Microphones*

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All types of microphones are discussed and the functioning of their transducer elements is explained.

0 INTRODUCTION

A microphone is an electroacoustic device containing a transducer, which is actuated by sound waves and delivers essentially equivalent electric waves [1]. An example of a transducer actuated by sound waves which fails to conform to this definition is the Rayleigh Disc, which converts the energy of sound waves into mechanical torque [2].

The classes of microphones are pressure, pressure gradient (velocity), combination pressure and pressure gradient, and wave interference. The electrical response of a pressure microphone results from pressure variations in the air. The directional (polar) pickup pattern is omnidirectional (nondirectional) because sound pressure is a scalar quantity, which possesses magnitude but no direction. The electrical response of a velocity microphone results from variations in the particle velocity of the air. The polar pattern is bidirectional (cosine or figure of eight) because particle velocity is a vector quantity, which possesses magnitude and direction. The electrical response of the combination pressure and pressure-gradient microphone is also proportional to the particle velocity. The polar pattern may be cardioid, hypercardioid, or similar cosine-function limaçon shape, and may be fixed or adjustable.

A particular class of microphones may include one of the following types of transducers: carbon, ceramic, condenser, moving coil, inductor, ribbon, magnetic, electronic, or semiconductor.

The functioning of various types of microphones is described in this paper by reference to the equivalent circuits of the acoustical and mechanical systems. The mechanical equivalent circuit is considered, for simplicity, when the discussion involves mathematical equations. In other instances, the discussion omits mathematics, and the acoustical network affords the clearest illustration of operating principles. Table 4.3 in Olson [3, pp. 86–87] lists analogous electrical, mechanical and acoustical quantities with the pertinent units.

1 PRESSURE MICROPHONES

1.1 Carbon Microphone

A carbon microphone depends for its operation on the variation of resistance of carbon contacts. The high sensitivity of this microphone is due to the relay action of the carbon contacts. It is almost universally used in telephone communications. This is because the high sensitivity eliminates the need for audio amplification in a telephone set. Restricted frequency range, distortion, and carbon noise limit the application of the carbon microphone in other than voice communications applications.

A typical single-button carbon microphone and electric circuit are shown in Fig. 1. The carbon transducer consists of a contact cup filled with carbon granules, which are usually made from anthracite coal [1]. The granules make contact with the electrically conductive diaphragm via the contact button on the diaphragm. The diaphragm is frequently made from a thin sheet of aluminum alloy. The periodic displacement of the diaphragm causes a variation in mechanical pressure applied to the carbon granules. This results in a periodic variation in electric resistance from the diaphragm to

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[illegible]

[illegible] output [illegible]

$$E_o = \frac{eR_L}{(R_m + R_L) + (hx \sin \omega t)} \quad (1)$$

where

e = dc voltage of bias source
h = constant of carbon element, ohms per centimeter
x = amplitude of diaphragm, centimeters
ω = $2\pi f$
f = frequency, hertz.

The useful audio output is, of course, the ac component of E_o. Eq. (1) may be expanded [3, p. 248] to show that the ac component consists of harmonics at f, $2f$, . . . , which means that the carbon transducer has intrinsic distortion. For a limited frequency range of reproduction, the distortion is not objectionable.

The large second-harmonic distortion component may be eliminated by use of two carbon buttons in push-pull. The double-button microphone is described in [3, pp. 251–253]. It was used in the 1920s for broadcasting, but was replaced by condenser, ribbon, and dynamic microphones. Although the double-button microphone has a wide-range frequency response and low distortion, it and the single-button types suffer from carbon compaction and carbon noise. These effects mean that the signal-to-noise ratio or dynamic range of the microphone is variable. Repeatability of frequency response, sensitivity, and noise measurements of carbon microphones is very poor.

For improved performance in telephone and speech communications, carbon microphones are being replaced by dynamic, magnetic, and electret condenser microphones, which have built-in amplifiers. These amplifiers are powered by the direct current normally provided by the communications equipment for carbon microphones. These "carbon replacements" may offer noise-canceling features as well as improved frequency response and low distortion and noise. They are offered as replacement cartridges for telephone handsets, in replacement handsets, in hand-held microphones, and in headsets.

1.2 Piezoelectric Microphone

The piezoelectric microphone contains a transducer element which generates a voltage when mechanically deformed. The voltage is proportional to the displacement in the frequency range below the resonance of the element. Rochelle salt crystals were used prior to 1960, but were sensitive to humidity and heat. Newer ceramic materials such as barium titanate and lead zirconate titanate are more resistant to environmental extremes and have replaced the Rochelle salt cystals. There are two general classifications of ceramic microphones: direct actuated and diaphragm actuated. Directly actuated transducers consist of stacked arrays [illegible] or "sound cells." These are now obsolete, and are described in [3, pp. 258–260], where it is also reported that a directly actuated microphone was constructed with a barium titanate element, but the sensitivity was low.

Fig. 2 shows the most common construction in use today for a ceramic microphone. The element is mounted as a cantilever and actuated by the diaphragm via the drive pin. The diaphragm is frequently made from thin aluminum sheet, although paper or polyester film may also be used. The impedance of the ceramic microphone is capacitative, on the order of 500–1000 pF. This permits use of a short length of cable with only a small loss in output level. The advantage of the ceramic microphone is that the output voltage is sufficient to drive a high-impedance input of an amplifier directly. The frequency response (with a very high input resistance) is uniform from a very low frequency up to the transducer resonance, which may be situated at 10 000 Hz or higher. The sensitivity and the frequency response are stable with time and over a wide range of temperature and humidity. The cost is relatively low. Therefore the ceramic microphone was widely used with tube-type home tape recorders and low-cost communications equipment. With the advent of solid-state equipment, low-impedance microphones are needed, and the ceramic microphone has been replaced by inexpensive moving-coil (dynamic) microphones or electret condenser microphones. They have integral field-effect transistor (FET) preamplifiers which convert their output to low impedance.

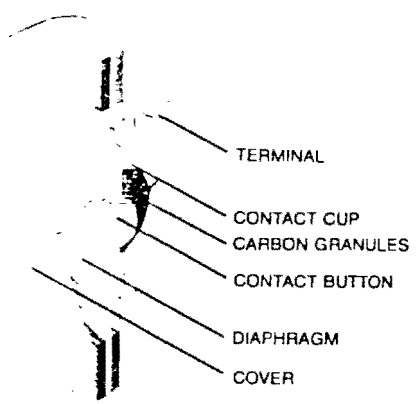


Fig. 1. Carbon microphone and electric circuit. (Courtesy of Shure Brothers, Inc.)

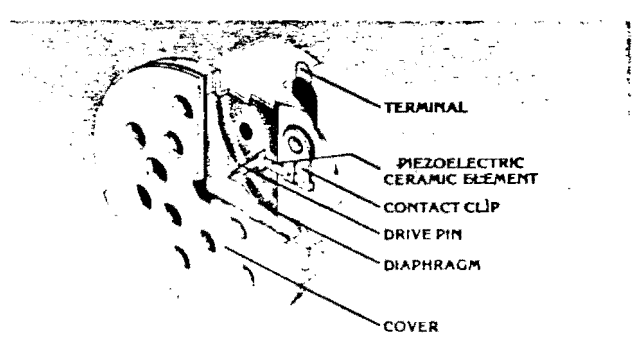


Fig. 2. Ceramic microphone. (Courtesy of Shure Brothers, Inc.)

A wide frequency range [illegible] microphone has been developed for hearing aids [4]. The novel construction includes a thick-film preamplifier which lowers the impedance of the microphone so that noise pickup in the cable is reduced, and the microphone impedance is suitable for driving a solid-state amplifier. More recently this microphone has been superseded by an electret unit with integral preamplifier with the same very small size [5].

A recent development is the piezoelectric diaphragm transducer. A thick or thin film of the polymer polyvinylidenefluoride (PVF_2) may be processed to form a piezoelectric element. Similar to the ceramic element, it must be provided with plated-on output terminals. There is much in the current literature about the application of PVF_2 in underwater sound. Joscelyn et al. [6] describe a small noise-canceling (pressure-gradient) microphone employing a PVF_2 diaphragm which is partially plated with nickel-chromium. The diaphragm is tensioned accurately by a device which is the subject of the patent. This is necessary to raise the diaphragm resonance to a high frequency, similar to a ceramic element.

1.3 Electrostatic (Condenser) Microphones

1.3.1 Condenser Microphone Operating Principles

A condenser microphone depends for its operation on variations in its internal capacitance. Fig. 3 shows the capsule of an omnidirectional pressure-sensing condenser microphone [7]. Condenser microphones are divided into two classes: externally polarized (air condenser) or prepolarized (electret condenser). The function of the polarizing voltage, or its equivalent, is to translate the diaphragm motion into a linearly related audio output voltage, which is amplified by a very-high-impedance FET or tube preamplifier, which must be located close to the capsule. Alternately, the capacitance variation may be used to frequency modulate an RF oscillator, but this scheme will not be discussed.

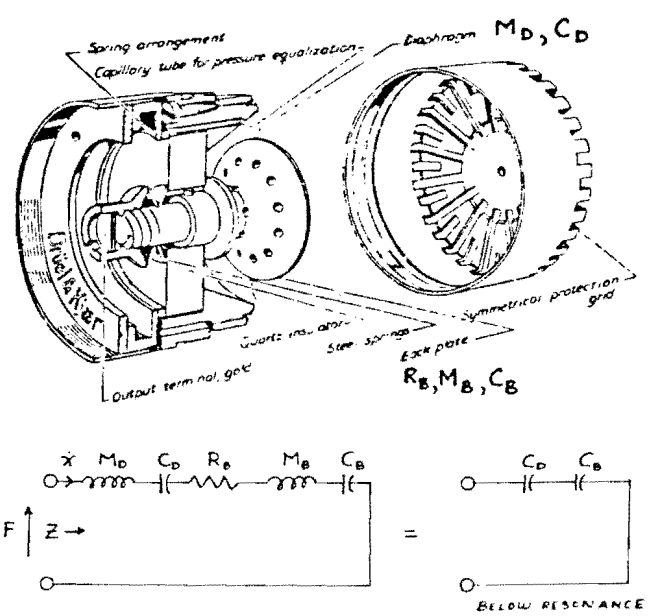


Fig. 3. Condenser pressure microphone and mechanical network. (From Rasmussen [7].)

The diaphragm of this microphone is a thin membrane of nickel which is spaced about 0.001 in (25 μm) from the back plate. Since the electroacoustical sensitivity is inversely proportional [Eq. (4)] to the spacing d, special measures must be taken to prevent this distance from changing due to temperature. The laboratory-grade microphone of Fig. 3 is almost entirely made of nickel and nickel alloys and has nearly constant sensitivity from 20 to 150°C.

The performance may be determined by consideration of the mechanical network (Fig. 3). The resonance is placed at the high end of the usable frequency range. The back plate air load includes mass M_B, compliance C_B, and resistance R_B. M_B and C_B plus the diaphragm mass M_D and compliance C_D determine the resonance frequency. R_B provides damping of the resonance. Below resonance frequency, the microphone is stiffness controlled (reciprocal of compliance) and only C_D and C_B appear in the circuit.

The open-circuit output voltage E is given by [3, pp. 253–257], [8]:

$$E = \frac{E_0}{d} x, \qquad x = \frac{\dot{x}}{j\omega} \tag{2}$$

where

E_0 = polarizing voltage (or equivalent voltage for electrets)
d = spacing from diaphragm to back plate, meters
x = diaphragm displacement, meters
$\dot{x}$ = diaphragm velocity, meters per second
ω = $2\pi f$
f = frequency, hertz.

The velocity is given by

$$\dot{x} = \frac{F}{Z} = \frac{PA}{(1/j\omega)(1/C_D + 1/C_M)} \tag{3}$$

where

F = force on diaphragm, newtons
P = sound pressure on diaphragm, newtons per square meter
A = area of diaphragm, square meters
Z = mechanical impedance of system, mechanical ohms.

The output voltage is obtained by combining Eqs. (2) and (3),

$$E = \frac{E_0 PA}{d(1/C_D + 1/C_B)} . \tag{4}$$

This means that, below resonance, the response is independent of frequency.

The polarization field strength for most condenser

[illegible] es, independent of the [illegible], is [illegible] order of 100 000 V/cm [9], so [illegible] the slightest [illegible] contamination between diaphragm and back plate will cause impulsive noise due to arcing. Microphones used in corrosive environments may develop pinholes in the diaphragm, and the resulting corrosion behind the diaphragm eventually may short-circuit the transducer. Normally, impulsive noise is caused by humidity, which can be eliminated by desiccation. Fredericksen et al. [9] recommend the use of foam windscreens for protection in damp or corrosive environments.

1.3.2 Electret Microphone

The simplest type of electret microphone is the charged diaphragm type. This is illustrated in Fig. 4. The spacing between diaphragm and back plate is exaggerated for clarity. Fig. 5 shows a schematic of the foil electret with the electric charge distribution illustrated. The electret foil is selected as a compromise between good electret properties and good mechanical properties as a diaphragm. Polymer materials such as polyacrylonitrile, polycarbonate, and some fluoric resins are examples of suitable plastic films used as electret diaphragms.

There are several methods of making an electret, and exact details are kept as trade secrets by the manufacturers. Typically, one side of the plastic film is coated by vacuum sputtering a conductive metal such as aluminum, gold, or nickel. The thickness of the coating is about 500 Å (50 nm). The film is then heated and charged with a high dc potential, with the electret-forming electrode facing the nonconductive side of the film [10]. A well-designed electret capsule will retain its charge and exhibit nearly constant sensitivity for 10 years, and it is predicted that it will take 30 to 100 years before the sensitivity is reduced by 3 dB.

These plastic foil electrets generally will not stand the tension required to obtain the high resonant frequencies commonly employed in externally polarized microphones. One solution is to reduce tension and support the diaphragm at many points by means of a grooved back plate (Fig. 6). This and other schemes used to increase stiffness lead to short-term instability [9].

Therefore the charged diaphragm electret generally does not possess the extended high-frequency response [illegible] condenser microphone. Its great advantage is that it can be made very cheaply by automated manufacturing methods.

An improved form of electret transducer is the "back electret" or charged back plate design [9]–[11]. Fig. 7 shows a simplified cross section of a typical design. (Dimensions are exaggerated for clarity. This is a pressure-gradient microphone, to be discussed later on.) The diaphragm is a polyester film such as Mylar,* approximately 0.0002 in (5 μm) thick. This is an ideal material and thickness for a diaphragm. The diaphragm is coated on one or both sides with a thick film of gold or other metal. The electret is made of a fluoric film such as Teflon,* which must be at least 0.001 in (25 μm) thick to form a stable electret. This electret is placed on the back plate, which must have a conducting surface to form the "high" output terminal. The electret element is charged similarly to the charged diaphragm electret. Since the electret does not function as a diaphragm, the material and thickness are chosen as optimum for high sensitivity and stability. The diaphragm to back plate (electret) spacing is the same as for the air condenser, approximately 0.001 in (25 μm). The equivalent polarization potential is 100–200 V, which

* Teflon and Mylar are trademarks of E. I. DuPont de Nemours and Co., Inc.

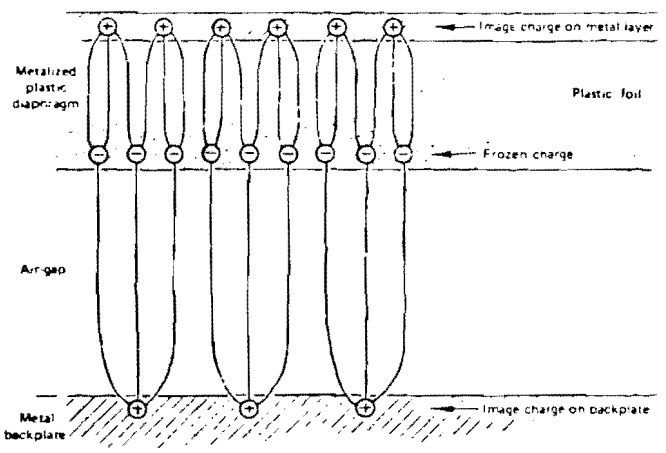


Fig. 5. Positions of charges for space charge electret when electret is an integral part of the diaphragm. Frozen charge and charge on back plate produce the field in the air gap that is necessary for microphone operation. (From Fredericksen et al. [9].)

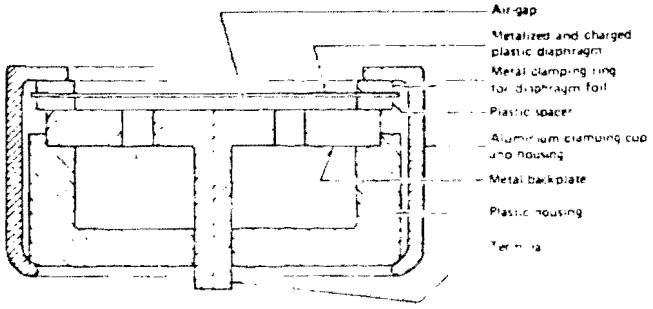


Fig. 4. Typical design of electret capsule with charged foil diaphragm. (From Fredericksen et al. [9].)

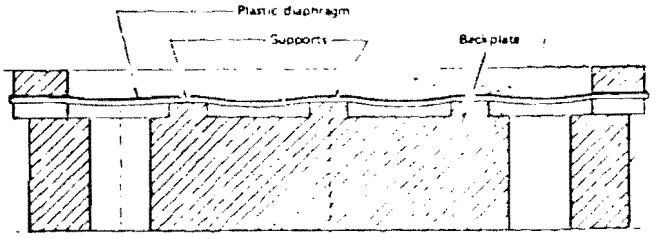


Fig. 6. Principle used by some manufacturers to obtain sufficiently high resonance frequency of plastic diaphragms having low creep stability. (From Fredericksen et al. [9].)

[illegible] the same [illegible] used in [illegible] microphones.

A measuring microphone must possess exceptional stability and resistance to corrosive environments. The back electret concept permits a metal diaphragm to be used. The laboratory-grade microphone developed by Rasmussen is identical to the metal diaphragm air condenser of Fig. 3, except that an electret is placed on the back plate.

Thus the back electret microphone is essentially identical to the air condenser save for the electret element on the back plate. This means that the capsule is actually more costly to make than an air condenser. This cost is offset by the savings involved in the omission of a high-voltage power supply for polarization.

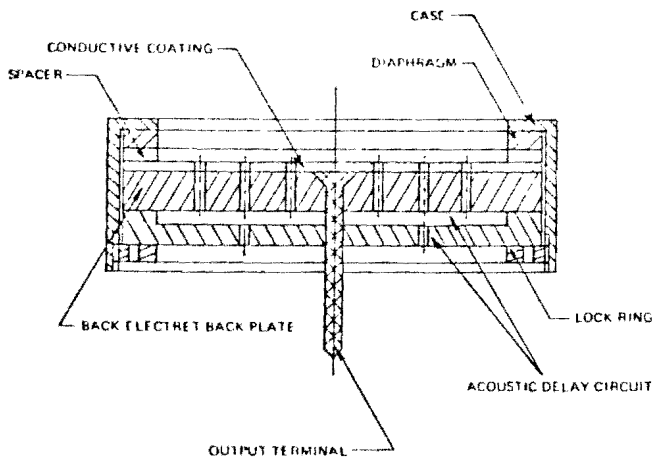


Fig. 7. Back electret capsule. (From Kubota [10].)

1.3.3 Condenser Microphone Frequency Response

This discussion, although about a condenser microphone, applies in principle to all pressure microphones.

Fig. 8 shows the frequency response curves of the Western Electric 640-AA condenser microphone. This is an ANSI type L laboratory microphone having a nominal 1-in (25-mm) diameter. It is similar to the Bruel & Kjaer microphone of Fig. 3, except that the latter is a newer design, which eliminates the cavity in front of the diaphragm. The 640-AA is illustrated in Beranek [13]. It was the preferred calibration standard at the National Bureau of Standards for many years.

