Chapter

4.1
Microphones

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4.1.1 Introduction

A microphone is an electroacoustic device containing a transducer which is actuated by sound waves and delivers essentially equivalent electric waves. The classes of microphones include 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 of a similar cosine-function limacon 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 chapter 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.

4.1.2 Pressure Microphones

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 widely used in telephone communications. This is true 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.

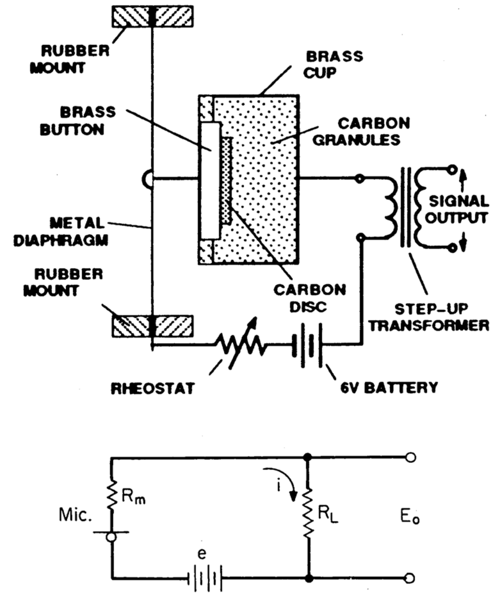


Figure 4.1.1 Carbon microphone and equivalent electric circuit.

A typical single-button carbon microphone and its electric circuit are shown in Figure 4.1.1. 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 the contact cup. For small displacements, the variation in resistance is proportional to the displacement.

The output voltage is given by

$$E_0 = \frac{eR_L}{(R_m + R_L) + (hx \sin \omega t)} \tag{4.1.1}$$

Where:
e = dc voltage of bias source
h = constant of carbon element, Ω/cm
x = amplitude of diaphragm, cm
$\omega = 2\pi f$
f = frequency, Hz

The useful audio output is, of course, the ac component of E_0. Equation (4.1.1) may be expanded ([2], pg. 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.

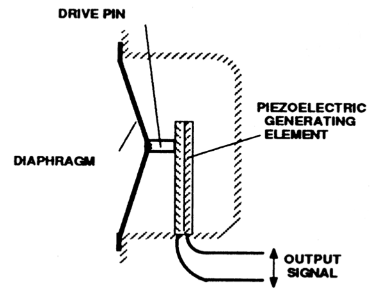


Figure 4.1.2 Typical construction of a ceramic microphone.

The large second-harmonic distortion component can be eliminated through use of two carbon buttons in push-pull. 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 are very poor.

For improved performance in telephone and speech communications, carbon microphones have largely been 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.

4.1.2a Piezoelectric Microphone

The *piezoelectric microphone* contains a transducer element that 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 crystals. There are two general classifications of ceramic microphones: direct-actuated and diaphragm-actuated. Directly actuated transducers consist of stacked arrays of bimotph crystals or *sound cells*.

Figure 4.1.2 shows a common construction 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 polyester film may also be used. The impedance of the ceramic microphone is capacitive on the order of 500 to 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

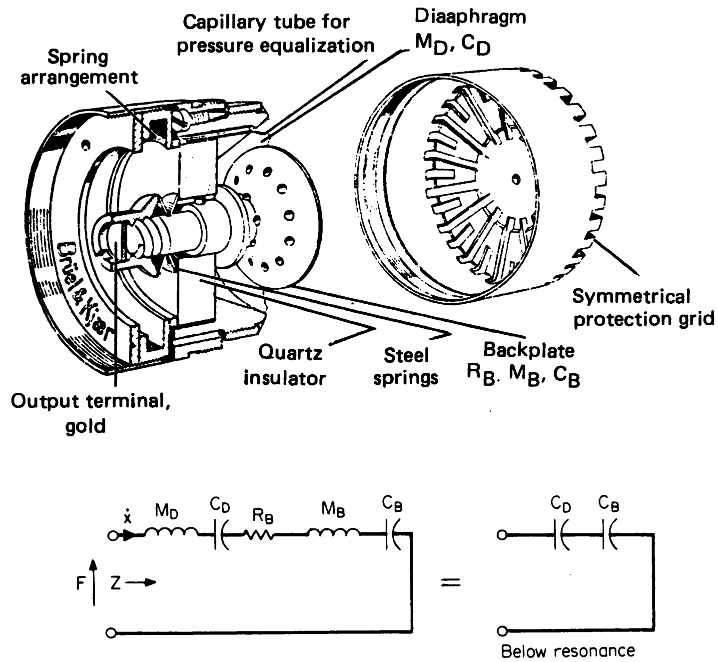


Figure 4.1.3 Condenser pressure microphone and mechanical network. (*From* [3]. *Used with permission.*)

