90°}$ and then to $P_{1-180°}$. The phasor connecting the ends of P_3 and P_1 plotted as a function of the angle θ will be a cardioid of revolution. By choosing properly the relative magnitudes of ϕ_0 and ϕ', any desired member of the limaçon family may be obtained. The above principle is employed in piezoelectric microphones intended for public address applications.

A moving-coil phase-shift microphone exhibiting cardioid operation is shown in Fig. 7(c), and its simplified equivalent circuit in Fig. 7(d). Here the impedances of the moving coil and the air load again are lumped together as Z_{am}. The phase-shift network is composed of the rear port resistance R_2 and inertance L_2, compliance of the volume under the diaphragm C_a and within the magnet C_b, and the impedance of the
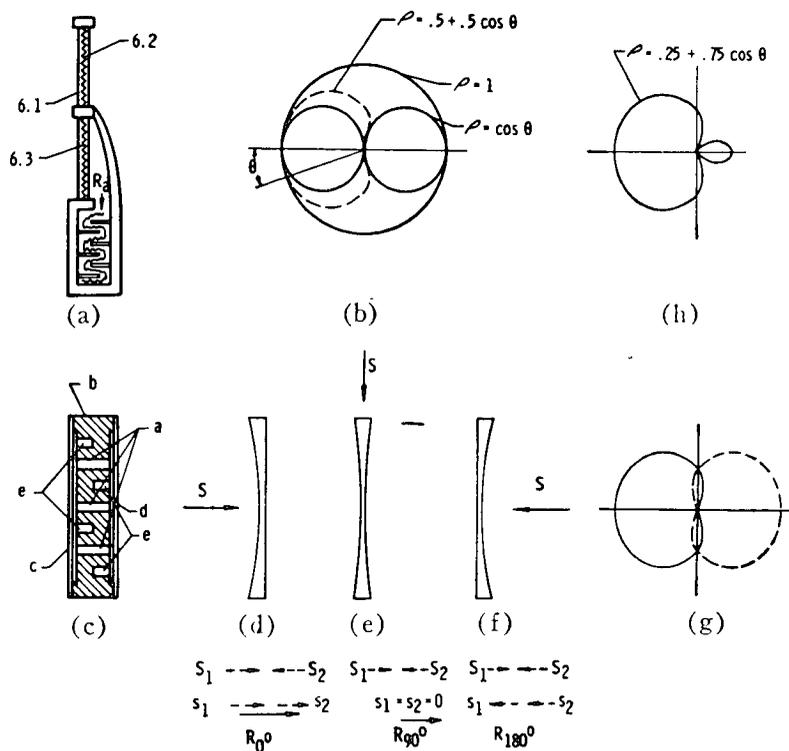

Fig. 6. Combination unidirectional microphones.

interconnecting screen R_3 and L_3. Subsequently, Black[59] and Wiggins[60] modified this structure by providing multiple rear entry ports. This approach allows the use of stiffer diaphragm suspension than that used with the microphone in Fig. 7(d), and serves to improve sensitivity to mechanically transmitted noise.

Practically all unidirectional moving-coil microphones built today use one of the principles described in the preceding paragraph.

A third phase-shift network to be found in the parent patent is especially adapted for use with mass-controlled transducers, such as the ribbon transducer. Shown in Fig. 7(e) is a frame 7.9 and ribbon transducer 7.10, and a phase-shift network comprised of the following elements: entry port 7.11 which defines an acoustic inertance L_3, a volume behind the ribbon 7.12 which furnishes a compliance C_3, and a damped pipe which defines a resistance R_3. The front-to-back distance is again defined as d. This network can be solved analytically for the cardioid with the following result[57]:

$$L_3 = dR_3/c \tag{8}$$

$$C_3 = L_3/2R_3^2 . \tag{9}$$

An improved version of this microphone was developed by Olson[61] in which the rear entry is adjustable for selection of polar pattern. Subsequently, Olson, Preston, and Bleazey reported achieving a further im-

provement by taking a phase-shift ribbon microphone with a limaçon characteristic where $\rho = 0.3 + 0.7 \cos \theta$ and providing a damped cavity in the vicinity of the rear entry ports.[62] The above microphones have found wide use in public address and television broadcasting.