The "pressure" response is the frequency response to a constant sound pressure on the diaphragm. This response can be very precisely measured by NBS by the closed-coupler reciprocity method [2]. This curve shows that the diaphragm resonance is approximately critically damped. The difference between the pressure response and the perpendicular incidence response (called the "free-field correction") depends only on the geometry of the microphone and is carefully measured on a typical microphone. The perpendicular incidence response for a particular microphone is computed by adding the free-field correction to the pressure response. The parallel incidence response is similarly computed. Not shown is the random incidence response, which is the response to randomly directed sound, such as that in a reverberation chamber. The random incidence response follows the general trend of the pressure response. The 640-AA microphone has essentially flat pressure or random incidence response (to 10 000 Hz), which is called for in ANSI standards for laboratory

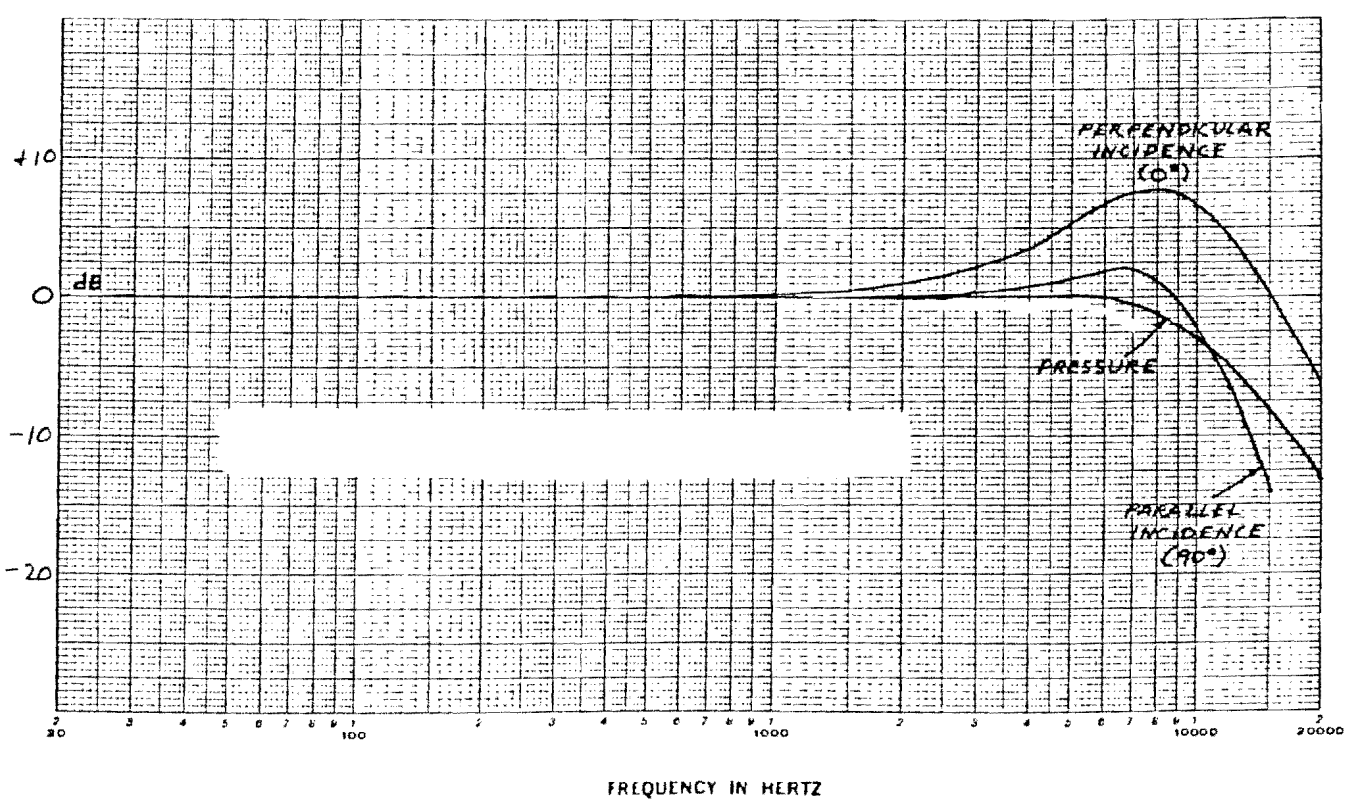


Fig. 8. Frequency responses of Western Electric 640-AA microphone. (After [12].)

microphones and sound level meters. [illegible] international standards require these microphones to have a flat response to sounds of perpendicular incidence ("flat for free field"). The response can be varied by changing the damping adjustment or the configuration of the protective grid. Therefore most manufacturers today offer both versions to satisfy both standards. For the calibration of sound sources used in testing microphones, the IEC type is universally used. The free-field correction, being a function of diameter, vanishes (below 20 000 Hz) as the microphone diameter becomes smaller than 0.50 in (12.5 mm).

Pressure microphones used for sound and communications systems are generally larger than 1 in (25 mm) in diameter, but need only have speech range response (200–6300 Hz). These may have moving-coil, magnetic, or ceramic transducers. They are generally designed to have a rising axial response characteristic, which means that the off-axis and pressure responses tend to be flat. If the axial response if flattened, the off-axis response is rolled off, speech sounds muffled, and system intelligibility is reduced. In contrast, microphones smaller than 1 in (25 mm) in diameter do not suffer when designed for flat axial response.

1.3.4 Boundary Microphone

Recently Long and Wickersham patented [14] what they call the "pressure recording process" and a device that positions a conventional microphone very close to a plane surface such as a floor. This has given rise to a number of products which basically function as shown in Fig. 9. A miniature electret microphone is spaced about (0.04 in) (1 mm) from a large reflecting plane. A conventional microphone, which is situated above the floor, receives the direct sound wave plus a reflected wave from the floor. It suffers from dips in frequency response, at the frequency where the spacing is one-quarter wavelength, and its harmonics, as the reflected sound wave interferes with the direct sound wave. When the spacing is reduced to about (0.04 in) (1 mm), the null frequency moves far above the audible range. Therefore in actual use, the boundary microphone does not suffer from the "comb filter" series of dips in frequency response. The system has, in essence, a directional gain of 6 dB due to pressure doubling at the reflecting plane; for example, the reflected wave is in phase and adds to the amplitude of the direct wave. This results in a hemispheric pickup pattern where the 90° response (direction parallel to the plane) is 6 dB down with respect to the 0° or perpendicular incidence response. Complete test data are reported in Sank [15].

A suitable transducer for the boundary microphone of Fig. 9 is the subminiature electret microphone developed by Killion and Carlson [5]. It incorporates an integral solid-state preamplifier. It is ideal for a floor-mounted microphone because it has extremely low vibration sensitivity. This type of microphone element is molded into a plastic housing which is fastened to a small metal plate in the commercial product described [illegible] ated acoustical performance, the small plate must, of course, be placed on a much larger plane surface.

In many applications it is desirable for a boundary microphone to be more directional. For instance, the rear portion of the hemispherical pattern may pick up audience noise when the microphone is mounted on a stage floor. Bullock and Woodard [16] have described a directional boundary microphone where an electret element with cardioid directivity is mounted close to a surface, with the principal pickup axis parallel to the surface.

1.3.5 Probe Microphone

For sound pressure measurements in very small spaces, a condenser microphone may be fitted with a small-diameter probe tube, as shown in Olson [3]. This introduces a high-frequency response rolloff plus dips and peaks. The latter may be reduced by acoustic damping in the tube. The damping may be porous polyurethane foam or similar material, or the tube may be packed with pieces of music wire. Alternately a very small capillary tube may be used as a probe which has very high acoustic resistance due to the small diameter. The need for a probe microphone in measurements is less today because condenser microphones as small as 0.125 in (3 mm) are available.

Commercial magnetic microphones have been fitted with small probe tubes for convenient use on lightweight telephone and radio communications headsets that are mounted on the ear or on eyeglass frames. Ceramic or dynamic microphones may be fitted with plastic probe tubes for diagnostic testing of machinery.

The term "probe microphone" has also been applied to pressure microphones which are small in diameter but relatively long.

1.4 Electrodynamic Microphones

1.4.1 Moving-Coil (Dynamic) Microphone

A cross section of a moving-coil microphone cartridge is shown in Fig. 10, and the complete microphone assembly in Fig. 11 [17]. The diaphragm, which is made of Mylar polyester film 0.00035 inches (9 μm) thick,

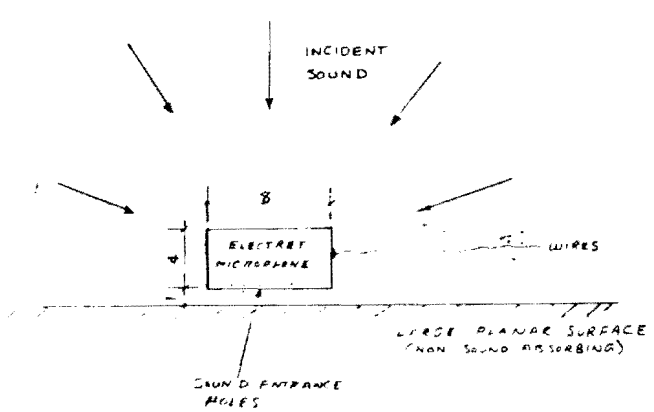


Fig. 9. Boundary microphone principle. Dimensions in millimeters.

is glued to a voice coil which [illegible] air gap. The flux density is 10 000 G (1 Wb/m²). The self-supporting coil is wound with four layers of #50 AWG copper wire, which results in a dc resistance of 220 Ω. The ac impedance of 220–250 Ω is suitable for [illegible] impedance microphone inputs of 150–600 Ω. Older microphone coils were on the order of 5–20 Ω resistance and required a stepup matching transformer in the microphone case. Thus the modern moving-coil microphone will drive standard bipolar

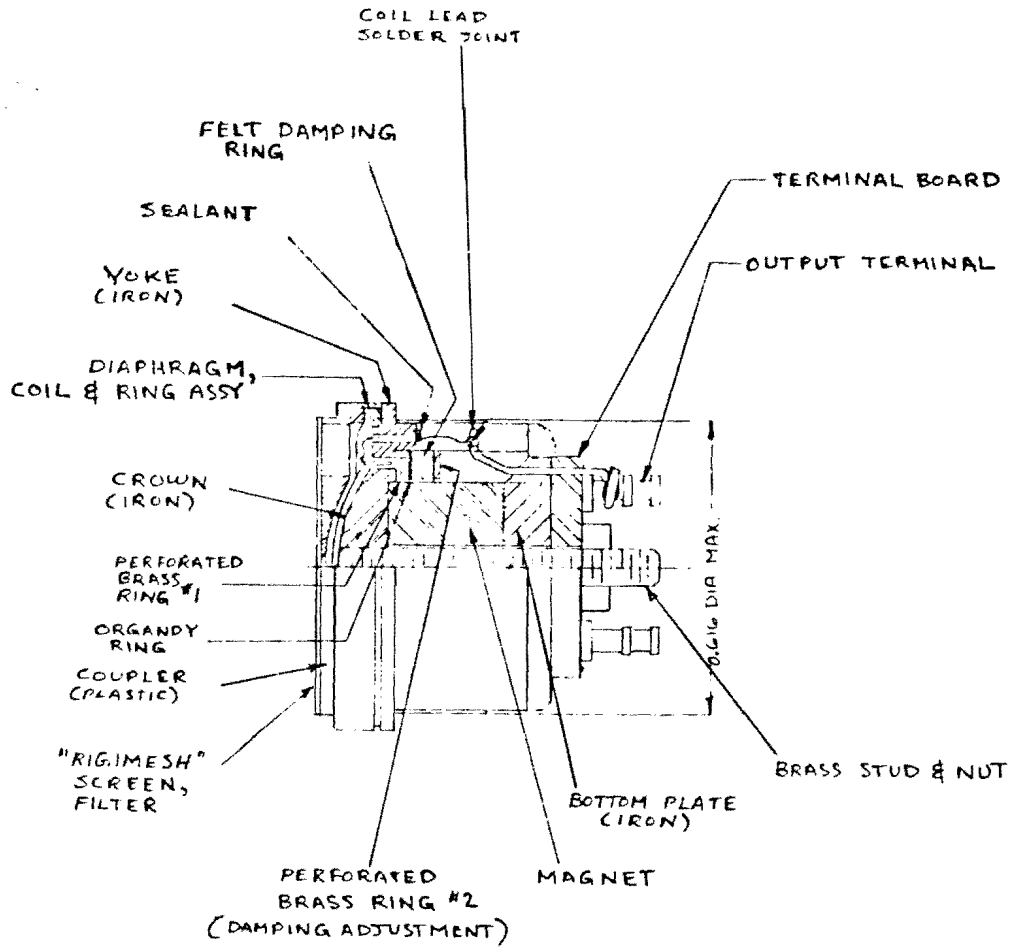


Fig. 10. Dynamic moving-coil pressure microphone cartridge (RCA type BK-16A).

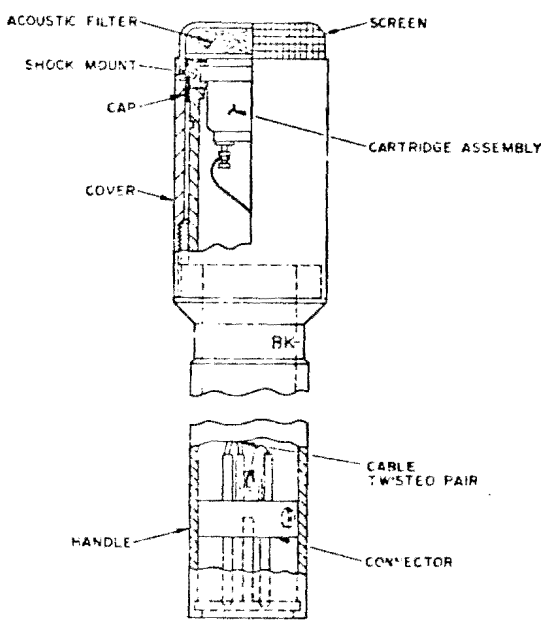


Fig. 11. Dynamic moving-coil microphone (RCA type BK-16A).

integrated circuits directly. The coupler (Fig. 10) fits closely to the diaphragm to provide mechanical protection without frequency discrimination. The cartridge is shockmounted in the case of Fig. 11, which includes a foam filter screen for dirt and breath "pop" protection. (The author developed this microphone; the parameter values are from memory.)

The voltage induced in the voice coil is given by

$$E = Bl\dot{x} \tag{5}$$

where

E = open-circuit voltage, volts
B = air gap flux density, webers per square meter
l = length of conductor in air gap, meters
$\dot{x}$ = velocity of coil, meters per second.

This shows that the microphone will have uniform E with respect to frequency if the coil velocity is uniform with frequency. The mechanical resonance of the coil and diaphragm (measured in a vacuum) is about 800 Hz. If not well damped, the coil velocity will peak at

800 Hz. This resonance is he[illegible] acoustic resistance of the [illegible] mping ring [illegible] the resulting response is uniform from 40 to 20 000 Hz. The coil motion is then said to be resistance controlled. The case volume is sufficient to support this extended low-frequency response. In older microphones, it was necessary to add a vent tube inside the case, possibly as long as 4 in (10 cm). This provided a sort of bass-reflex action where the mass of the air in the tube resonates with the compliance of the air in the case. This resulted in extended low-frequency response, and was known as a Thuras tube, being incorporated in the famous Western Electric "eight-ball" microphone, which was developed in the 1930s by Wente and Thuras [2].

1.4.2 Inductor Microphone

Olson [3, p. 263] shows the RCA design, now obsolete, where a straight metal conductor is molded into a plastic diaphragm which positions the conductor in a magnetic air gap. These microphones were used in broadcasting and sound systems for many years, primarily for speech reproduction. This operated according to the acoustical principles of the moving-coil dynamic microphone described in the preceding section.

A new printed ribbon microphone has been developed [18]. The moving system consists of a flat polyester film diaphragm with a printed-on spiral aluminum ribbon. It is different from the linear inductor microphone above because the capsule operates according to the principle of the ribbon velocity microphone. The manufacturer states that the back of the capsule may be enclosed by a damped cavity to form an omnidirectional microphone. However, they do not presently offer a pressure microphone version, and [18] does not mention it. Therefore we choose to classify the printed ribbon microphone as a pressure-gradient type (see Sec. 2).

1.4.3 Ribbon Pressure Microphone

The ribbon transducer is discussed in Sec. 2 because it is a pressure-gradient (particle velocity-sensing) device. It is included in this section because an omnidirectional (pressure-sensing) ribbon microphone was developed by Olson 35 years ago [3, p. 268] and is shown in Fig. 12. The back of the ribbon transducer, which would be open to the atmosphere in a velocity (bidirectional) microphone, is terminated in an acoustic labyrinth. The labyrinth, to save space, consists of a cylinder which has many holes drilled or cast in the axial direction. Slots are cut or cast between holes, thus forming a folded pipe which is much longer than the microphone itself. This damped pipe must present a constant acoustical resistance over the useful frequency range of the ribbon, so it is lightly packed with tufts of felt or ozite. The front side of the ribbon is terminated in a small pipe to form an unobtrusive interview-type microphone. The end of the pipe is flared to a horn shape which accentuates the response above 5000 Hz. This microphone was used for many years in television broadcasting, but was replaced by dynamic moving coil microphones.

1.5 Magnetic Microphone

A magnetic microphone is shown in Fig. 13 and consists of a diaphragm, drive pin, and magnetic assembly. The magnetic assembly includes a magnet, pole pieces, coil, and moving armature. The motion of the armature results in a corresponding variation in magnetic flux through the coil. This flux variation induces a voltage in the coil in accordance with Faraday's law:

$$E = -N\frac{d\phi}{dt} \tag{6}$$

where

E = open-circuit voltage, volts
N = number of turns in coil
ϕ = flux in coil, webers

Olson [3, pp. 271–275] shows that $d\phi/dt$ is proportional to $\dot{x}$, the velocity of the armature. Similar to the moving coil, flat frequency response requires that the

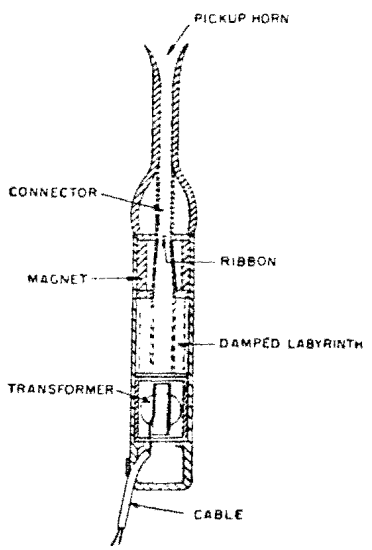


Fig. 12. Cross section of ribbon-type pressure microphone. (From Olson [3, pp. 271–275].)

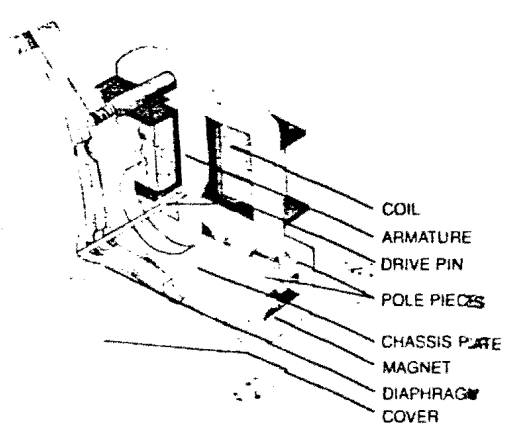


Fig. 13. M[illegible] microphone. (Courtesy of Shure Brothers, Inc.)

velocity be resistance controlled. Therefore the back of the cartridge of Fig. 13 must be enclosed and the cavity damped with acoustical resistance material.

1.6 Vacuum Tube and Solid-State Electronic Microphones

1.6.1 Vacuum Tube Microphone

The vacuum tube microphone (Fig. 14) is an amplitude-sensing transducer which consists of a diaphragm and drive pin enclosed in a housing. It is a special vacuum tube, called the mechanoelectronic transducer. The tube has a movable anode which modulates the flow of electrons. Olson [3, pp. 271–275] shows the equations for the amplitude with respect to frequency. Due to the complicated mechanical network, uniform amplitude of diaphragm motion and flat frequency response seem to have been difficult to obtain. The microphone of Fig. 14 was never developed as a commercial product.

1.6.2 Transistor and Semiconductor Microphones

An experimental transistor microphone is described in Sikorski [19] and is shown in Fig. 15. The sapphire indenter is fastened to the diaphragm and applies stress to the emitter region of the transistor. The output is taken from the collector, with suitable dc biasing of the transistor. The reasons for the stress sensitivity of transistors is not easily explained. The frequency response of the microphone was very nonuniform. The output was adequate to drive an amplifier, but the signal-to-noise ratio was only about 40 dB. This microphone was not commercialized.

A semiconductor microphone was developed by Grover and Wood [20] and produced by Euphonics Corporation as a hand-held, close-talking communications microphone. The frequency response is smooth from 100 to 1000 Hz, then peaks at 2500 Hz. This microphone appears to have been intended as a carbon microphone replacement. The semiconductor element was a twister silicon transducer element which was supplied by Endevco Corp. Dc bias was applied to the element, which modulated the current flow. This is said to be a piezoresistive microphone.

A tunnel diode microphone was developed by Rogers et al. [21] and is shown in Fig. 16. This microphone functioned in two ways. First, it functioned as a piezoresistive element where the applied stress modulates the applied direct bias current. Second, by adding some inductors and capacitors, the diode was made to oscillate at about 30 mHz with FM audio modulation. However, the carrier frequency was subject to much drift.

The frequency responses of this microphone were wide ranging, but there were many ragged peaks in the 1000–5000-Hz region. The signal-to-noise ratio was about 40 dB. This microphone has not been commercialized.