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 were needed and the ceramic microphone has since been replaced by inexpensive moving-coil (dynamic) microphones or electret condenser microphones, which typically include integral field-effect transistor (FET) preamplifiers that convert their output to low impedance.

The piezoelectric diaphragm transducer is a variation on the basic theme. A thick or thin film of the polymer polyvinylidene fluoride (PVF_2) may be processed to form a piezoelectric element. As with the ceramic element, it must be provided with plated-on output terminals.

4.1.2b Electrostatic (Condenser) Microphones

A *condenser microphone* depends for its operation on variations in its internal capacitance. Figure 4.1.3 shows the capsule of an omni-directional pressure-sensing condenser microphone [3]. Condenser microphones are divided into two classes: externally polarized (air condenser) and 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 preamplifier, which must be located close to the capsule. Alternately, the capacitance variation can be used to frequency-modulate a radio-frequency (RF) oscillator.

The diaphragm of this microphone is a thin membrane of nickel that is spaced about 0.001 in (25 μm) from the backplate. Because the electroacoustical sensitivity is inversely proportional to the spacing *d,* special measures must be taken to prevent this distance from changing because of temperature. The laboratory-grade microphone of Figure 4.1.3 is made almost entirely 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 (Figure 4.1.3). The resonance is placed at the high end of the usable frequency range. The backplate 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 D_D determine the resonance frequency. R_B provides damping of the resonance. Below the 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 ([2] and [4])

$$E = \frac{E_0}{d}x \quad x = \frac{\dot{x}}{j\omega} \tag{4.1.2}$$

Where:
E_0 = polarizing voltage (or equivalent voltage for electrets)
d = spacing from diaphragm to backplate, m
x = diaphragm displacement, m
$\dot{x}$ = diaphragm velocity, m/s
$\omega = 2\pi f$
f = frequency, Hz

The velocity is given by

$$\dot{x} = \frac{F}{Z} = \frac{PA}{(1/j\omega)(1/C_{\mathrm{D}} + 1/C_{\mathrm{M}})} \tag{4.1.3}$$

Where:
F = force on diaphragm, N
P = sound pressure on diaphragm, N/m^2
A = area of diaphragm, m^2
Z = mechanical impedance system, mechanical ohms

The output voltage is obtained by combining Equations (4.1.2) and (4.1.3).

$$E = \frac{E_0 PA}{d\left(\frac{1}{C_D} + \frac{1}{C_B}\right)} \tag{4.1.4}$$

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

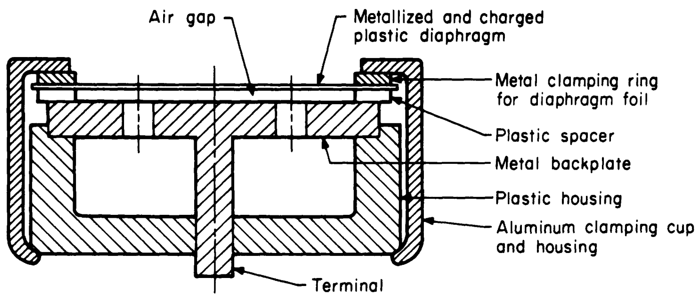


Figure 4.1.4 Typical design of an electret capsule with a charged foil diaphragm. (*From* [7]. *Used with permission.*)

Because of the high polarization field strength for most condenser microphones, the slightest bit of contamination between diaphragm and backplate 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.