13 SUPERDIRECTIONAL MICROPHONES

Three approaches have been taken to provide microphones with directional characteristics sharper than those possible with limaçon patterns.

13.1 Reflectors, Refractors, Diffractors

From optical analogy, the idea of using a parabolic mirror for improved directivity must have occurred to various investigators. The microphone is placed at or near the focus of the reflector. The angular resolution for short wavelengths is given by Rayleigh's criterion[63] as $\theta_r = 0.61 \lambda/r$ radian, where λ is the wavelength, r the radius, and θ the resolution angle. The directional capability is very high at high frequency and nil at low frequency. Hanson[64] describes a parabolic reflector used with condenser microphones. Olson and Wolff[65] pro-

[59] Black, U.S. Patent 2,401,328 (1946); filed 1943 Jan. 16.

[60] A. M. Wiggins, "Unidirectional Microphone Utilizing a Variable Distance between the Front and Back of the Diaphragm," *J. Acoust. Soc. Am.*, vol. 26, pp. 687–692 (1954 Sept.).

[61] H. F. Olson, "Polydirectional Microphone," *Proc. IRE*, vol. 32, pp. 77–82 (1944 Feb.).

[62] H. F. Olson, J. Preston, and J. C. Bleazey, "The Uniaxial Microphone," *IRE Trans Audio*, vol. AU-1, pp. 12–19 (1953 July–Aug.).

[63] See, for example, G. S. Monk, *Light, Principles and Experiments* (McGraw-Hill, New York, 1937), p. 206.

[64] O. B. Hanson, "Microphone Technology in Radio Broadcasting, *J. Acoust. Soc. Am.*, vol. 3, pp. 81–93 (1931 July).

[65] H. F. Olson and I. Wolff, "Sound Concentrator for Microphones," *J. Acoust. Soc. Am.*, vol. 1, pp. 410–417 (1930 Apr.).
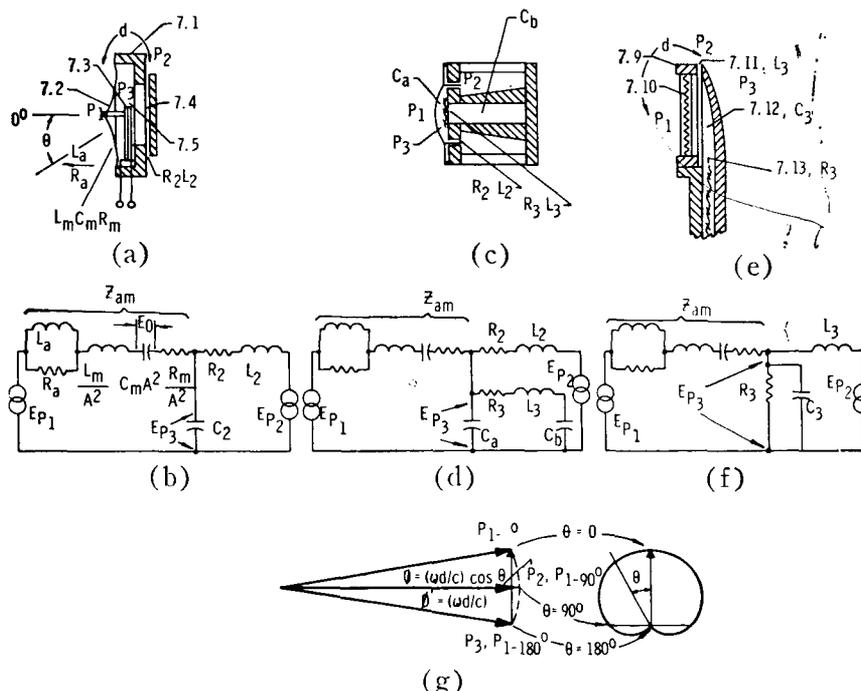
Fig. 7. Phase-shift unidirectional microphones.