1.6.3 Integrated-Circuit Microphone

The piezoresistive microphone developed by Sank [22] is shown in Fig. 17. The transducer is a directly actuated strain gauge bridge deposited on a silicon chip. The chip was originally intended as a pressure transducer. This microphone is different from other solid-state microphones in that no diaphragm is used. As a result of this simple construction, it was possible to obtain a flat frequency response from 20 to 20 000 Hz, comparable to a laboratory condenser microphone of similar size (0.3 in, 7.6 mm). The signal-to-noise ratio was not sufficient for even a close-talking microphone, but was satisfactory for the intended application, which was headphone measurements. Presumably the maximum input sound pressure level capability was very high, but experiments along this line were not conducted. Development work was discontinued when the headphone measurements were completed. Presumably

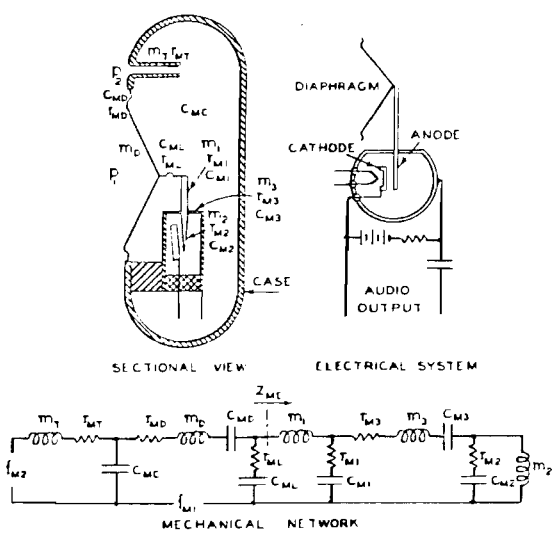


Fig. 14. Vacuum tube microphone. (From Olson [3, pp. 271–275].)

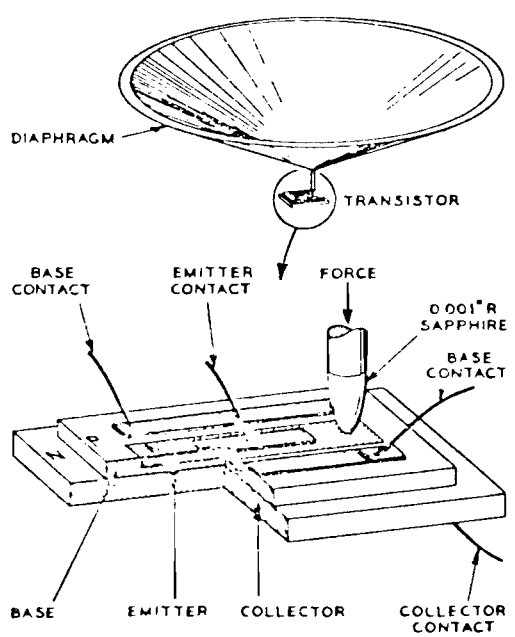


Fig. 15. Transistor microphone. (From Sikorski [19].)

[illegible] chip con[illegible] optimized for acoustic sensitivity. However, National Semiconductor, the manufacturer of the transducer, sold the product line, and this was another factor which has slowed the development work.

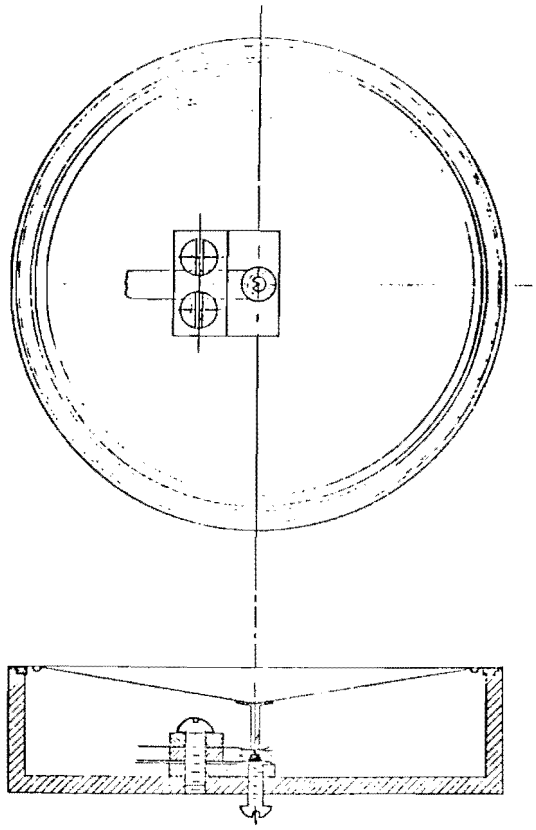


Fig. 16. Direct-contact tunnel diode microphone assembly. (From Rogers et al. [21].)

[illegible] that the military showed interest in the transducer because it has a symmetrical, low-impedance, balanced electrical output. This is important in military aircraft which have much electromagnetic and radio-frequency interference. They were opposed to electrets because of the high-impedance unbalanced circuitry involved, plus potential humidity and temperature problems. The silicon pressure transducers are designed to resist liquids and have a wide temperature range.

2 PRESSURE-GRADIENT (VELOCITY) MICROPHONES

2.1 Bidirectional Ribbon Microphone

A sectional view of a ribbon velocity microphone (RCA type BK-11A) developed by Sank and described by Olson [23] shown in Fig. 18. This microphone has an air gap 0.125 in (3.2 mm) wide with a flux density of 6500 G (0.65 Wb/m^2). The ribbon is made from pure aluminum foil weighing 0.56 mg/cm^2. This corresponds to a thickness of 0.000082 in (2 μm). The ribbon is 1.4 ins (36 mm) long and corrugated transversely, as shown. Magnetic fine-mesh steel screens are on both sides of the ribbon to provide resistance damping of the ribbon and dirt protection. The ribbon resonance is approximately 30 Hz. The ribbon is soldered to the clamp after assembly and tuning. Soldering has no effect on tuning when done properly. Without soldering, in several years the microphone impedance may rise and eventually result in an open circuit at the ribbon. The 0.2-Ω ribbon impedance is stepped up to 30/150/250 Ω by the transformer. The reactor and switch

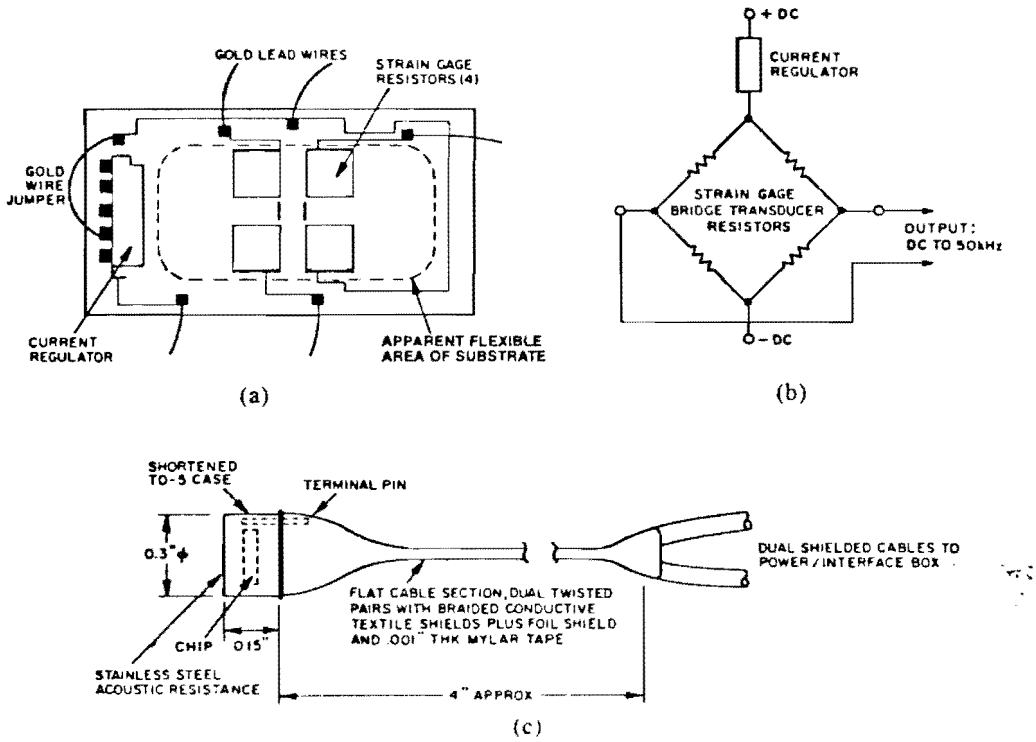


Fig. 17. Integrated-circuit microphone. (a) Simplified sketch of chip, approximately 0.08 by 0.15 in (2 by 3.8 mm). (b) Schematic of chip. (c) Details of microphone assembly (From Sank [22]).

provide low-frequency roll-off for the proximity effect. The frequency response is ± 2 dB, 30 Hz to 10 000 Hz. Figure 18 shows an *LR* equalizer which provides about 3 dB boost at 10 000 Hz with corresponding reduction in sensitivity.

The elements of the complete equivalent mechanical circuit (Fig. 18) are R_L and M_L, the mechanical resistance and mass of the air load on the ribbon, imposed by the damping screens; M_R and C_R, the mass and compliance of the ribbon; and M_S and R_S, the mass and mechanical resistance of the slits formed by the ribbon to pole piece clearance, which is nominally 0.005 in (125 μm). Above resonance, the circuit is simplified as shown, and the ribbon velocity is given by

$$\dot{x} = \frac{(P_1 - P_2)A_R}{j\omega(M_R + M_L)} \tag{7}$$

where

$\dot{x}$	=	ribbon velocity, meters per second
$(P_1 - P_2)$	=	difference in sound pressure (pressure gradient) between two sides of ribbon, newtons per square meter
A_R	=	area of ribbon, square meters
M_R	=	mass of ribbon, kilograms
M_L	=	mass of the airload acting on ribbon, kilograms
ω	=	$2\pi f$
f	=	frequency, hertz.

The driving sound pressure gradient $(P_1 - P_2)$ at a given frequency is proportional to the size of the baffle formed by the magnet structure. The ribbon to pole piece clearance forms a "leak" which, if excessive, will reduce sensitivity. To maintain a constant ribbon velocity with mass control per Eq. (7), the pressure gradient must increase linearly with frequency. The open-circuit ribbon voltage is given by

$$E = Bl\dot{x} \tag{8}$$

where

E	=	open-circuit voltage, volts
B	=	air gap flux density, webers per square meter
l	=	length of ribbon, meters
$\dot{x}$	=	ribbon velocity, meters per second.

At zero frequency the pressure gradient is zero. At the frequency where the path length around the baffle, from the front to back of the ribbon, corresponds to one-half the sound wavelength, the pressure gradient departs from a linear characteristic to 65% of the value needed for a constant ribbon velocity. At the frequency where the path length equals one wavelength, the pressure gradient is zero. Fig. 19 shows the resulting E versus frequency for an ideal microphone, applicable to the region well above ribbon resonance. A practical microphone may have small ripples in response in the region just above resonance frequency, plus dips or peaks at high frequencies due to pole piece shape or transverse resonances of the ribbon.

Figure [illegible] shows how the figure-of-eight polar pattern becomes [illegible]ly distorted above the half-wavelength frequency (D equals the path length). Below this frequency, the patterns are essentially perfect cosines.

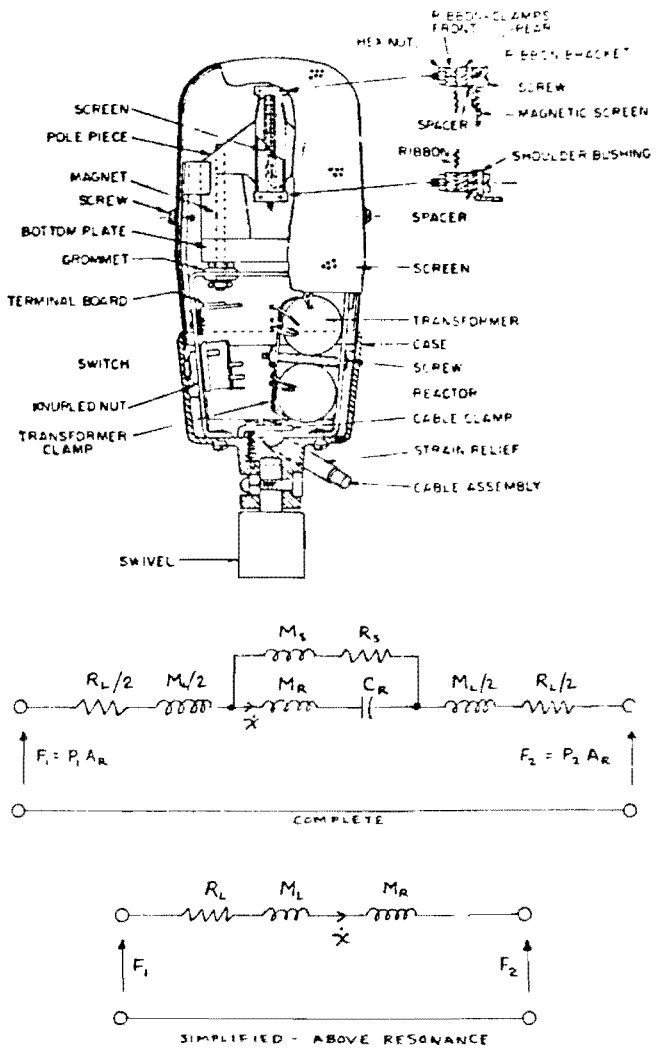


Fig. 18. Ribbon velocity microphone (RCA type BK-11A) and mechanical networks.

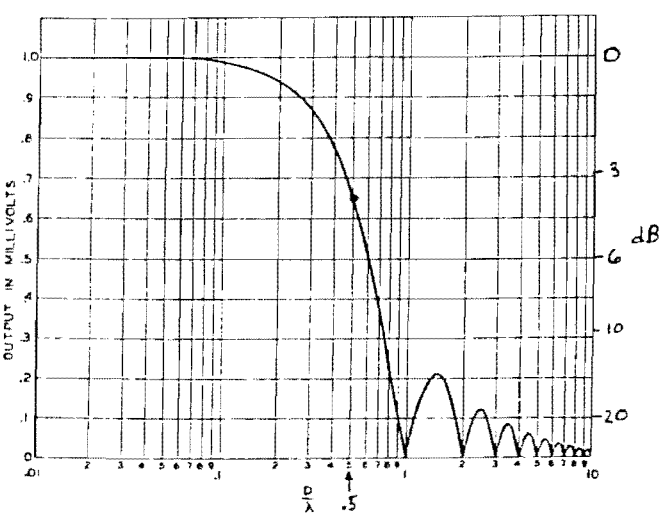


Fig. 19. Computed open-circuit voltage response frequency characteristic of pressure-gradient mass-controlled electrodynamic microphone. (From Olson [23].)

Olson describes a microphone built for use with loudspeakers that has essentially uniform response and directivity from 20 to 20 000 Hz. Olson notes that the pattern in the vertical plane at high frequencies shows some sharpening, but this is not a serious problem for pickup of sound sources in the horizontal plane. A pressure condenser microphone of analogous quality must be less than 0.5 in (12.5 mm) in diameter. Unfortunately, for sound reproduction purposes, the sensitivity of both of these is too low.

A compromise solution is found in the contemporary ribbon velocity microphone (Beyer M130) shown in Fig. 21. The head diameter is only 1.5 in (38 mm). The magnetic assembly is extremely small but efficient. The two ribbons are electrically in parallel and make use of most of the space and magnetic flux available in the air gap. The ribbons are corrugated longitudinally for most of their length, but a few conventional transverse corrugations are formed near the ends to provide compliance. This ribbon, while very difficult to make, can potentially solve several problems as compared to the conventional ribbons with transverse corrugations: (1) The rigid central portion resists twisting, sagging, [illegible] along the pole pieces. (2) With the more rigid ribbon, the pole piece to ribbon clearance may be reduced, thus increasing sensitivity. (3) The short length of transverse corrugations may reduce the need for laborious manual stretching and tuning, and may greatly reduce the downward drift of tuning with time. (4) The longitudinal corrugations may reduce or eliminate transverse resonances which produce small dips and peaks in frequency response above 8000 Hz. (5) The short length of the ribbon makes the polar pattern in the vertical plane more uniform with frequency.

How much sensitivity is adequate for an electrodynamic microphone? This is easy to calculate by first assuming that the microphone impedance is 250 Ω, resistive. 250 Ω is a handy value because the dBm sensitivity rating is equal *numerically* to the dBV rating. The dBm rating is the power output level in decibels with respect to 1 mW that would theoretically be obtained if the microphone were operated into a matched load with a sound pressure input of 1 Pa (94 dB SPL) (1 N/m^2). Similarly, the dBV rating is the open-circuit voltage of the microphone in decibels with respect to 1 V with a sound pressure input of 1 Pa. The latter rating corresponds to the real world, where microphones are operated into a relatively high impedance. Sank [24] discusses microphone ratings and measurements.

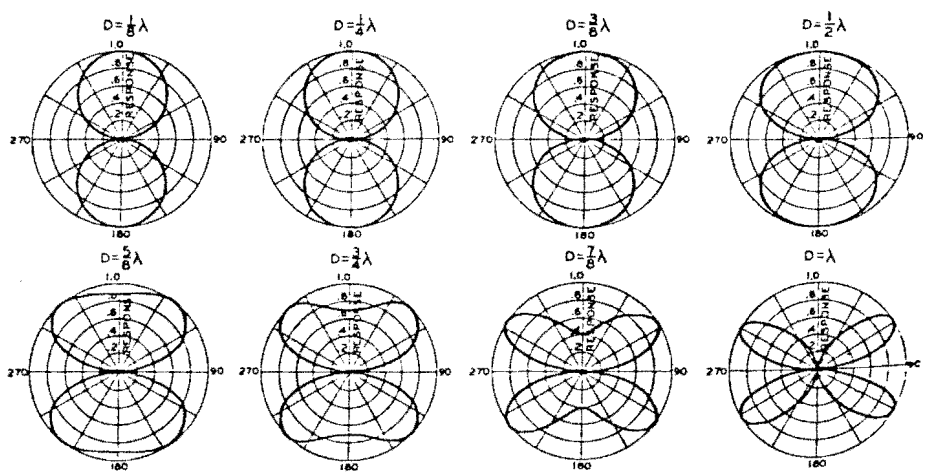


Fig. 20. Directional characteristics of pressure-gradient microphone as a function of dimensions and wavelength. The polar graph depicts output, in volts, as a function of angle, in degrees. The maximum response is arbitrarily chosen as unity. (From Olson [23].)

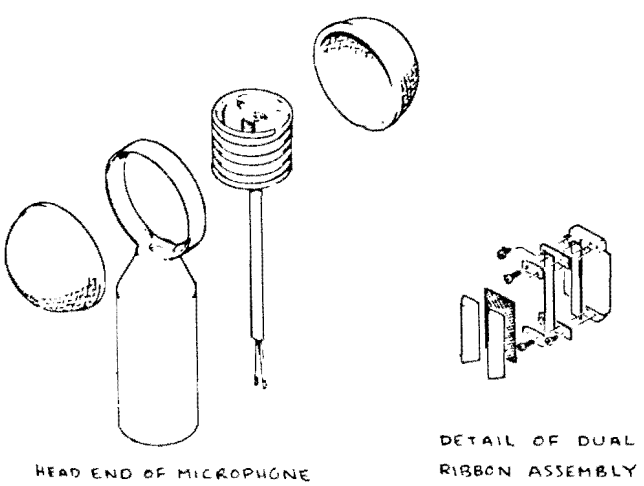


Fig. 21. Beyer M130 bidirectional dynamic ribbon microphone. (Courtesy of Beyer Dynamic Inc.)

The thermal noise of a 250-Ω resistor in a 15 000-Hz bandwidth is calculated by Sank [25] to be −132 dBV. A typical noise figure for a modern solid-state mixer is 4 dB, which means an equivalent input noise voltage of −128 dBV. Therefore for a 250-Ω electrodynamic microphone, the mixer noise exceeds the microphone noise. A good condenser microphone (Shure SM-81) has an *unweighted* equivalent noise level of 26 dB SPL, with the A-weighted value 16 dB. If we demand similar performance from an electrodynamic microphone, let −128 dBV equal the microphone output for a 26-dB SPL input. The output (sensitivity rating) at 1 Pa (94 dB) will therefore be −60 dBV.

Olson's ideal microphone had a sensitivity of −74 dBV/Pa, which is obviously much too low. The RCA BK-11A microphone has a sensitivity of −56 dB/Pa, which is more than adequate. The Beyer M130 sensitivity of −59 dBV/Pa is minimal but adequate.

Most ribbon microphones have low magnetic hum sensitivity because the ribbon circuit is easily designed to be "humbucking." Ribbon microphones have the lowest vibration sensitivity because the moving mass is very low. (The printed ribbon of the following section may have high vibration sensitivity because of the relatively massive diaphragm.) Wind sensitivity of all microphones, as Olson stated on many occasions, is "proportional to electroacoustical sensitivity," so ribbon microphones, contrary to popular belief, are not inherently wind sensitive. To the contrary, microphones such as the RCA BK-5B and Beyer M500 incorporate efficient blast filters. The latter microphone, with its accessory foam screen, resists "popping" by very close and loud vocalists. Most of the catastrophic ribbon failures observed by the author seem to have been caused by checking of microphones or lines with ohmmeters or continuity checkers. Connecting a ribbon microphone to a condenser microphone line with A-B powering can also produce the same effect: the ribbon is blasted out of the gap.