4.1.2c Electret Microphone

The simplest type of electret microphone is the charged-diaphragm type. This is illustrated in Figure 4.1.4. The spacing between diaphragm and backplate is exaggerated for clarity. Figure 4.1.5 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. 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 A (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 [5]. 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 backplate (Figure 4.1.6). This and other schemes used to increase stiffness can lead to short-term instability [6]. Therefore, the charged-diaphragm electret generally does not possess the extended high-frequency response and stability of the air-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 [7]. Figure 4.1.7 shows a simplified cross section of a typical design. (Dimensions are exaggerated for clarity. (This is a pressure-gradient microphone, to be discussed later.) The diaphragm is a polyester film such as Mylar, approximately 0.0002 in (5 μm) thick. This is an ideal material and

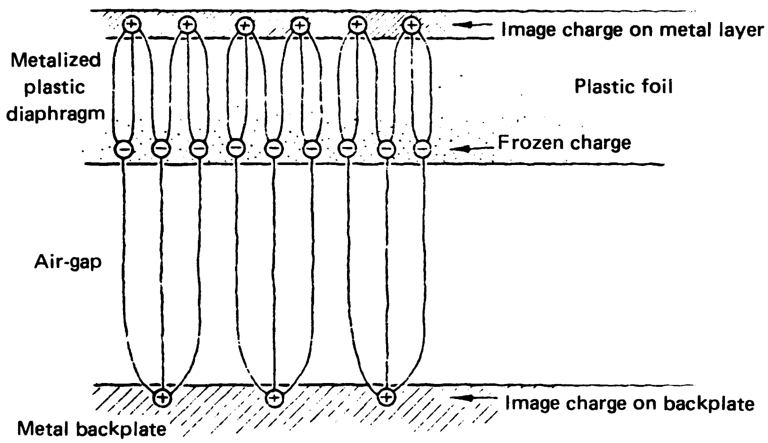


Figure 4.1.5 Positions of charges for space-charge electret when the electret is an integral part of the diaphragm. The frozen charge and the charge on the backplate produce the field in the air that is necessary for microphone operation. (*From* [7]. *Used with permission.*)

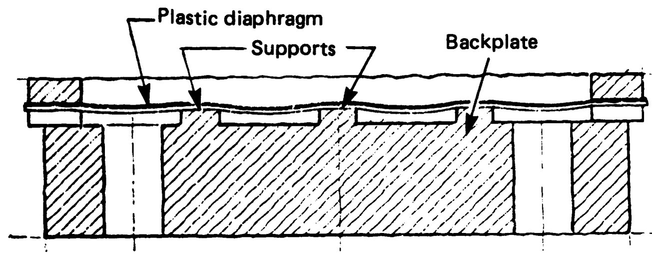


Figure 4.1.6 Principle used by some manufacturers to obtain a sufficiently high resonance frequency of plastic diaphragms having low creep stability. (*From* [7]. *Used with permission.*)

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 backplate, 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 optimal 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 to 200 V, which is the same as that used in high-quality air-condenser microphones. (Teflon and Mylar are trademarks of E. I. du Pont de Nemours and Co., Inc.)

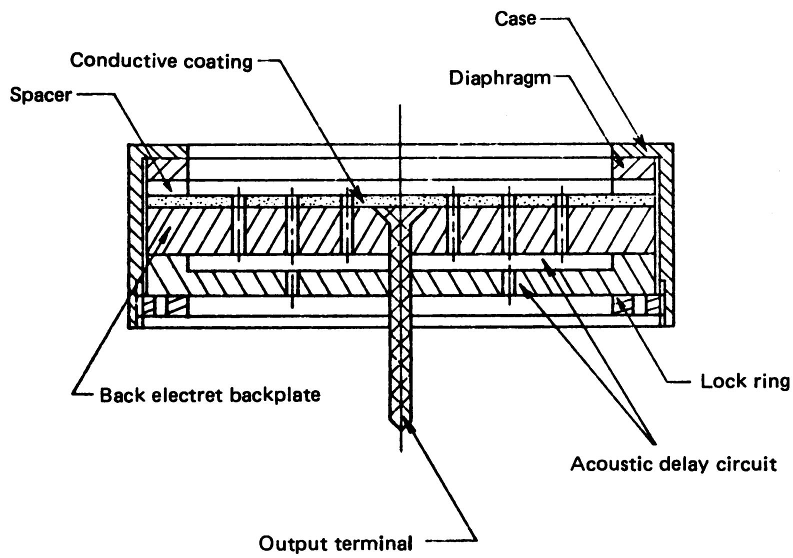


Figure 4.1.7 The back-electret capsule. (*From* [5]. *Used with permission.*)