posed a concentrator consisting of parabolic and conical sections arranged in the form of a horn. Aamodt and Harvey[66] devised a wide-area electrostatic microphone which attains notable directivity simply because of its large size. Further improvements in performance can be obtained by combining an acoustical lens[67] with a conical horn.[68]

13.2 Line Microphones

In 1939, Mason and Marshall described a microphone attachment consisting of 50 small tubes whose lengths vary by equal increments from 3 cm to 150 cm. These are assembled into a circular bundle and coupled to the diaphragm of a pressure microphone.[69] This microphone is roughly equivalent in directional effects to a 3-foot parabolic reflector, but with considerably less bulk and frequency dependence. The same year Olson described an improved line microphone in which directional characteristics were substantially independent of frequency, obtained by combining several multipipe units, each designed for operation over a given frequency range.[70]

13.3 Higher Order Combination Microphones

It has been seen that subtraction of pressures at two points in space produces a gradient mode of operation described by $\rho = \cos \theta$. Subtraction of two gradient modes at two points in space will produce a second-order gradient $\rho = (\cos \theta)(\cos \theta) = \cos^2 \theta$. By continuing this process, in theory infinite improvement in directivity could be obtained in theoretically infinitesimal space.

A microphone with a higher mode of operation was developed in 1938 and described in the parent phase-shift microphone case, U.S. Patent 2,237,298.[57] By providing an appropriate electrical network with two gradient transducers a polar pattern defined by equation $\rho = (1 + \cos \theta)(\cos \theta)$ was obtained. The reissue Patent 2,305,599[58] describes how the same effect may be achieved by the subtraction of outputs of two spaced-apart cardioid microphones. Olson and Preston have carried out this work further by combining two special phase-shift microphones[62] with electrical networks to obtain a polar pattern defined by $\rho = (0.3 + 0.7 \cos \theta \cos \theta/3)(\cos \theta)$.[71]

A second-order gradient differential microphone employing a single diaphragm and a case of suitable

configuration was developed by Wiggins for speech transmission from noisy environment.[72]

14 FUTURE DEVELOPMENTS

The art of microphone design still taxes the ingenuity of the physicist and the radio scientist. Despite the century of progress many problems remain unsolved.

Improved directional characteristics will continue to receive considerable attention. A "zoom" microphone, in which the directional pattern can be adjusted to conform, say, to the optical angle of a television camera may find important use in the broadcasting industry. Light and highly effective directional microphones would aid with picking out the desired sounds amidst crowd noise.

The problem of an effective, reliable, and inexpensive multichannel wireless microphone is yet to be solved. Such a microphone would be a boon to broadcasting, entertainment, and similar industries.

One feels intuitively that we should be due for a "breakthrough" in transducer technology. Microphones especially suitable for use with transistor amplifiers and those with sufficient sensitivity and low noise for use in broadcasting recording and sound level meter applications would be very welcome.

Unconventional methods of sound reception will be further explored: Throat microphones already have been widely used in military actions, but they provide poor articulation. Microphones placed within the mouth, attached to the teeth, inserted in the ear canal, and otherwise coupled to the skeletal structure of the head have already received considerable study.

Ultimately, lest we forget, speech is merely an end-product of the thought processes, and there is no reason why eventually these should not be directly picked up without the intervening aerial vibrations. One should not be surprised to see an astronaut, someday, with a radio "thought" transmitter permanently implanted in his cranium. But then, alas, all this microphone development would have been in vain.

15 ACKNOWLEDGMENT

[66] T. Aamodt and F. K. Harvey, "A Large Area Condenser Type of Transducer" (abstract only), *J. Acoust. Soc. Am.*, vol. 25, p. 825 (1953 July).