2.2 Printed Ribbon Microphone

A new type of inductor microphone has been developed which is called a "printed ribbon" type [18]. It is shown in Fig 22. The diaphragm is made of 0.0002-in (4-μm) polyester film upon which is printed a spiral ribbon of aluminum 0.0008 in (20 μm) thick. The unconventional magnetic structure includes two ring magnets in front of the diaphragm and two in the back. Like poles face each other so the magnetic lines of force lie parallel to the diaphragm. Thus axial motion of the diaphragm causes the ribbon to cut lines of force, which induces a voltage in the ribbon, according to Eq. (6). The magnetic structure is symmetrical on both sides of the diaphragm, so that the transducer capsule operates according to the principle of the velocity microphone (Sec. 2.1). This requires a mass controlled transducer with the resonance at the lower end of the useful frequency range. The printed ribbon diaphragm resonance is in the region of 50–100 Hz. The resonance cannot be as low as for a ribbon because of the relatively high stiffness of the diaphragm. Therefore the response of the printed ribbon microphone is somewhat limited at low frequencies. Bidirectional and unidirectional types are available, and the frequency responses are generally uniform from 70 to 15 000 Hz. Sensitivity of the bidirectional model is quite high, −52 dBV/Pa, but this value is somewhat inflated due to the 600-Ω impedance. These microphones are recommended for voice and pickup of individual musical instruments.

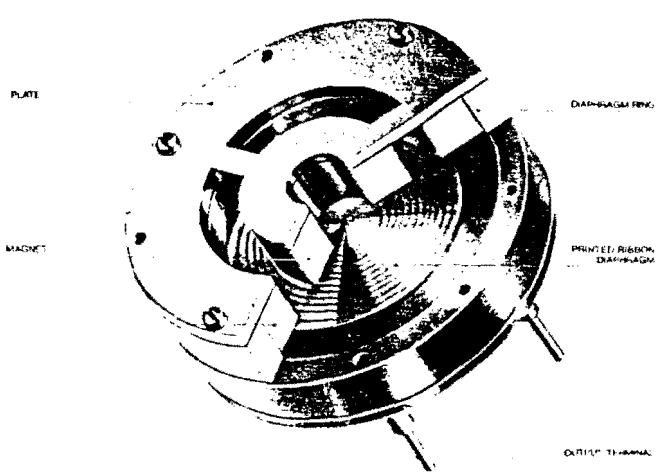


Fig. 22. Printed ribbon microphone capsule. (Courtesy of Fostex Corporation of America.)

3 COMBINATION PRESSURE AND PRESSURE-GRADIENT MICROPHONES

3.1 Unidirectional Microphone Operating Principles

3.1.1 Combining the Polar Patterns

Fig. 23 illustrates graphically how the outputs of a bidirectional and a nondirectional microphone transducer may be mixed to obtain three unidirectional polar patterns. Actually, there are an infinite number of unidirectional patterns which may be obtained. The three patterns shown are: hypercardioid, cardioid, and limaçon, from left to right. The energy responses to random sounds (such as room noise and reverberant sound) are also shown, relative to the nondirectional, which is assigned a value of unity. Note that the bidirectional and cardioid have exactly the same response, but the hypercardioid is superior to both of them in discrimination against random sound. Quite a few unidirectional microphones produced today are hypercardioids, but the cardioid remains the most popular. The limaçon is not as popular, and so to obtain this pattern, a microphone with variable directivity is needed. An alternate way to obtain a unidirectional pattern is by using a single transducer with an appropriate acoustical phase-shifting system. Some single-transducer microphones have a mechanically variable delay system so that the pattern can be varied from bidirectional to cardioid to nondirectional.

3.1.2 Frequency Response as a Function of Distance

The low-frequency response of the velocity microphone is accentuated when the distance between source and microphone is less than a wavelength. This happens to a lesser degree with the unidirectional microphone. Olson [3, pp. 293–297] shows the equations. Fig. 24 shows Olson's curves for the velocity and unidirectional microphones. If the curves for zero degrees are plotted to a decibel scale, it turns out that the slopes follow linear 6-dB per octave characteristics. The unidirectional curves exhibit a corner (+3 dB) frequency which is one octave higher than those of the velocity micro-

phone. The +3-dB frequencies rise one octave when the distance is halved. Therefore for each distance, a simple resistance capacitance rolloff equalizer can be designed to provide flat response. This so-called "proximity effect" pertains to all pressure-gradient (velocity) and combination pressure and pressure-gradient (unidirectional cardioid) microphones to the same degree. These characteristics are essentially invariant between models of microphones. The exception to these rules is the variable-distance unidirectional microphone (Sec. 3.4.6), which has a reduced proximity effect.

3.2 Dual-Element Unidirectional Microphones

3.2.1 *Dual-Ribbon Unidirectional Microphone*

The dual-ribbon unidirectional microphone (RCA type 77-B) was developed by Olson [3, p. 291] and is shown in Fig. 25. A common magnet structure is employed for both velocity and pressure sections. The ribbons for both sections are formed from one continuous ribbon. Therefore the air gap and ribbon dimensions and the flux density are identical for both sections. A very long folded pipe provides nearly constant

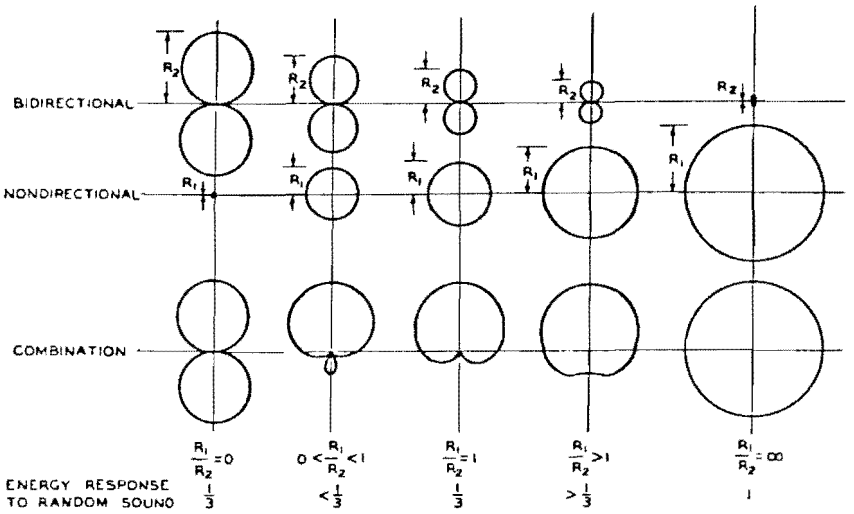


Fig. 23. Directional diagrams of various combinations of bidirectional and nondirectional microphones and energy response to random sounds. (From Olson [3, pp. 293–297].)

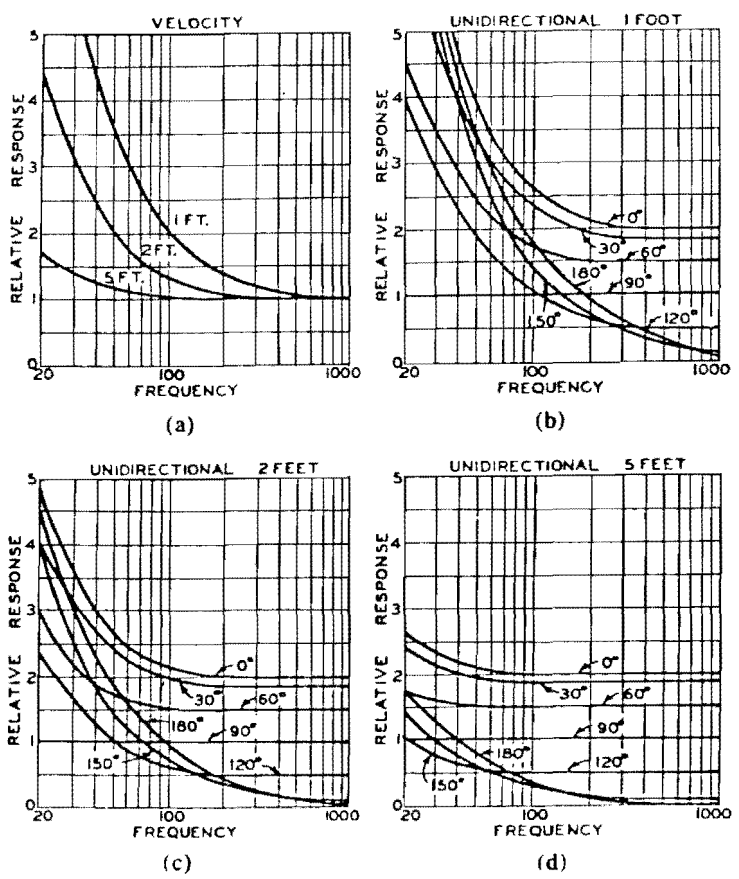


Fig. 24. (a) Relative voltage output of a velocity (or pressure-gradient) microphone as compared to a nondirectional pressure microphone for distances of 1, 2, and 5 ft (0.3, 0.6, and 1.5 m). (b)–(d) Relative voltage output of a unidirectional microphone as compared to a nondirectional pressure microphone for distances of 1, 2, and 5 ft (0.3, 0.6, and 1.5 m) and for various angles of incident sound. (From Olson [3, pp. 293–297].)

acoustical resistance versus frequency to the [illegible] ribbon. This microphone had a fixed cardioid pattern. It was superseded by the polydirectional type 77-D, and the later model 77-DX is still in use today.

3.2.2 Ribbon and Moving-Coil Polydirectional Microphone

Fig. 26 shows the Western Electric 639B microphone. The switch provides six mixing ratios of the outputs of the transducer units, and six polar patterns: bidirectional, nondirectional, two cardioid patterns, and two hypercardioid patterns [26]. According to Olson electric equalizers are incorporated to correct the amplitude and phase of the dynamic element to equal that of the velocity element.

3.2.3 Dual-Diaphragm Condenser Polydirectional Microphone

Eargle [27] gives a complete explanation of the workings of the dual-diaphragm polydirectional microphone transducer. Fig. 27 shows the basic scheme which is used in nearly all dual-diaphragm microphones.

The vibrating system consists of two diaphragms, each spaced a small distance from the back plate, similar to the pressure microphones of Sec. 1.3. The space behind each diaphragm provides acoustical resistance damping as well as acoustical capacitance (stiffness). The cavities behind the diaphragms are interconnected by small holes in the back plate. The phase shift in this system plus the variable electrical polarizing system make possible the variety of directional patterns shown in Fig. 27.

With switch position 1, the diaphragms are oppositely polarized, and the transducer has a bidirectional pattern. This may be deduced by observing that sound incident at 90° or 270° will produce equal but oppositely phased outputs from each diaphragm, and thus the net voltage output is a null.

With the switch at position 5, the diaphragms are similarly polarized, and the outputs are in phase at all angles of incidence, resulting in an omnidirectional pattern. At intermediate switch settings, a variety of unidirectional patterns are obtained, as in Fig. 27. Note that at switch setting 3, a cardioid pattern is obtained with maximum polarizing voltage E_0 on the front diaphragm and 0 V on the back diaphragm. The unenergized diaphragm and the acoustical capacitance and resistance of the back plate form a phase shift network similar to the rear sound aperture of a single-element unidirectional microphone, to be discussed in Sec. 3.3.

The frequency response of the polydirectional microphone will be flat and the polar pattern uniform with frequency, if the diaphragms are carefully matched and the resistance elements are the controlling acoustical impedances. Similar to the velocity microphone, acoustical characteristics deteriorate as the frequency approaches that where the path length from front to back approaches a wavelength of sound. A diameter of 0.5 in (12.5 mm) maximum is required for uniform directional characteristics to 15 000 Hz. However, the axial frequency response of a 1-in (25-mm) diameter polydirectional microphone can be made uniform to 20 000 Hz, so some uniformity of polar pattern is often traded for the higher sensitivity and lower noise level which are obtained with the larger diaphragm transducers.

3.2.4 Twin Cardioid Element Polydirectional Condenser Microphone

The dual-diaphragm polydirectional condenser microphone may be thought of as a superposition of two single-diaphragm cardioid microphones (Sec. 3.3) back to back. Fig. 28 shows how two cardioid capsules placed

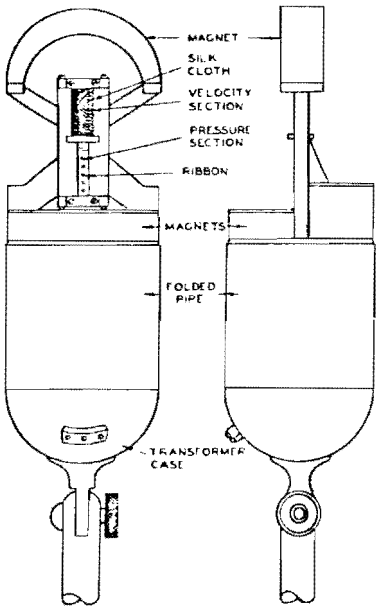


Fig. 25. Unidirectional microphone with screen removed. Ribbon-type pressure and velocity elements.

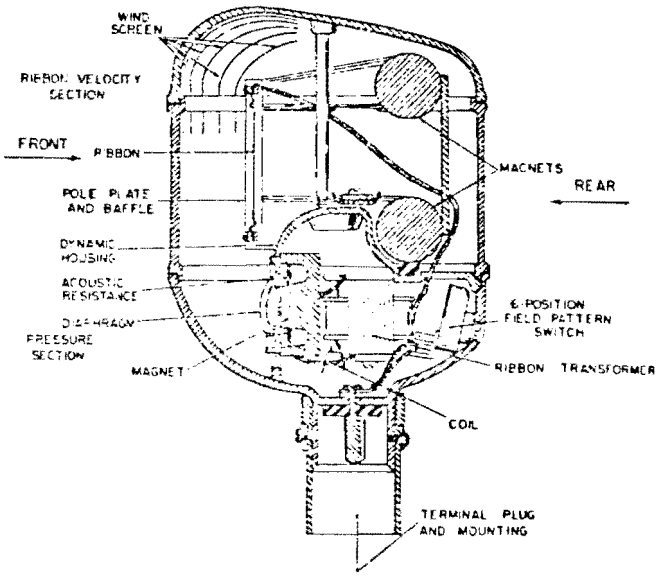
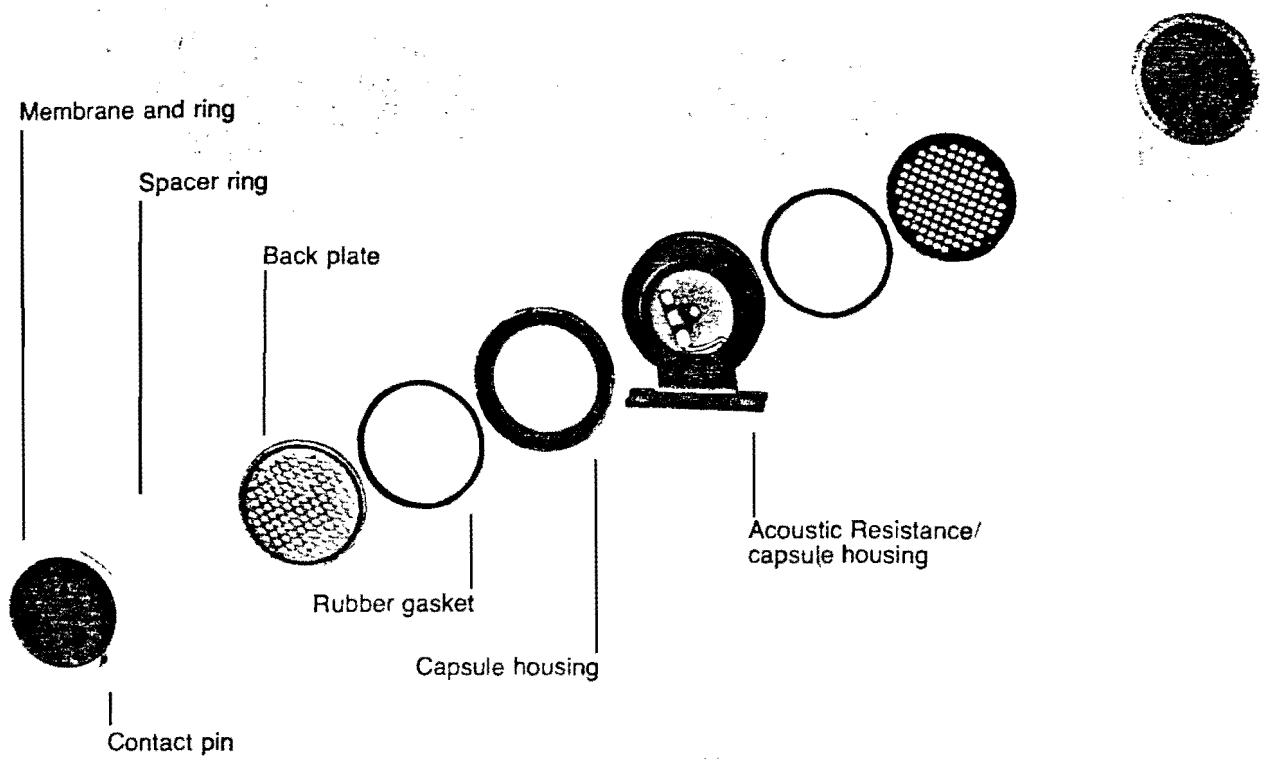


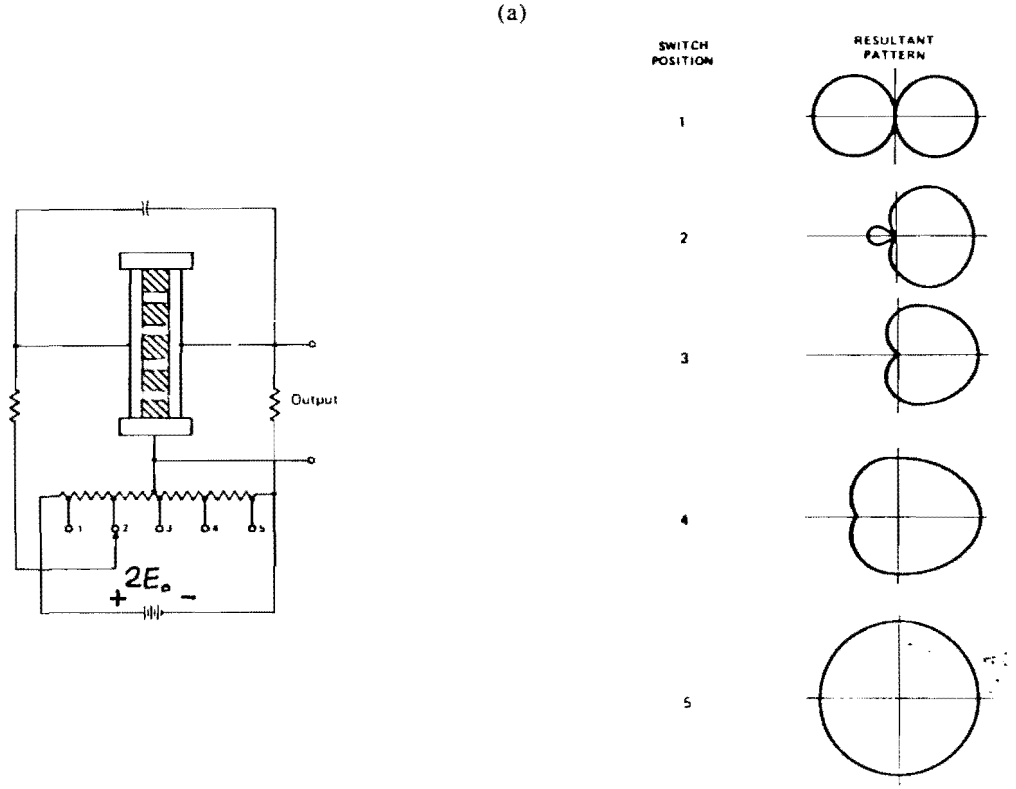
Fig. 26. Ribbon and moving-coil unidirectional microphone (Western Electric 639B). (From Tremaine [20].)

back to back will function as a polydirectional microphone. Similar to the dual diaphragm transducer, the front transducer has maximum polarizing voltage E_0 at all times, and maintains cardioid response with maximum sensitivity. The voltage on the rear transducer is varied down to zero and up to $\pm E_0$, the same as in the dual-diaphragm transducer. The same polar patterns are obtained. Likewise, the same effect can also be obtained by mixing the individual audio outputs in the various amplitude ratios and polarities.

This polydirectional microphone obviously has the most uniform acoustical properties in the cardioid mode, because only one transducer is involved. In the other modes, the spacing between capsules, which may be 0.4–1.2 in (10–30 mm), comes into play, and the polar characteristics at high frequencies become nonuniform.



(a)



(b)

Fig. 27. Dual-diaphragm condenser polydirectional microphone (a) Exploded view (Courtesy of AKG Acoustics.) (b) Principle of operation. (Adapted from Eargle [27].)

3.3 Single-Element Unidirectional Microphones

3.3.1 Ribbon Polydirectional Microphone

A single-element ribbon polydirectional microphone (RCA type 77 DX) is shown in Fig. 29. The ribbon is located between the pole pieces of a relatively large horseshoe magnet. The flux density is 13 000 G (13 Wb/m^2), which results in high sensitivity in all modes of operation. The vertical tube behind the magnet leads to a damped pipe (acoustic line) in the central body of the microphone. The acoustic line has a developed length of about 3 ft (1 m) and is lightly packed with ozite so as to provide a constant acoustical resistance to the ribbon over a wide frequency range. The vertical connector tube is D shaped in cross section and has a long narrow slot which opens to the rear. This slot is covered with an organdy screen, which is inside the tube. The rotary shutter varies the effective size of the slot or rear sound opening. This provides six polar patterns by means of a detent, but the actual number of available patterns is infinite. The shutter is shown at the bidirectional setting with the slot fully uncovered. When the shutter is rotated 60° counterclockwise, the slot is fully covered, and a nondirectional pattern is obtained. An additional 60° rotation results in the slot being about 10% uncovered, which yields a cardioid pattern.