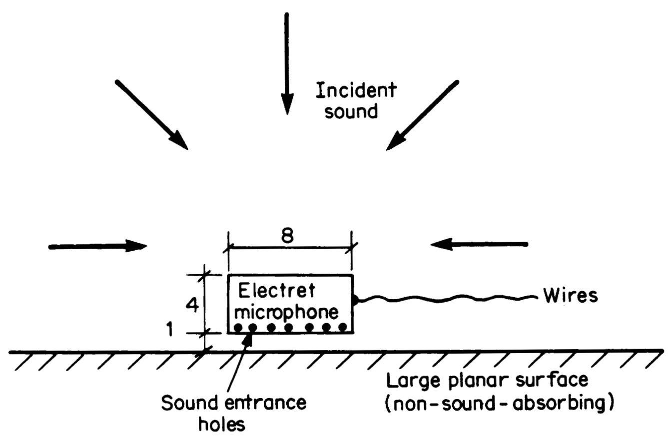


Figure 4.1.8 Boundary-microphone principle. Dimensions are in millimeters.

4.1.2d Boundary Microphone

The boundary microphone involves a *pressure-recording process* in which a conventional microphone is placed very close to a plane surface such as a floor [8]. This has given rise to a number of products which basically function as shown in Figure 4.1.8. 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

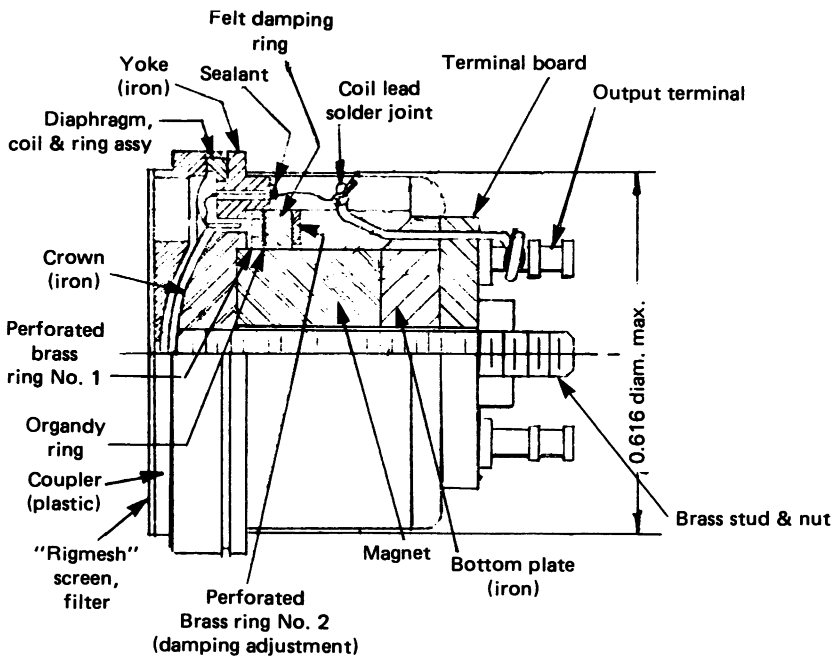


Figure 4.1.9 Dynamic moving-coil pressure-microphone cartridge.

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.

4.1.2e Electrodynamic Microphones

A cross section of a moving-coil-microphone cartridge is shown in Figure 4.1.9, and the complete microphone assembly in Figure 4.1.10 [9]. The diaphragm, which is made of Mylar polyester film 0.00035 in (9 μm) thick, is glued to a voice coil, which moves in the magnetic air gap. The flux density is 10,000 G (1 Wb/m^2). The self-supporting coil is wound with four layers of no. 50 AWG copper wire, which results in a dc resistance of 220 Ω. The ac impedance of 200 to 250 Ω is suitable for standard low-impedance microphone inputs of 150 to 600 Ω. Older microphone coils were on the order of 5- to 20-Ω resistance and required a step-up matching transformer in the microphone case. Thus the modern moving-coil microphone will drive standard