[67] W. E. Kock and F. K. Harvey, "Refracting Sound Waves," *J. Acoust. Soc. Am.*, vol. 21, pp. 471–481 (1949 Sept.).

[68] M. A. Clark, "An Acoustic Lens as a Directional Microphone," *IRE Trans. Audio*, vol. AU-2, pp. 5–7 (1954 Jan.–Feb.).

[69] W. P. Mason and R. N. Marshall, "A Tubular Directional Microphone," *J. Acoust. Soc. Am.*, vol. 10, pp. 206–216 (1939 Jan.).

[70] H. F. Olson, "Line Microphones," *Proc. IRE*, vol. 27, pp. 438–446 (1939 July).

[71] H. F. Olson and J. Preston, "Directional Microphone," *RCA Rev.*, vol. 10, pp. 339–347 (1949 Sept.).

[72] A. M. Wiggins, U.S. Patent 2,552,878 (1951); filed 1947 Sept. 24.

[73] H. F. Olson, *Acoustical Engineering* (Van Nostrand, Princeton, N.J., 1957).

been most useful in reviewing modern developments. Friends and associates too numerous to mention have been helpful with the location of references. To those of them who are still young enough reasonably to expect

to celebrate the 100th anniversary of the IRE, this article will hopefully be an acceptable starting point in appraising the progress in microphones that will have taken place during the next 50 years!

THE AUTHOR

Benjamin B. Bauer graduated from the Pratt Institute in 1932, where he studied industrial electrical engineering. In 1937 he earned an E.E. degree from the University of Cincinnati and pursued postgraduate studies in physics, mathematics, and acoustics at Chicago and Northwestern Universities. Mr. Bauer became associated with Shure Brothers Incorporated, where he was director of engineering and vice president.

From 1957 he guided major developments at the CBS Technology Center (formerly CBS Labs.) in the fields of acoustics and magnetics in a broad range of the communications science and became vice president and general manager of the Technology Center.

Mr. Bauer's career spanned more than 40 years in research, development, engineering, management, teaching, writing, and lecturing in acoustics and communications. He authored numerous papers, contributed to textbooks on acoustical subjects, and lectured widely on acoustics and research administration in the United States and abroad.

Mr. Bauer, who died in 1979, was a fellow of the Institute of Electrical and Electronics Engineers and a fellow of the Acoustical Society of America and associate editor of its *Journal*. He was a fellow of the Audio Engineering Society, its executive vice president (1967–68), president (1968–69), honorary member (1972), and a recipient of its Gold Medal Award. A founder, past editor-in-chief, and past national chairman of the IEEE Professional-Technical Group on Audio and Electroacoustics, he received the Group's Achievement Award in 1955. He held more than 70 patents in his name.

Editor's Note: The biography of Kenneth L. Kantor, coauthor of "A Psychoacoustically Optimized Loudspeaker" (published in 1986 Dec.), which was not available at press time, is published here.

THE AUTHOR

Kenneth L. Kantor received a Bachelor of Science degree in electrical engineering from M.I.T. in 1979, where his research into psychoacoustics and loudspeaker design led to a thesis describing a prototype direct-ambient loudspeaker. He returned to M.I.T. for a Master of Science degree in 1981, then received a research fellowship at the M.I.T. Center for Advanced Visual Studies to investigate the sociological and artistic implications of communications technologies.

As a consultant to the consumer electronics industry, Mr. Kantor is responsible for the development of numerous loudspeaker and electronics products and is a frequent contributor to the popular audio press. He joined Teledyne Acoustic Research in 1984 as director of research and development. At AR he developed the MGC-1 loudspeaker and the SRC audio remote-control system and administered the company's electronics and acoustics research efforts.

Mr. Kantor now serves as vice president of engineering at MultiVision Products, Inc. in San Jose, California, and is founder and president of Product Design and Evaluation Services, Inc., a San Francisco-based consumer electronics consulting firm. He is a member of the Audio Engineering Society.