The simplified acoustical equivalent circuit of the microphone (Fig. 29) consists of the following elements:

M_R = inertance (acoustical mass) of ribbon plus air load on ribbon
R_L = acoustical resistance of air load on ribbon, including front damping screen
M_s = inertance of air in slot, including screens
R_s = acoustical resistance of air in slot, including screens
R_p = acoustical resistance of acoustic line
p_1 = front sound pressure
p_2 = rear sound pressure

The circuit applies to the frequency range above ribbon resonance, where the acoustical capacitative reactance of the ribbon is negligible. When the shutter fully uncovers the slot, the impedance of $(M_s + R_s)$ becomes very small and short-circuits R_p. Then the circuit becomes that of a pressure-gradient (velocity) microphone. The quantity $(p_1 - p_2)$ is the input pressure gradient. The acoustical circuit impedance is that of the ribbon plus air load and is inductive or mass controlled. This results in a constant volume current U in $(M_R + R_L)$, constant ribbon velocity versus frequency, and uniform ribbon output voltage (Sec. 2.1). The polar pattern is bidirectional or figure of eight.

With the shutter fully closed, the impedance of $(M_s + R_s)$ becomes very large, so p_2 no longer drives the ribbon circuit. The acoustic line resistance R_p is large compared to the impedance of $(M_R + R_L)$, so the volume current U is given by

$$U = \frac{p_1}{R_p} . \tag{9}$$

This means that the microphone is pressure responsive and has a nondirectional polar pattern.

With the shutter set for cardioid pattern, part of the

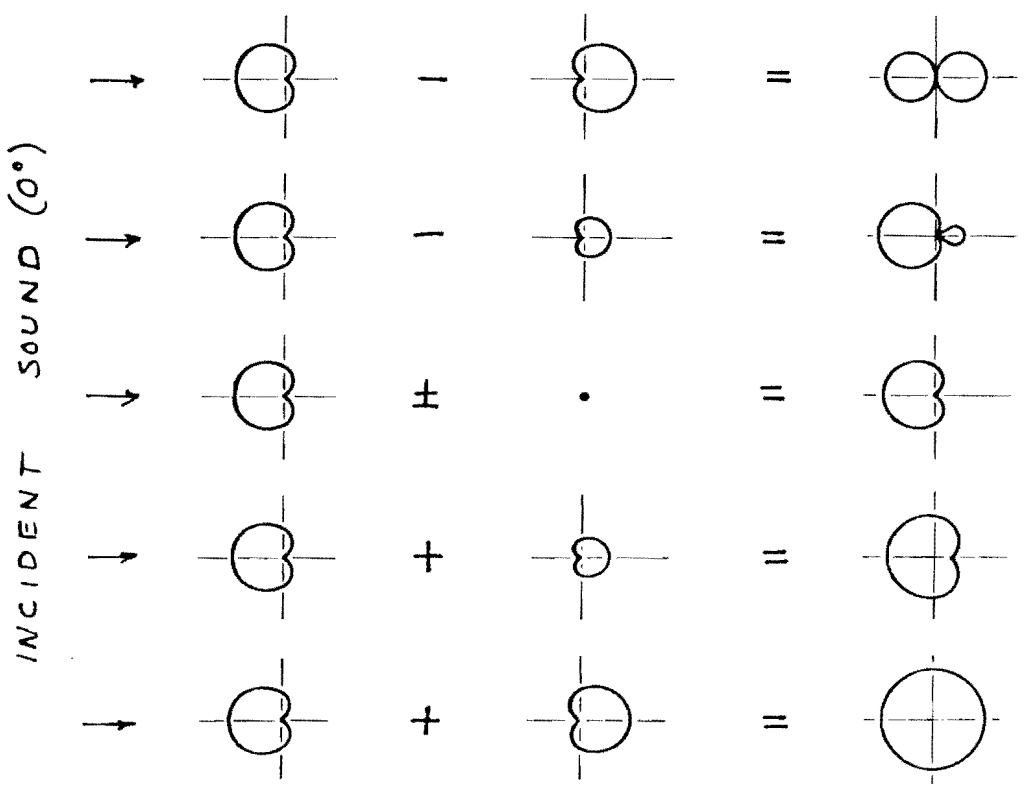


Fig. 28. Condenser polydirectional microphone using two cardioid transducers back to back. (Adapted from Eargle [27].)

ribbon volume current U flows through K_s [illegible] through $(M_s + R_s)$. Thus the ribbon is partly controlled by P_1 and the line resistance R_p, and is pressure responsive. The balance of the ribbon volume current U flows through $(M_s + R_s)$, so the transducer is partly velocity responsive. The shutter setting for a cardioid pattern is at a critical point where the phase shift through $(M_s + R_s)$ is such that sound incident from 180° arrives at point "Y" somewhat delayed in time so as to match the phase of sound at p_1. Thus $U = 0$, a null in response occurs at 180°, and a cardioid pattern is obtained. This is the principle by which all single-element unidirectional electrodynamic microphones operate.

Three additional directional patterns are detent selectable. The axial frequency response at the cardioid setting is reasonably flat from 30 to 15 000 Hz. The response at bidirectional setting slopes downward with frequency, whereas response at the nondirectional setting slopes upward. This is a limitation of the ribbon polydirectional microphone.

[illegible]ional Ribbon Microphone

The "uniaxial" microphone (RCA type BK-5B) developed by Olson [3, pp. 303–305] is shown in Fig. 30. The operation is similar to that of the polydirectional ribbon microphone with unidirectional setting. The ribbon (M_R, C_{AR}) is positioned between the pole pieces of a magnet structure which develops about 11 000 G (11 Wb/m^2) in the air gap. The lobes and screens $(M_{B1}, r_{AB1}, M_{B1}, r_{AB1})$ form a blast filter. The damped holes M_2, r_{A2}, M_{2s}, r_{A2s}) provide the principal phase shift elements for sound pressure p_2. Sound pressure p_1 is the frontal incident sound pressure. p_3 and associated elements form a third phase shift network which sharpens the polar pattern so that the 90° response is −8 dB instead of −6 dB as in a cardioid. Therefore the BK-5B has lower response to random sounds than a cardioid or a hypercardioid.

The simplified acoustical network of Fig. 30 illustrates the principle of operation in the frequency range above

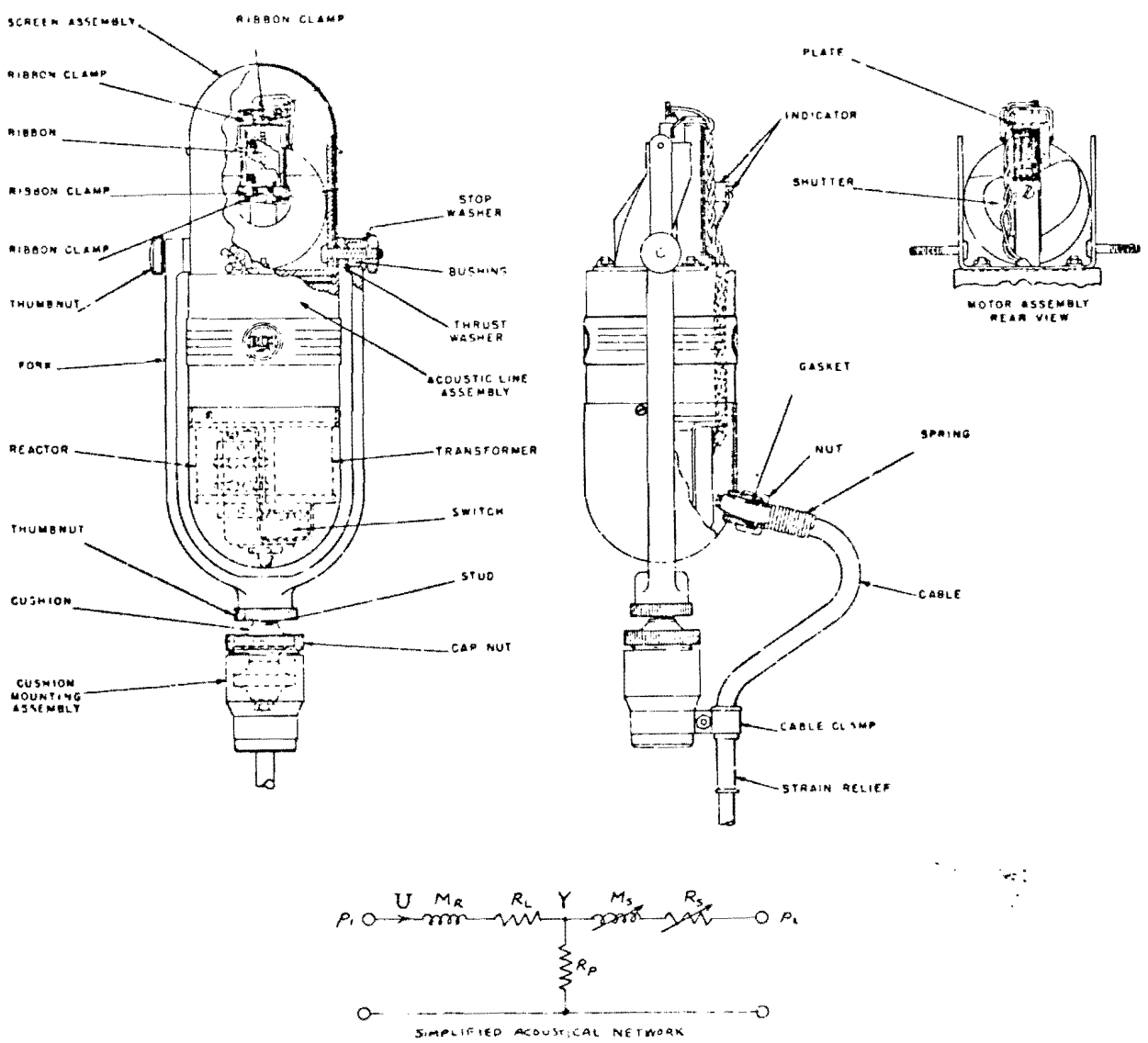


Fig. 29. Ribbon polydirectional microphone and acoustical network (RCA type 77-DX).

ribbon resonance. M_K and r_{AK} are the ribbon inertance and air load resistance. r_{AP} is the acoustical resistance of damped pipe. R_s and M_s are the acoustical resistance and inertance of the damped holes. Therefore the simplified circuit is exactly the same as Fig. 30, and so the basic operating principle of the unidirectional ribbon microphone is the same as that of the polydirectional microphone in the unidirectional mode.

3.3.3 Unidirectional Condenser Microphone

The unidirectional condenser microphone is a relatively recent invention. An early patent is Olson's "Directional Electrostatic Microphone" [8]. A modern high-quality microphone is described by Schulein and Seeler [11]. This is pictured in Fig. 31(a). It is a prepolarized capsule where the electret is on the backplate. The construction of the diaphragm and back plate was described previously (Sec. 1.3.2). The unidirectional capsule back plate has holes which communicate through an acoustic resistance screen into the case volume (normally having a closed bottom end) and to the atmosphere through resistance screens and rear entry ports.

The operation of the microphone of Fig. 31(b) may be determined from a consideration of the simplified mechanical network. M_D and C_D are the mass and compliance of the diaphragm. R_1 is the resistance of the air film between diaphragm and back plate. R_3 is the resistance of the screen which connects to the case volume C_3. R_2 and M_2 represent the holes and screens at the rear sound entry. (This simplified network is from [8], whereas the microphone of [11] has a more complex network.)

The velocity $\dot{x}$ of the diaphragm is given by

$$\dot{x} = \frac{F_D}{Z_M} = \frac{j\omega\, KPA}{Z_M} \tag{10}$$

where

Z_M = mechanical impedance of vibrating system, mechanical ohms
F_D = force on diaphragm, newtons
K = transducer
P = sound pressure, newtons per square meter
A = area of diaphragm, square meters
ω = $2\pi f$
f = frequency, hertz

and the displacement is given by

$$x = \frac{\dot{x}}{j\omega} = \frac{KPA}{Z_M}\,. \tag{11}$$

The output voltage is given by Eq. (2).

Thus for displacement (and output voltage) to be uniform with frequency, Z_M must be resistive. The resistance elements R_1, R_2, and R_3 are the controlling elements.

The phase shift network R_2, M_2, R_3, and C_3 may take a variety of configurations, similar to the various networks in ribbon and dynamic microphones. The operation of the phase shift network in a unidirectional cardioid was described in Sec. 3.3.1.

3.3.4 Condenser Polydirectional Microphone

Fig. 32 shows the microphone developed by Schoeps. It is physically symmetrical left to right. The diaphragm is centrally located between two back plates, which are perforated with holes. The mechanical assembly on the right slides left and right to provide three polar patterns. Note how the symmetry of the capsule favors a symmetrical figure-of-eight polar pattern.

When the actuating finger moves to the left, the cavity behind the diaphragm is sealed and becomes very small. The result is an omnidirectional pressure microphone where the moving system is stiffness controlled (Sec. 1.3).

When the actuator moves right, the back of the diaphragm is open to the atmosphere, and a figure-of-eight pattern results. For uniform amplitude of motion of the diaphragm, as in Sec. 3.3.3, the moving system is resistance controlled by the perforated back plates.

When the actuator is centrally located, a phase shift network is formed, and rear entry ports provide the input to the phase shift network. A cardioid pattern results, and the moving system is resistance controlled.

3.3.5 Moving-Coil Unidirectional Microphone

Fig. 33 shows the mechanical cross section and the acoustical network of the UNIDYNE* unidirectional microphone developed by Bauer in 1941. All unidirectional moving-coil microphones which have one rear sound entry location follow these operating principles. The resonance of M_1 and C_{A1}, the diaphragm and coil assembly inertance and acoustical capacitance, is at the low end of the usable audio frequency range. Depending on the application of the microphone, this may be anywhere from approximately 70 to 140 Hz. Similar to the printed ribbon transducer, the lowest attainable resonance is limited by the stiffness of the plastic film diaphragm material.

The moving-coil system is mass controlled above resonance, similar to the ribbon transducer. Therefore the difference in sound pressure between the two sides of the diaphragm must be proportional to frequency so as to maintain a constant volume current and a constant diaphragm and coil velocity throughout the useful audio frequency range. This is done by selection of the parameter values of the phase shift network. Also, the network values must provide for the correct delay time versus frequency such that a null is maintained at 180° for a cardioid pattern. Alternately, the network values may be adjusted for a hypercardioid pattern.

3.3.6 Variable-Distance Unidirectional Microphone

Fig. 34 shows a sectional view and the acoustical network of the variable-distance unidirectional micro-

phone. The front to rear sound entry distance varies approximately inversely with frequency [3, pp. 305–307]. Sound pressure P_1 acts on the front of the diaphragm. Pressures P_2, P_3, and P_4 act on the back of the diaphragm through suitable acoustic impedance. P_2 acts in the high-frequency region, P_3 at middle frequencies, and P_4 at low frequencies. The advantage of this design is that accentuation of low frequencies due to the proximity effect is reduced. Similar to the UNIDYNE, the moving system resonance is in the region of 100 Hz and is mass controlled at higher frequencies.

4 ULTRADIRECTIONAL MICROPHONES

For the purpose of this paper, we define an ultradirectional microphone as one that has an energy response to random sound of less than 0.25, relative to an omnidirectional microphone, over a major portion of its useful audio frequency range. According to [28], 0.25 is the random energy efficiency of a hypercardioid, which represents the highest directivity obtainable with a first-order gradient microphone. This category includes higher order pressure-gradient microphones and wave interference types of microphones. The applications of ultradirectional microphones include long-distance pickup of sound in the presence of random noise and/or reverberant sound, or close talking in very high noise environments.

It should be noted that, of the many types of ultra-

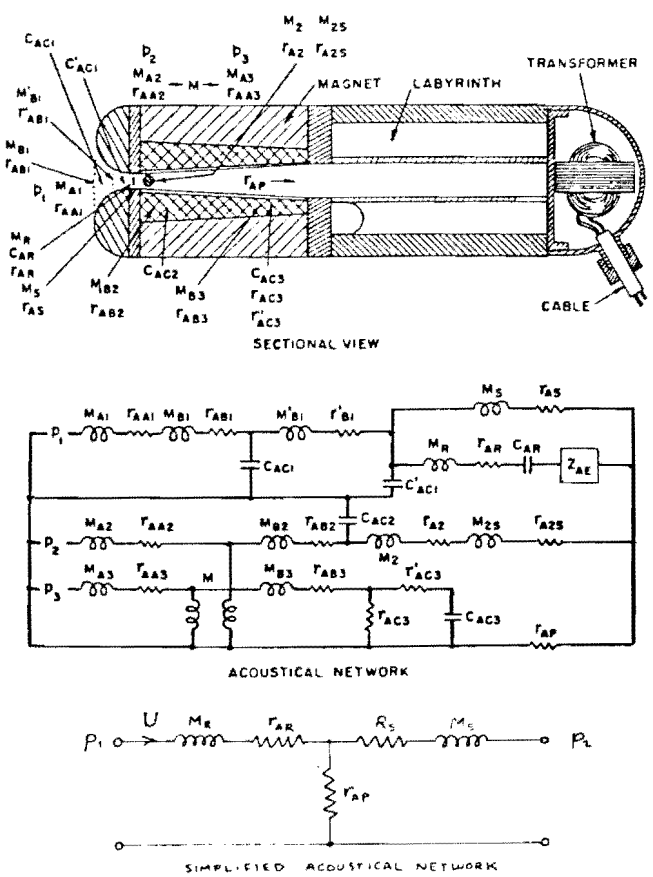


Fig. 30. Unidirectional ribbon microphone. (Adapted from Olson [3, pp. 303–305].)

al microphones developed since 1938, only the line type microphone remains in common use today. It employs high sensitivity condenser or moving-coil electrodynamic transducers.

4.1 Higher Order Gradient Bidirectional Microphones

First-order pressure-gradient bidirectional microphones were described in Sec. 2.1. The polar pattern of the first-order gradient microphone has a cosine-squared pattern. The power of the cosine is the order of the gradient. Fig. 35 shows a second-order bidirectional gradient microphone made up from two first-order bidirectional gradient units connected in phase opposition. The cosine-squared pattern of this microphone is shaded in Fig. 35. A family of cosine patterns is shown, beginning with order zero, which is the omnidirectional pattern.

The frequency response of a first-order gradient microphone with a mass-controlled moving system is uniform above the resonance frequency. The response of a similarly constructed second-order gradient microphone is proportional to frequency, that is, the response rises at 6 dB per octave. The response of a third-order gradient microphone rises at 12 dB per octave, and so forth. The useful frequency response range of a second-order microphone extends to the frequency where the spacing d equals one wavelength, as is discussed in the next section.

The applications for higher order bidirectional gradient microphones have been primarily limited to close-talking noise-canceling microphones. The random energy response of a gradient bidirectional microphone

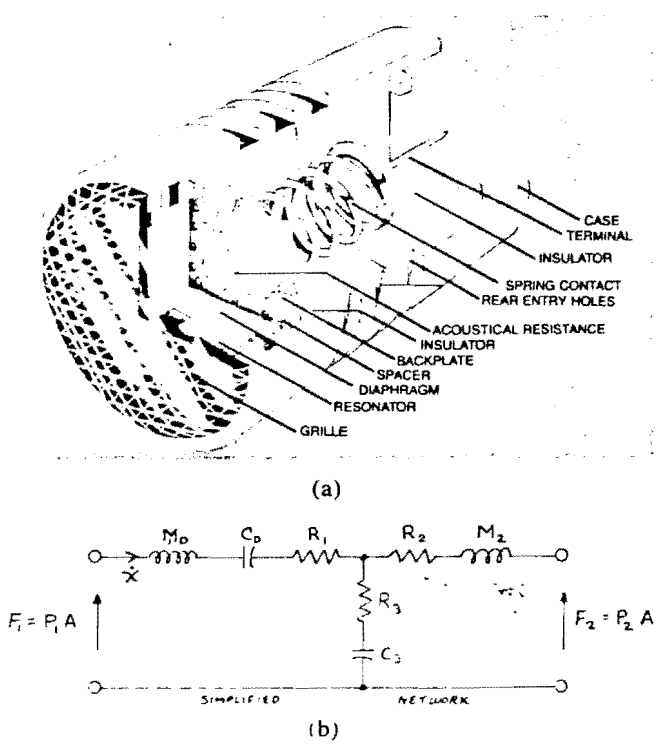


Fig. 31(a). Unidirectional condenser microphone. (Courtesy of Shure Brothers, Inc.) (b) Simplified mechanical network. (From Olson [8]).