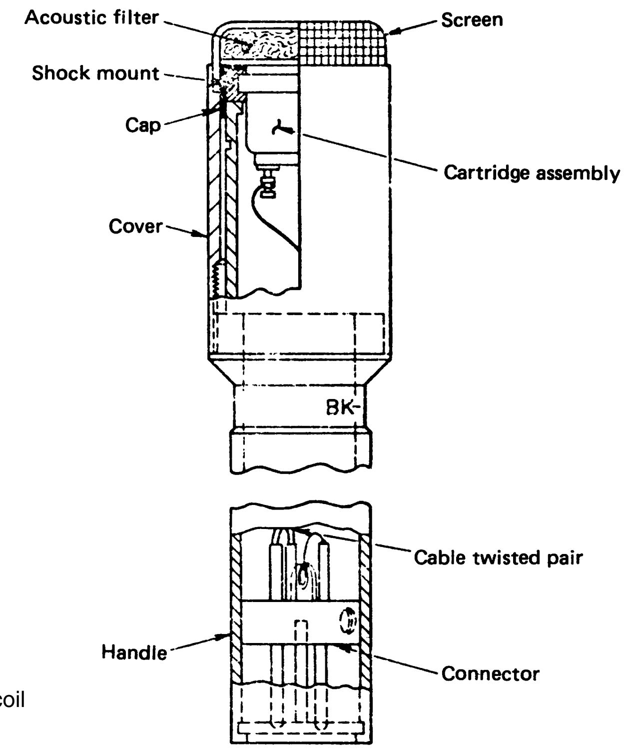


Figure 4.1.10 Dynamic moving-coil microphone.

bipolar integrated circuits directly. The coupler (Figure 4.1.9) fits closely to the diaphragm to provide mechanical protection without frequency discrimination. The cartridge is shock-mounted in the case of Figure 4.1.10, which includes a foam filter screen for dirt and breath "pop" protection.

The voltage induced in the voice coil is given by

$$E = Bl\dot{x} \tag{4.1.5}$$

Where:
E = open-circuit voltage, V
B = air-gap flux density, Wb/m^2
l = length of conductor in air gap, m
$\dot{x}$ = velocity of coil, m/s

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 a typical coil and diaphragm (measured in a vacuum) is about 800 Hz. If the resonance is not well damped, the coil velocity will peak at 800 Hz. This resonance is heavily damped by the acoustic resistance of the felt damping ring so that 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 form of bass-reflex action in which the mass of the air in the tube resonated with the compliance of the air in the case.

4.1.3 Pressure-Gradient (Velocity) Microphones

A sectional view of a classic ribbon velocity microphone (RCA type BK-11A) is shown in Figure 4.1.11. 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 of 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 in (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 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 provide low-frequency rolloff for the proximity effect. The frequency response is + 2 dB, 30 to 15,000 Hz.

The elements of the complete equivalent mechanical circuit (Figure 4.1.11) 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

$$\dot{x} = \frac{(P_1 - P_2)A_R}{j\omega(M_R + M_L)} \tag{4.1.6}$$

Where:
$\dot{x}$ = ribbon velocity, m/s
$(P_1 - P_2)$ = difference in sound pressure (pressure gradient) between two sides of ribbon, N/m^2
A_R = area of ribbon, m^2
M_R = mass of ribbon, kg
M_L = mass of air load acting on ribbon, kg
$\omega = 2\pi f$
f = frequency, Hz

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-polepiece clearance forms a *leak* which, if excessive, will reduce sensitivity. To maintain a constant ribbon velocity with mass control per Equation (4.1.6), the pressure gradient must increase linearly with frequency. The open-circuit ribbon voltage is given by