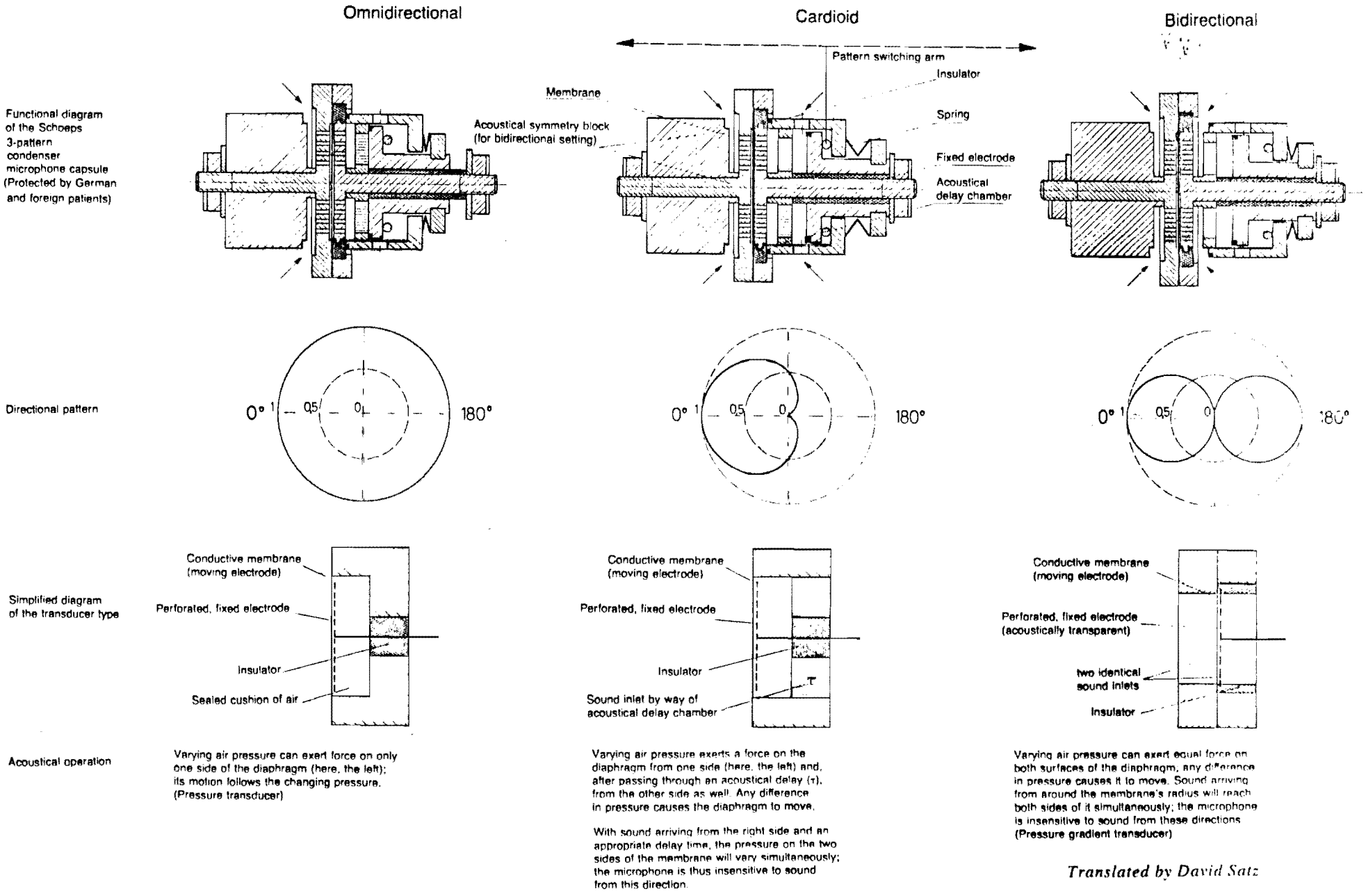


Fig. 32. Single-diaphragm polydirectional condenser microphone. (Courtesy of Posthorn Recordings/Schoeps).

of order n is given by [3, pp. 312–328]

$$\text{directional efficiency} = \frac{1}{2n + 1}.$$

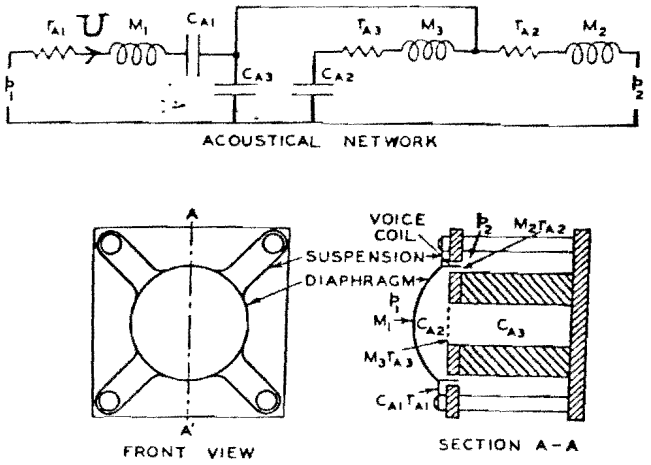


Fig. 33. Front view, sectional view, and acoustical network of UNIDYNE unidirectional microphone. In the acoustic circuit, M_1, r_{A1}, and C_{A1} = inertance, acoustical resistance, and acoustical capacitance of diaphragm and suspension system; M_2 and r_{A2} = inertance and acoustical resistance of slit between voice coil and pole; C_{A2} = acoustical capacitance of air space between diaphragm and pole; M_3 and r_{A3} = inertance and acoustical resistance of silk cloth; C_{A3} = acoustical capacitance of air space in magnet; p_1 = pressure at diaphragm; p_2 = pressure at voice coil. (From Olson [3, pp. 305–307].)

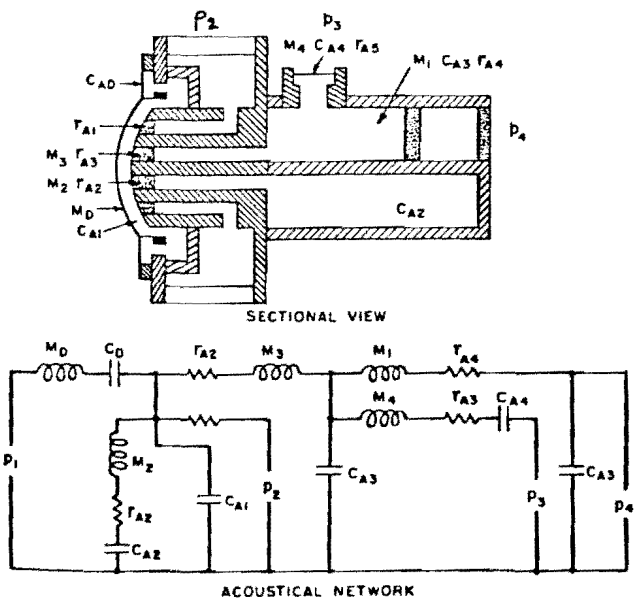


Fig. 34. Sectional view and acoustical network of variable-distance microphone. p_1 = sound pressure on front of microphone; p_2, p_3, and p_4 = sound pressures acting at different parts on back of microphone; M_D = inertance due to mass of diaphragm; C_{AD} = acoustical capacitance of diaphragm suspension system; C_{A1} = acoustical capacitance of volume back of diaphragm; r_{A1} = acoustical resistance of shortest path; M_4, C_{A4}, and r_{A5} = inertance, acoustical capacitance, and acoustical resistance of diaphragm in circuit of medium path; M_1, M_3, C_{A3}, r_{A3}, and r_{A4} = inertances, acoustical capacitance, and acoustical resistances involved in largest path; M_2, r_{A2}, and C_{A2} = inertance, acoustical resistance, and acoustical capacitance in a side branch. (From Olson [3, pp. 305–307].)

This equation applies when the source of sound is greater than n times a wavelength of sound from the microphone. An additional increase in discrimination against unwanted noise from distant sources occurs when the sound source is very close to the microphone. This is because the low-frequency accentuation due to the proximity effect increases with the order number. Fig. 35 shows an example where the frequency responses of zero-, first-, and second-order microphones are compensated to be flat at a source distance of 0.75 in (19 mm). The graph shows the responses of these microphones to random sounds at a distance from the microphone. Thus the noise discrimination of a second-order microphone, relative to a pressure microphone, exceeds 30 dB at 100 Hz. This permits speech communications in very-high-noise environments. In most noisy environments, however, the first-order gradient microphone is satisfactory. Therefore higher order bidirectional gradient microphones are not in common use today. A novel second-order noise-canceling microphone employing a single diaphragm is found in [29].

4.2 Higher Order Gradient Unidirectional Microphone

The higher order bidirectional microphones described in the preceding section are undesirable for many applications where a unidirectional microphone is more suitable. Fig. 36 shows that a second-order gradient unidirectional microphone can be made from two car-

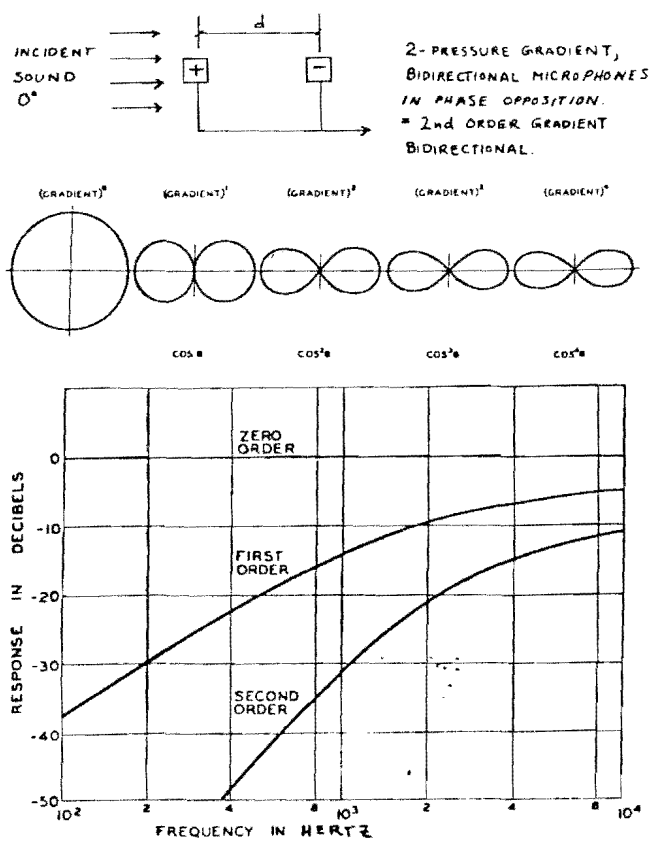


Fig. 35. Characteristics of higher order gradient microphones. (From Olson [3, pp. 312–328].)

dipole elements connected in phase opposition [illegible] a delay network. The frequency response is proportional to frequency as shown and the upper limit of the useful frequency range is the frequency where D equals one wavelength of sound. Fig. 37 shows the experimental model of the second-order gradient uniaxial microphone commercialized briefly by RCA. This microphone was made from two uniaxial ribbon microphones (Fig. 30). It required carefully matched elements and was costly to make. The audio output was rather low when it was used at a distance from the source, plus the transition to cardioid polar pattern above 2000 Hz turned out to be a significant disadvantage compared to less costly line microphones with high-output dynamic or condenser transducers.

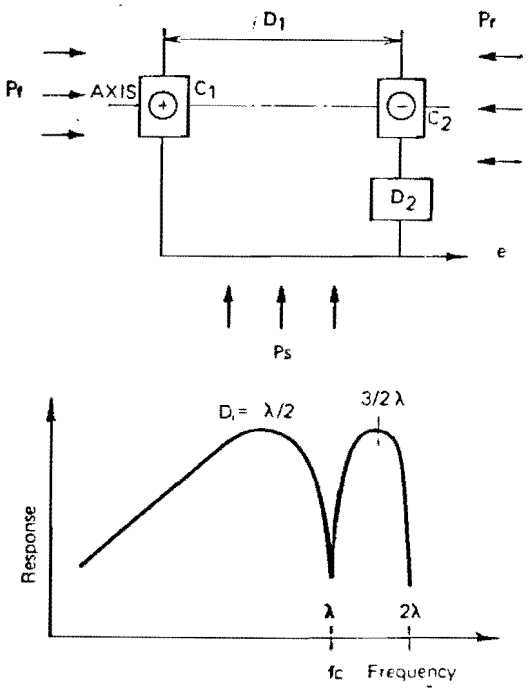


Fig. 36. Operating principles of second-order gradient unidirectional microphone. (From [30].)

Beavers and Brown [31] recently developed a third-order gradient unidirectional microphone employing four condenser elements. The stated application was speech pickup. Woszczyk [28] reported experiments with spaced cardioid microphones where second-order unidirectionality was obtained to 200 Hz. The application was music recording.

4.3 Line Microphone

A simple line microphone is shown in Fig. 38. An acoustic line (pipe) with equally spaced sound openings along its entire length is connected to a pressure microphone element. The transducer element may be of the electrostatic or electrodynamic varieties described previously. A high order of directivity is indicated by the frequency response curves in the mid- and high-frequency region where the 90° and 180° responses are far below the 0° curve. The low-frequency limit of the useful range of ultradirectional characteristics is given by [32]

$$f_c = \frac{c}{2L}$$

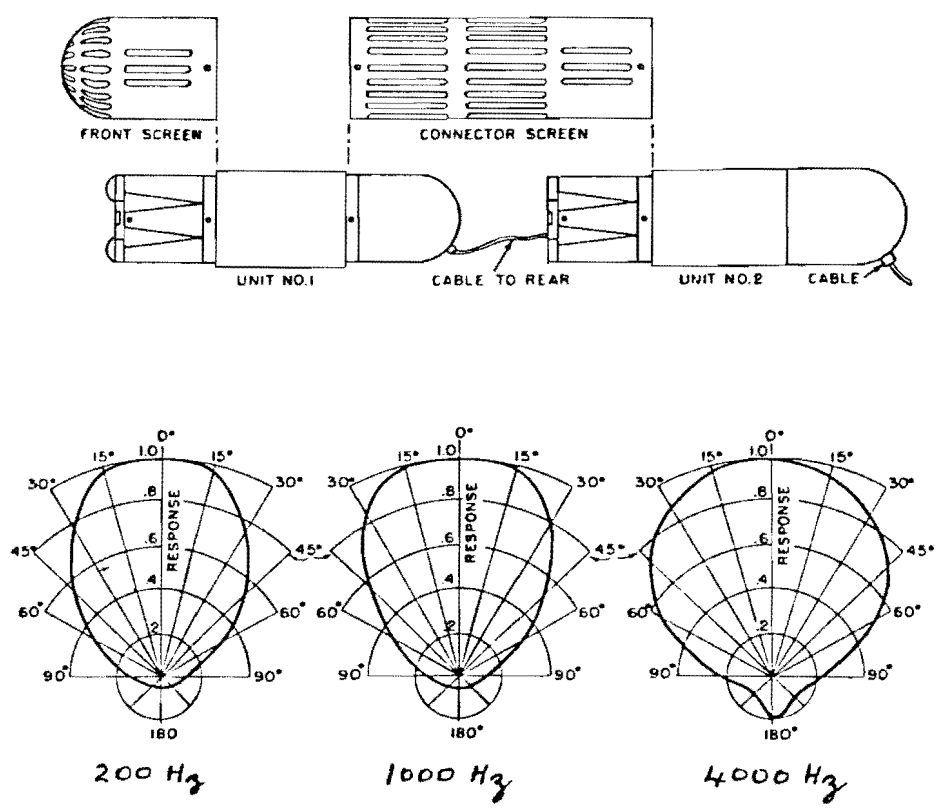


Fig. 37. Second-order gradient unidirectional microphone (RCA type BK-10A). (From Olson [3, pp. 312–328].)

where

f_c = frequency, hertz

c = velocity of sound, ≈ 331 m/s

L = total length of line.

The high-frequency limit of the ultradirectional region is determined by the hole spacing dS:

$$f_n = \frac{c}{2dS}$$

where dS is the hole spacing in meters.

If f_c is chosen to be 100 Hz, then L must equal 65 in (1.66 m), which is too long for most practical applications. However, this requirement may be eased by substituting a pressure-gradient cardioid element. This provides good 180° rejection below f_c, and with careful optimization of parameters, a microphone of practical length can have good rejection at 90°, well below f_c. It is relatively easy to achieve f_n = 10 000 Hz or higher with practical hole spacings.

Alternately, the line may consist of a bundle of small tubes of lengths which vary from dS to L in even steps of dS. Similarly, a single pipe with a series of slots may be used. With modern small-diaphragm condenser transducers, the single pipe is appropriate, because the diameters of the tubes in a bundle would be so small that the acoustic resistance (viscosity) loss would reduce sensitivity and roll off the high-frequency response.

Olson [33], [34] developed many types of line microphones in the late 1930s. These were generally complex, involving a lot of metal tubing. He obtained a variety of polar patterns, using pressure or pressure-gradient ribbon elements. His patents were voluminous. All modern line microphones utilize the technology developed by Olson prior to 1940, although they are much different in form and more suited to today's applications. At the time RCA introduced television at the 1939 World's Fair, it was thought that a wide-frequency-range line microphone would be needed for long-distance pickup of voice or music. Olson developed

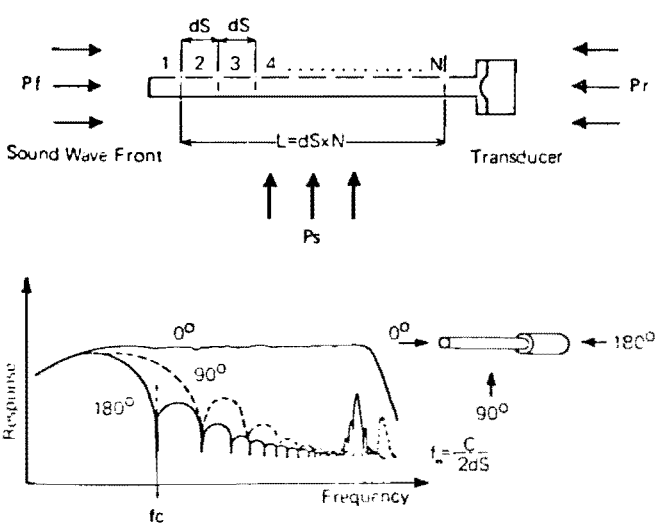


Fig. 38. Operating principles of line microphone (From [30].)

[illegible] which was 10 ft (3.05 m) long, employed five lines and five ribbon transducers covering contiguous frequency bands. It had sharp directivity down to 85 Hz.

The modern era in line microphones began in 1961 when Olson [8] patented the single-diaphragm condenser unidirectional microphone. M. Rettinger of RCA in Burbank, CA, did the product design of the M1-10006A varidirectional microphone [Fig. 39(a)], which consisted of a bundle of plastic tubes attached to a cardioid condenser element based on Olson's patent. The novelty of the design was that the microphone could be changed to a cardioid by removing the pipes. This microphone was used for a time in motion picture sound recording, but reportedly suffered from electric impulse noise.

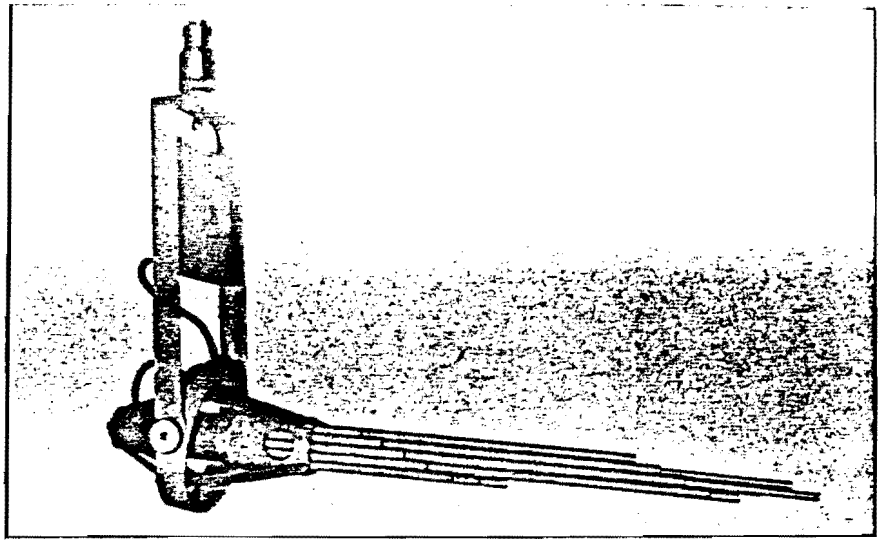
Concurrently, Electro-Voice introduced the model 642 and 643 line microphone. Each used dynamic moving-coil cardioid transducers, which had large, heavy magnets and high sensitivity. The 642 employed a short line, only 12 in (0.3 m) long, whereas the 643 was 6 ft (1.8 m) long. The 642 proved to be very popular for television and film recording and is still used today. The 643 was used for specialized applications such as presidential news conferences, but is little seen today. The f_c of the 12-in (0.3 m) line is 552 Hz, but with the cardioid element plus low-frequency cutoff filters, the 642 was satisfactory for voice pickup.

Fig. 39(b) shows a modern electret condenser line microphone with a very-small-diameter line and a transducer capsule only 0.6 in (16 mm) in diameter. The capsule and line are made as an assembly which is interchangeable with standard cardioid and pressure elements. Although f_c is 420 Hz, 15-dB rejection is maintained at 90° down to 100 Hz, according to measurements by Sank [35]. The author has often used this microphone as a "direction finder" in outdoor studies where multiple sources are involved. The close spacing dS of holes in the line results in f_n = 32 600 Hz.

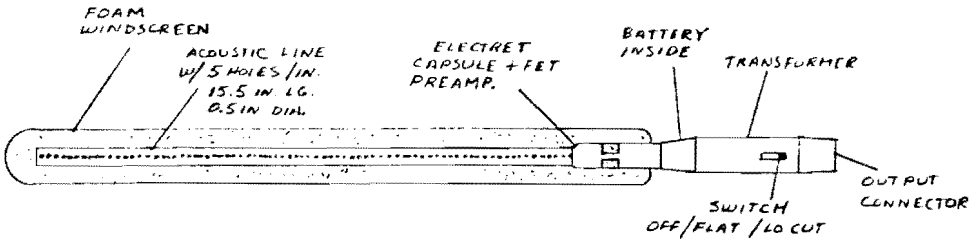
4.4 Combination Line and Gradient Microphone

Olson [3, p. 319], in reference to his second-order gradient uniaxial microphone, states: "Since operation shifts from the two microphones to the single microphone in the front in the high frequency region, it would be a comparatively simple task to develop a microphone with a sharper directivity pattern in the high-frequency region for use as the front microphone if this appeared to be desirable."

Fourteen years later, Kishi and colleagues patented a microphone [32] which had three elements instead of two as Olson suggested, but otherwise conformed to the idea of a second-order gradient microphone with improved high-frequency directivity. Fig. 40 shows the principle of operation: a line microphone with a cardioid condenser capsule (Sec. 4.3) is combined with a second-order gradient unidirectional microphone having two cardioid condenser capsules. The line microphone operates above 1000 Hz, and the gradient microphone below 1000 Hz. The sensitivities of the



(a)



(b)

Fig. 39. Line microphones. (a) Bundled pipes (RCA type M1-10006A), varidirectional, air condenser. (b) Single pipe with holes (Nakamichi type CM700/CP703), electret condenser.

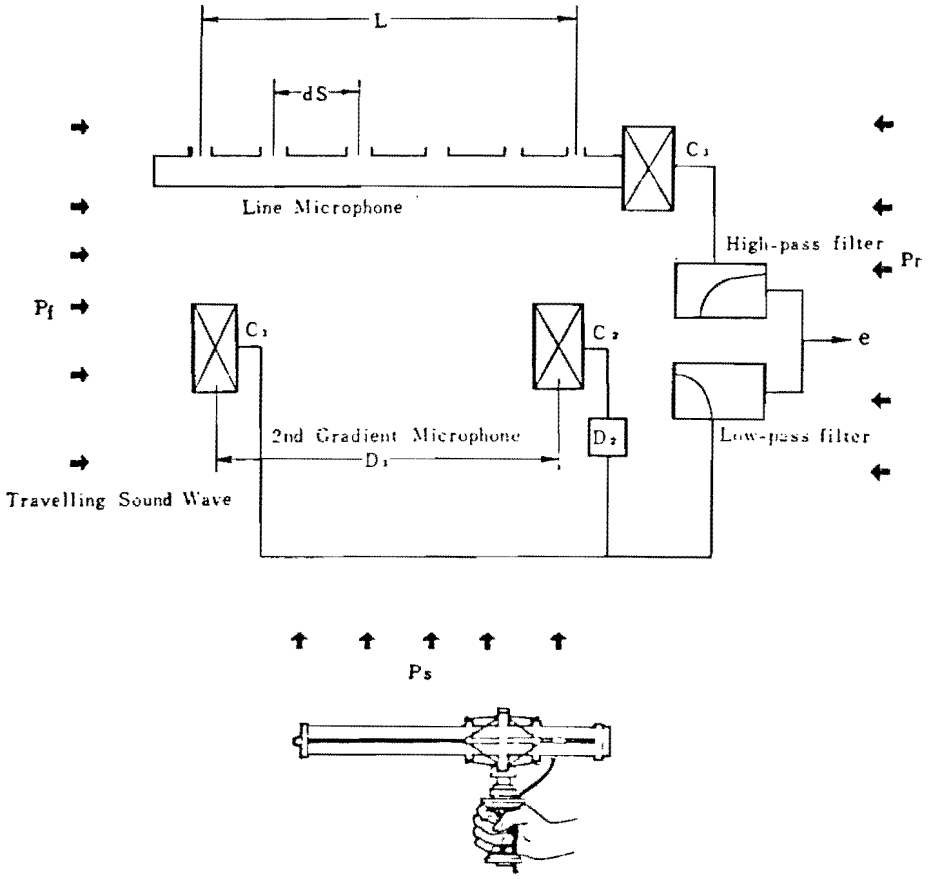


Fig. 40. Combination line and gradient microphone. (From [30].)

transducers are balanced by adjustments in the FET preamplifiers in the microphone. Therefore a high order of directivity is maintained over the entire audio-frequency range. This microphone was briefly commercialized by Sony as model C-77 Telemicrophone.

4.5 Parabolic Reflector Microphone

A parabolic reflector may be used to concentrate distant, parallel rays of sound at a microphone placed at the focus [Fig. 41(a)]. As in all wave-type microphones, the reflector must be large compared to a wavelength of sound to obtain a high order of directivity. Olson [3, pp. 312–328] shows the polar patterns of a dish 3 ft (0.91 m) in diameter, fitted with a pressure microphone.

4.6 Acoustic Lens

An acoustic lens is a lens-like device made of sheet metal which can focus sound rays onto a microphone similar to the parabolic reflector [Fig. 41(b)]. The directivity follows the laws of wave-type microphones much the same as the parabola [3, pp. 312–328].

4.7 Large-Surface Microphone

A large-surface microphone consisting of a large number of pressure microphone elements arranged on a spherical surface is shown in Fig. 41(c). Olson [3, pp. 312–328] indicates that the polar pattern is similar to that of a curved surface sound source, which emits uniformly over a solid angle subtended by the surface

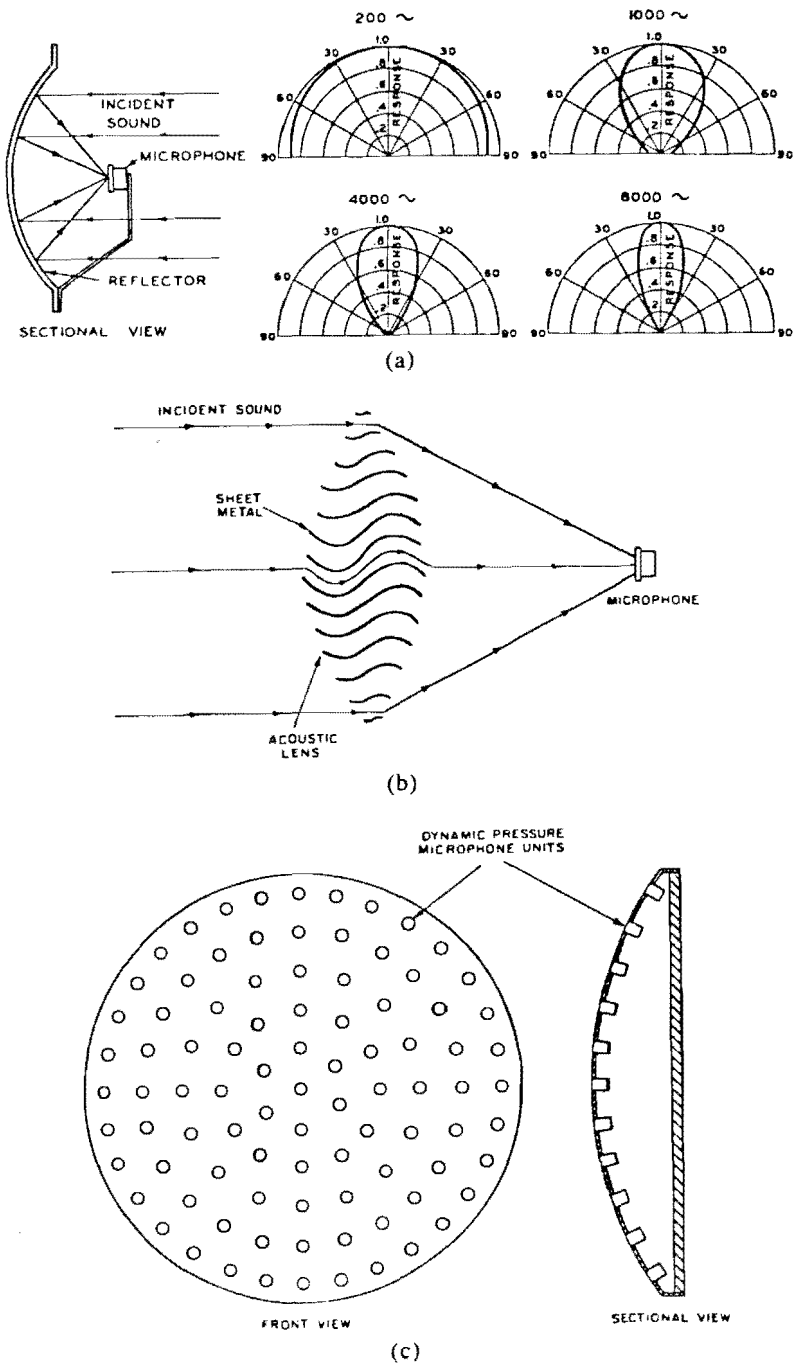


Fig. 41. Wave microphones. (a) Parabolic reflector. (b) Lens. (c) Large surface. (From Olson [3, pp. 312–328].)

at the center of curvature. The microphone in Fig. 41(c) is 4 ft (1.22 m) in diameter and has an angular spread of 50°. The pattern is reasonably uniform above 300 Hz.

5 MISCELLANEOUS TYPES OF MICROPHONES

5.1 Stereophonic Condenser Microphone

A two-channel microphone such as the one shown in Fig. 42 is a convenient tool for sound pickup in the x–y or M–S stereophonic modes where coincident microphone transducers are required. The AKG C-422 utilizes two dual-diaphragm condenser transducers, which were described in Sec. 3.2.3. These are mounted on top of each other, and in adjacent capsules sharing a common axis, and the capsules may be rotated with respect to each other. A remote-control unit permits any one of nine polar patterns to be selected for each channel.

5.2 Soundfield Microphone

The original soundfield microphone was developed for the "ambisonic" surround sound system patented by the United Kingdom National Research Corporation and was produced by Calrec Audio Limited. This system was a form of quadraphonic sound. As interest in quad sound waned, Calrec introduced a new version of the soundfield microphone (Fig. 43), which is essentially an electronically steerable stereophonic microphone. Four single-diaphragm cardioid condenser capsules are mounted in a tetrahedral array and connected to an electronic control unit. This unit permits selection of cardioid, figure-of-eight, and omnidirectional patterns for each stereo output. In addition, the sound pickup axes may be electronically steered in azimuth and elevation. By processing the pressure and pressure-gradient components of the audio signal, the microphone may be apparently moved fore and aft as the ratio of direct to reverberent sound is varied. The electronic steering may be done before or after the audio is recorded, allowing flexibility in the postproduction phase of sound recording.

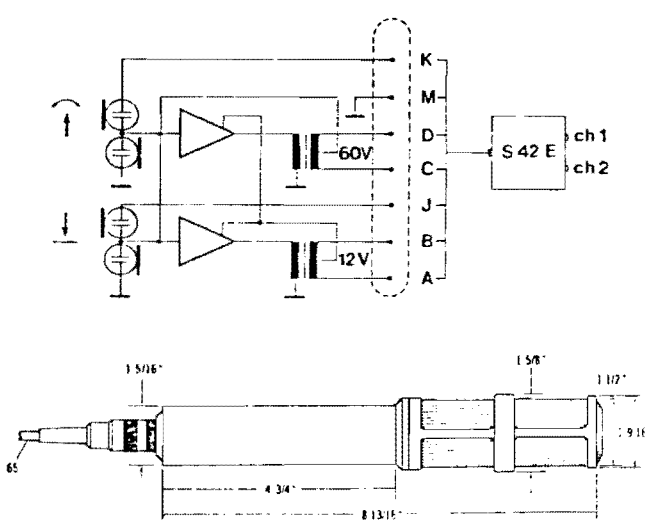


Fig. 42. Stereophonic condenser microphone (AKG-C422).

5.3 Quadraphonic Microphone

Fig. 44 shows two quadraphonic microphones developed by Yamamoto [36]. The ribbon version consists of four ribbons mounted at right angles to each other. These are apparently backed up by a common air volume and a common acoustic labyrinth which provides the resistive termination required for unidirectional polar patterns. Apparently this microphone was never constructed. The condenser version was constructed experimentally and consists of four cardioid condenser capsules, with pipes providing back-to-back acoustical communication between capsules.

Both the ribbon and the condenser versions include common air chambers behind the transducer elements, which essentially provides crosstalk between channels. The need for this feature is obscured by complex mathematics. The frequency response measured by Yamamoto on the condenser version extends to only 8000 Hz. This performance, plus the waning interest in quadriphony may account for these microphones not being commercialized.

5.4 Two-Way Dynamic Unidirectional Microphone

Fig. 45 shows the two-way dynamic unidirectional microphone (AKG model D-202) developed by Weingartner. His paper [37] describes a comprehensive study

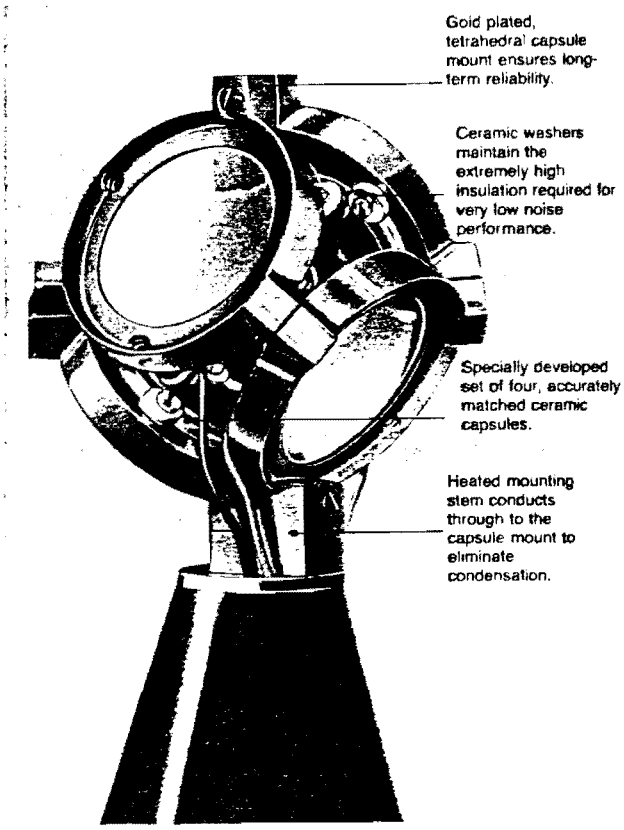


Fig. 43. Soundfield microphone transducers (Calrec type MK IV).

of acoustical networks of unidirectional dynamic microphones. He concluded that it would be difficult to manufacture a microphone with one transducer that would maintain uniform frequency response and polar pattern over the entire audio frequency range. His solution was to divide the range at 500 Hz and use separate dynamic transducers for high and low frequencies. This resulting microphone has uniform frequency response and cardioid pattern from 30 to 15 000 Hz. According to the author, the performance is comparable to a condenser microphone. The D-202 microphone is still in use today.

5.5 Lavalier Microphone

The term refers to a small microphone which is fastened to the clothing or suspended by a lanyard around the neck. Olson, Preston, and Bleazey [38] described the application of personal microphones. They showed that a microphone mounted on the chest should have a rising high-frequency response to compensate for the loss in response due to its location off the axis of the mouth. The early models of lavalier microphones were omnidirectional dynamic microphones which were suspended by a lanyard. Newer models include omnidirectional dynamic and electret microphones, which are small and light in weight, and are clipped to clothing. The microphone shown in Fig. 46(a) is one of several very small electret condenser models available today, [illegible] miniature element similar to that developed by Killion and Carlson [5]. It is light enough in weight so that it may be fastened to the clothing by means of a small clip attached to the cable below the microphone. The flat frequency response of this microphone requires high-frequency equalization when used on the chest.

Fig. 46(b) shows the RCA BK-12A dynamic moving-coil lavalier microphone, which was developed by the author. It has a 250-Ω coil, requires no output transformer, and is 0.75 in (19 mm) in diameter by 1.5 in (38 mm) long. It clips onto the clothing, and the frequency response is acoustically equalized for use on the chest. The transducer cartridge is similar to that shown in Fig. 10. The microphone is designed to withstand a 6-ft (1.8-m) drop to a concrete floor, and is virtually dirt- and waterproof.

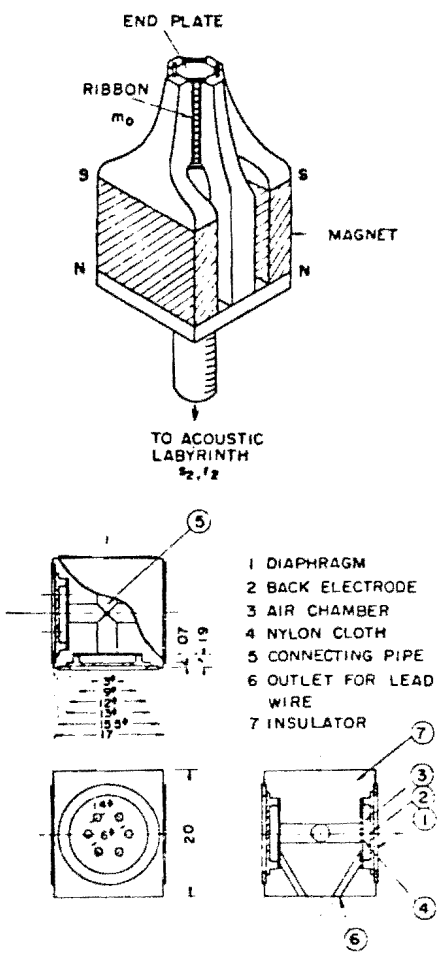


Fig. 44. Quadraphonic microphones. (From Yamamoto [36].)

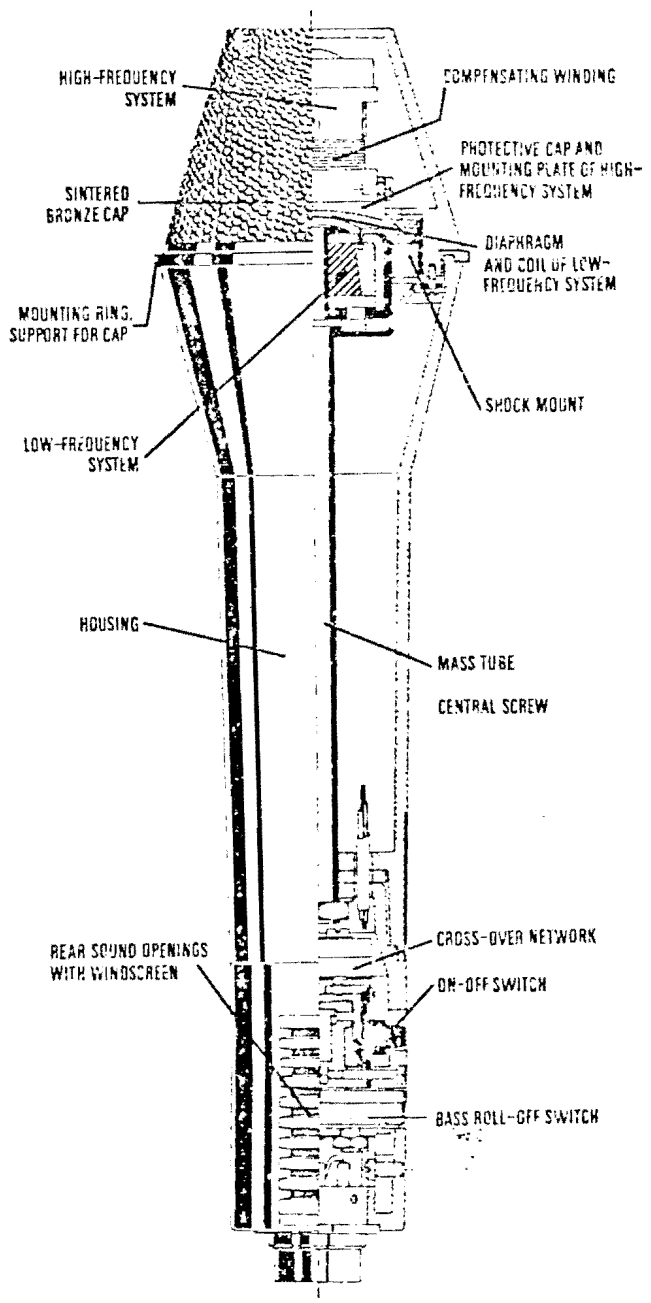


Fig. 45. Two-way dynamic unidirectional microphone. (From Weingartner [37].)

5.6 Wireless Microphone

Fig. 47 shows a system (VEGA models T87/R 42) which uses a handheld microphone with a built-in transmitter. This unit transmits on a VHF band to the receiver illustrated. The receiver audio is fed to the sound reinforcement, broadcast, or recording mixing console. Alternately, a "body pack" transmitter may be used with an electret lavalier microphone similar to that shown in Fig. 46(a). These systems are widely used in television broadcasting and in professional entertainment applications. They are not as frequently used in schools and churches due to the high cost.

5.7 Auto-Mixer Microphone

These are special microphones to be used with automatic mixing systems. Julstrom and Tichy [39] describe an automatic mixing system involving multiple microphones, where a particular microphone is gated "on" only when a talker is positioned in front of the microphone within ± 60° of the microphone axis. The microphones (Fig. 48) contain two cardioid electret condenser elements positioned back to back. The gating of the system is done by measuring the ratio of the outputs of front and rear elements.

Fig. 48(a) shows one model of the microphone (Shure AMS-22) which contains two electret condenser elements placed very close to the table upon which the microphone is placed. This follows the principle of the boundary microphone described in Sec. 1.3.4. Fig. 48(b) shows a more conventional style (Shure AMS-26), in which the two elements are contained in the elongated screen section.

5.8 Zoom Microphone

Ishigaki et al. [40] describe a microphone intended for use with video cameras which has variable directivity (Fig. 49). The system has three unidirectional electret microphone units, and the polar pattern can be continuously varied from omnidirectional through cardioid to second-order gradient unidirectional. The directivity control is linked with the zoom lens control on the camera. The authors do not show a photograph or sketch of the experimental microphone.

5.9 Noise-Canceling Microphone

Fig. 50 shows a drawing of the Knowles BW-1789 subminiature electret noise-canceling microphone element. This is similar in construction to the pressure-sensing microphone developed by Killion and Carlson [5], except that both sides of the diaphragm are open to the atmosphere, similar to a pressure-gradient velocity

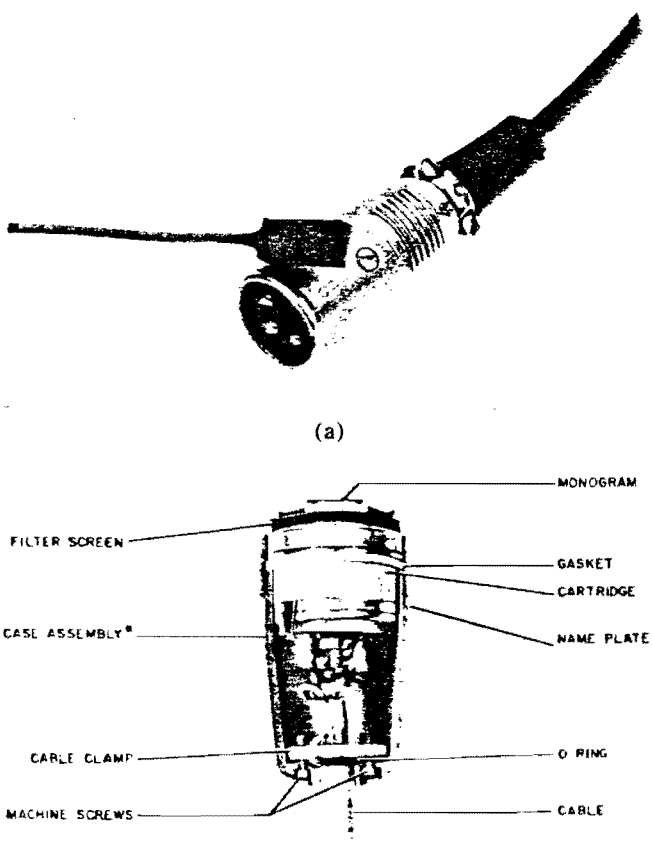


Fig. 46. Lavalier microphones. (a) Electret condenser (Countryman Associates model ISOMAX 11-0). (b) Dynamic moving coil (RCA type BK-12A).

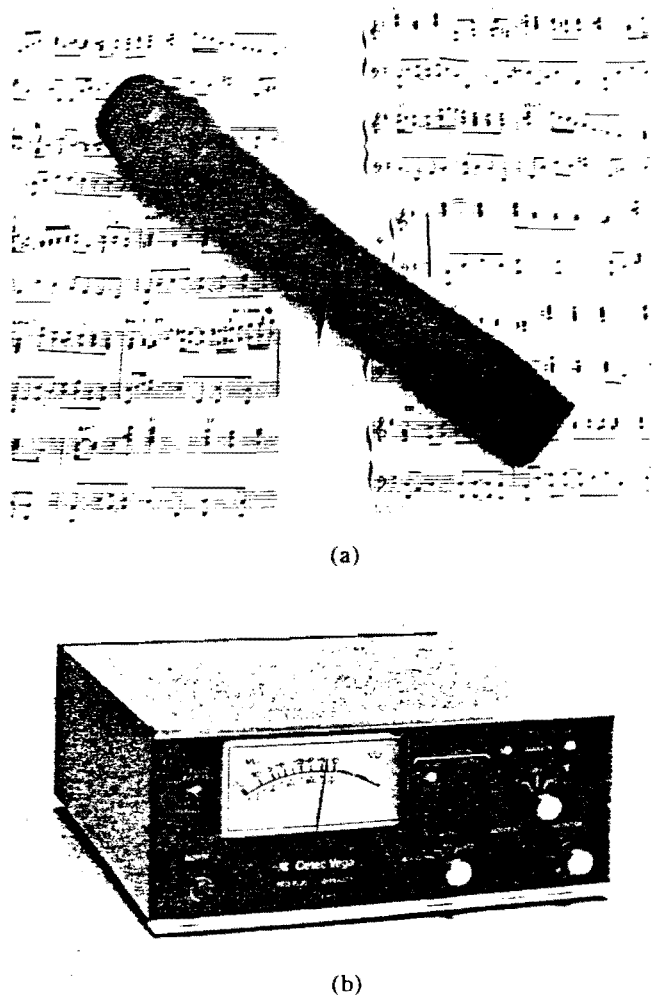


Fig. 47. Wireless microphone system. (a) Vega hand-held transmitter Model T-87 and (b) diversity receiver Model R-42.

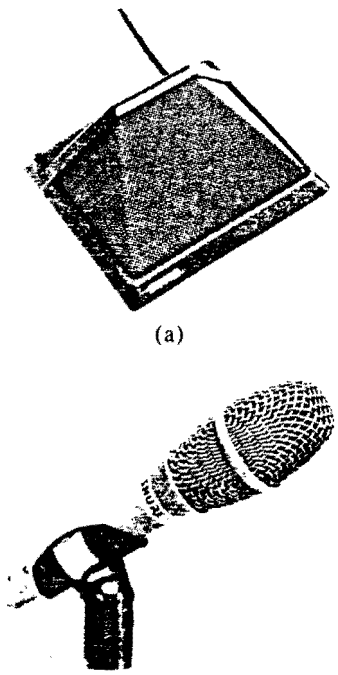
phone. The element in Fig. 50 is a cartridge [illegible] must be mounted in housing for use on a headset.

The graph shows the principle of operation: the far-field response to a distant sound source rises at 6 dB per octave because the displacement-sensing element is actuated by the pressure difference between the front and back sound openings, which rises with frequency. The near-field response, with a person speaking very close to the microphone, is uniform with frequency due to the proximity effect of a velocity microphone being additive to the far-field response curve.

If the far-field sound sources are ambient noise, the noise-canceling effect is the difference between the near- and far-field curves. Therefore the noise-canceling microphone is most effective in canceling low-frequency noise, and is used in voice communications in commercial and military aircraft, spacecraft, land mobile, and marine applications. Dynamic moving-coil and [illegible] used in these microphones, and the electret condenser is rapidly replacing many of these transducers. Carbon transducers were used in noise-canceling microphones, but are little used today. Styles of noise-canceling microphones include hand-held and stand-mounted types in addition to the boom-mounted headset models.

5.10 Conference Microphone

Fig. 51(c) shows a teleconferencing microphone which was described by Snyder [41]. This microphone is currently being provided by Bell Telephone as part of their teleconferencing system. The microphone is placed at the center of a conference table and is claimed to provide uniform pickup of speech from all participants, while rejecting reverberant sound and noise. The microphone consists of a vertical array of omni-



(a)

(b)

Fig. 48. Direction-sensing microphones. (a) Shure model AMS-22. (b) Shure model AMS-26.

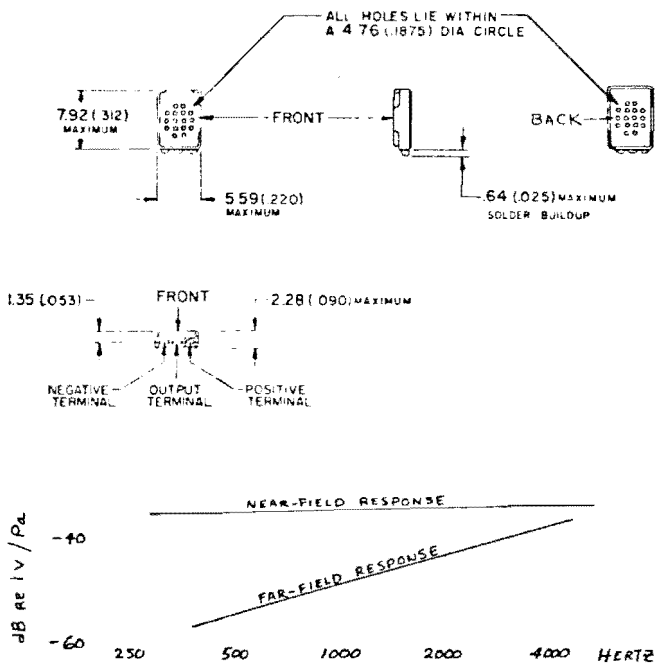


Fig. 50. Noise-canceling microphone element (Knowles Electronics model BW-1789). Dimensions in millimeters (inches). Nominal weight 0.28 gram.

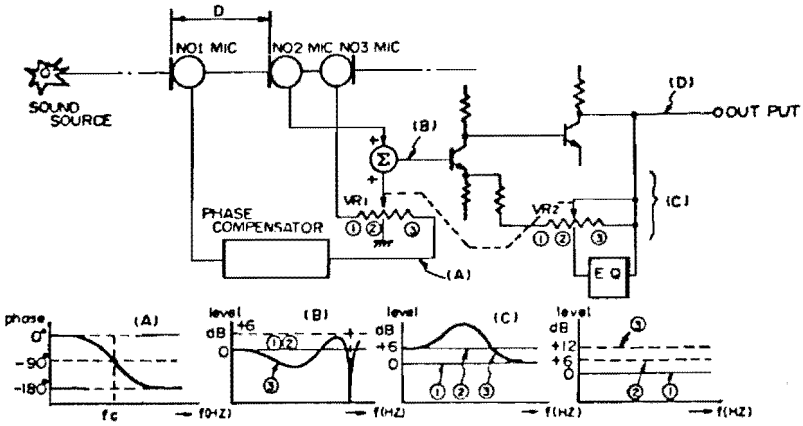


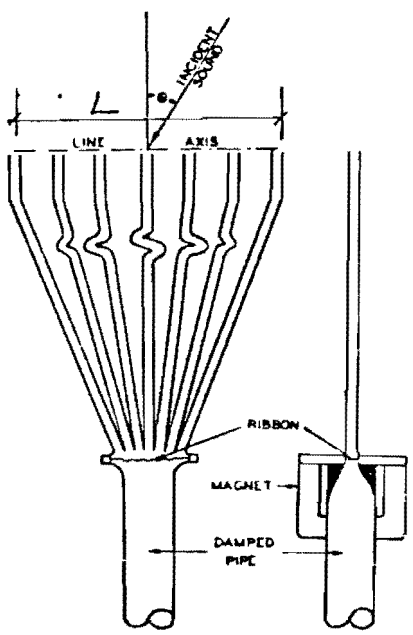
Fig. 49. Zoom microphone. (From Ishizaki et al. [40].)

directional electret condenser elements which [illegible] a 360° toroidal shaped pickup pattern with maximum sensitivity in the plane of the talkers' mouths. The uneven spacing of the elements provides better rejection of sounds at 90° to the plane of maximum sensitivity.

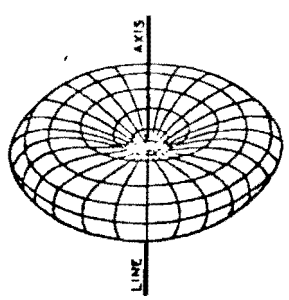
Olson [33] describes a line microphone with a ribbon pressure element which has maximum sensitivity at right angles to the line axis and a toroidal pattern as shown in Fig. 51(a) and (b). This line microphone is equivalent to a vertical array of pressure microphones, and so the theory developed by Olson applies to the teleconferencing microphone.

5.11 Hot-Wire Microphone

The hot-wire microphone (Fig. 52) consists of a fine wire which is heated by direct current and cooled by the alternating air flow of a sound wave. This causes a change in the electric resistance of the wire. The output waveform is twice the frequency of the sound wave because the wire is cooled by positive and negative particle velocities. Therefore according to Olson [3, pp. 329–331], it cannot be used for the reproduction of sound.



(a)



(b)

5.12 Throat Microphone

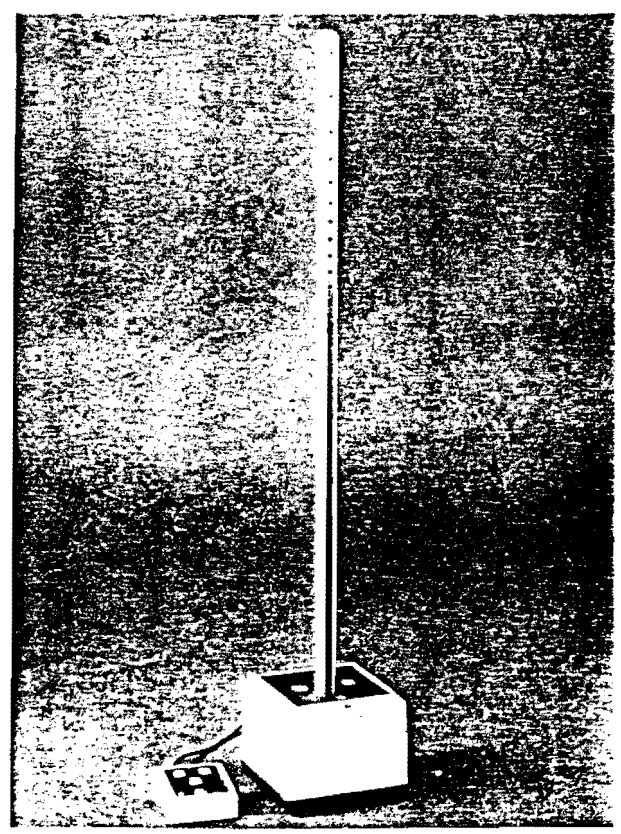
The throat microphone is pictured in Fig. 53 and described by Olson [3]. The carbon transducer is directly driven by contact with the throat. The acoustical impedance of the vibrating system is higher than for a microphone that is used in air, because of the high acoustical impedance of the flesh of the throat. The high-frequency response of the microphone must be boosted to compensate for loss of high-frequency consonants in passing through the throat. Other kinds of transducers may be used. The throat microphone was used in military aircraft in World War II, but is now obsolete.

5.13 Ear Microphone

The ear microphone pictured in Fig. 54 was introduced a few years ago by Lear-Siegler for radio communications applications where the hands remain free. It is simply a magnetic earphone transducer used in reverse. The voice sound present in the ear canal is missing much of the high-frequency consonant sounds, so high-frequency boost in the amplifying system is required. The author heard a demonstration of a system, and speech was quite intelligible. An additional novelty of the system is that the transducer is used as an earphone as well, thus providing two-way communications.

5.14 Tooth Microphone

This was developed by Brouns [42] for providing



(c)

Fig. 51. Conference microphone. (a) Ribbon/line type, Olson, 1939. (From Olson [33].) (b) Three-dimensional polar pattern of (a) at $L = 2\lambda$. (c) Teleconference microphone.

improved intelligibility of speech from deep [illegible] who are breathing helium. It consists of a piezoelectric accelerometer which is fastened to a tooth (Fig. 55). The author indicates that the microphone produces intelligible speech but reports considerable difficulty in having a wire protrude from the mouth. He recommends some form of telemetry to eliminate the hard wiring.

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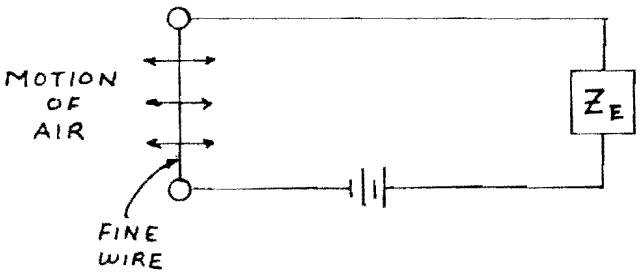

Fig. 52. Hot-wire microphone. (From Olson [3, pp. 329–331].)

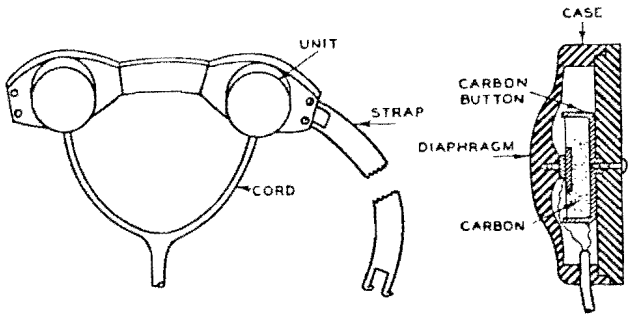

Fig. 53. Throat microphone. (From Olson [3, pp. 329–331].)

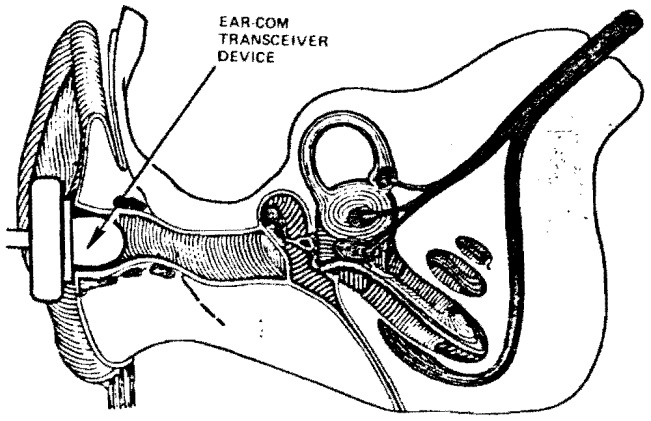

Fig. 54. Ear microphone. (Courtesy of Centurion International)

7 REFERENCES

[1] H. F. Olson, Ed., *McGraw-Hill Encyclopedia of Science and Technology*, 5th ed. (McGraw-Hill, New York 1982), vol. 18, p. 506.

[2] L. L. Beranek, *Acoustic Measurements* (Wiley, New York, 1949), pp. 148–158.

[3] H. F. Olson, *Acoustical Engineering* (Van Nostrand, Princeton, NJ, 1957).

[4] M. C. Killion and E. V. Carlson, "A Wideband Miniature Microphone," *J. Audio Eng. Soc.*, vol. 18, pp. 631–635 (1970 Dec.).

[5] M. C. Killion and E. V. Carlson, "A Subminiature Electret-Condenser Microphone of New Design," *J. Audio Eng. Soc.*, vol. 22, pp. 237–243 (1974 May).

[6] E. Joscelyn, M. Ferrante, and R. Saiya, "Accurately Tensioned Piezoelectric Diaphragm Microphone," U.S. patent 4,379,211 (1983 Apr. 5).

[7] G. Rasmussen, "A New Condenser Microphone," *Tech. Rev.*, Brüel & Kjaer, Copenhagen, no. 1 (1959).

[8] H. F. Olson, "Directional Electrostatic Microphone," U.S. patent 3,007,012 (1961 Oct. 31).

[9] E. Fredericksen, N. Eirby, and H. Mathiasen, "Prepolarized Condenser Microphones for Measurement Purposes," *Tech. Rev.*, Brüel & Kjaer, Copenhagen, no. 4, (1979).

[10] H. Kubota, "Back Electret Microphones," presented at the 55th Convention of the Audio Engi-

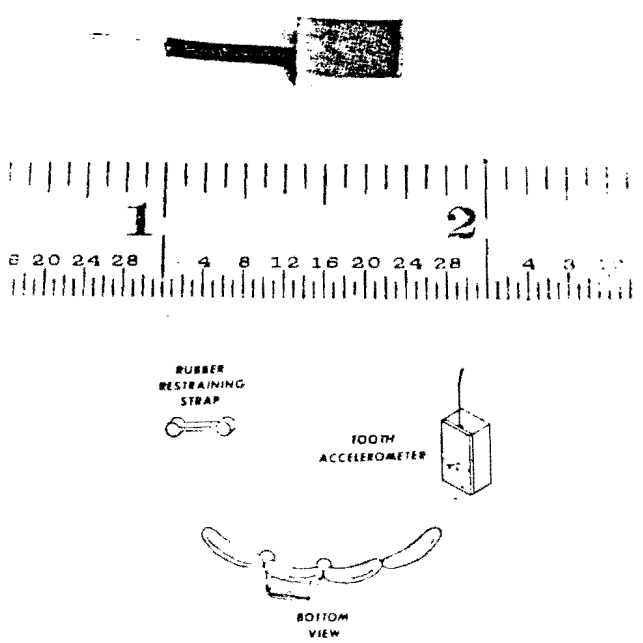

Fig. 55. Tooth microphone. (From Brouns [42].)