$$E = Bl\dot{x} \tag{4.1.7}$$

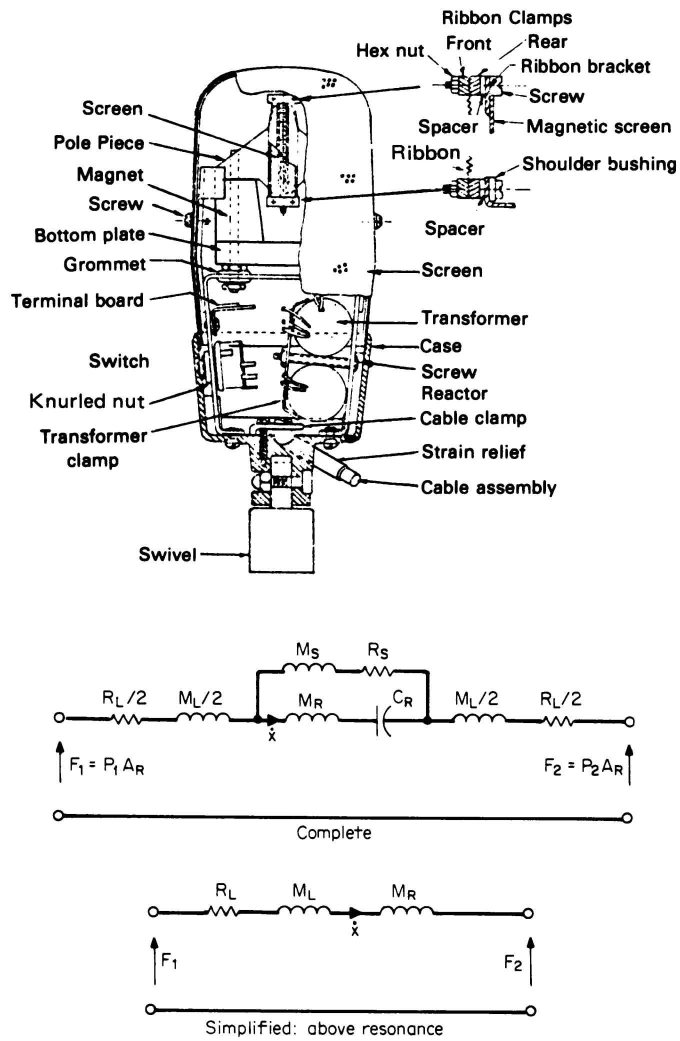


Figure 4.1.11 Classic ribbon velocity microphone (RCA type BK-11A) and equivalent electrical networks.

Where:
E = open-circuit voltage, V
B = air-gap flux density, Wb/m^2
l = length of ribbon, m
$\dot{x}$ = ribbon velocity, m/s

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 of the sound

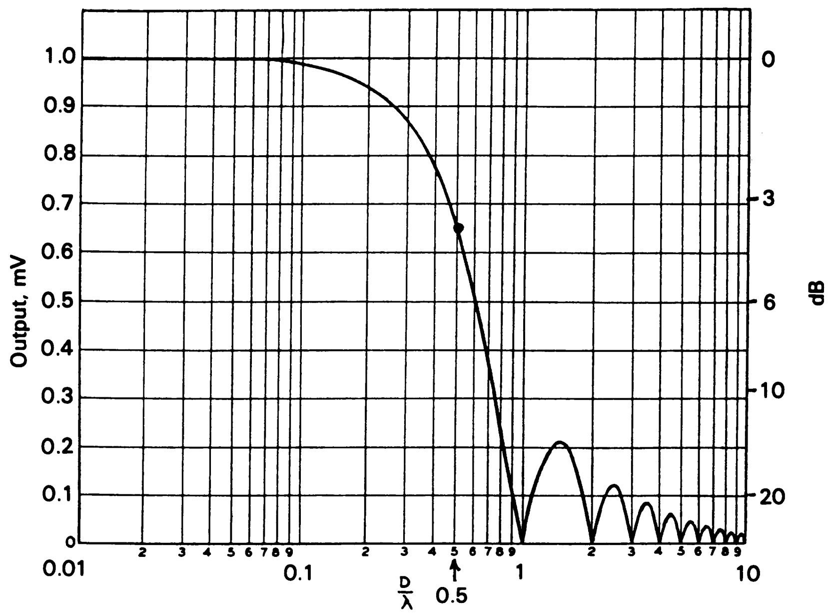


Figure 4.1.12 Computed open-circuit voltage response frequency characteristic of a pressure-gradient mass-controlled electrodynamic microphone. (*From* [10]. *Used with permission.*)

wavelength, the pressure gradient departs from a linear characteristic to 65 percent of the value needed for a constant ribbon velocity. At the frequency where the path length equals one wavelength, the pressure gradient is zero. Figure 4.1.12 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 4.1.13 shows how the figure-of-eight polar pattern becomes severely distorted above the half-wavelength frequency (*D* equals the path length). Below this frequency, the patterns are essentially perfect cosines.

A compromise solution is found in the contemporary ribbon velocity microphone. The head diameter is typically on the order of 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. They are usually corrugated longitudinally for most of their length, but a few conventional transverse corrugations may be formed near the ends to provide compliance. This type of ribbon, while difficult to make, can potentially solve several problems as compared with the conventional ribbons with transverse corrugations:

- The rigid central portion resists twisting, sagging, and scraping along the pole pieces.
- With the more rigid ribbon, the pole-piece-to-ribbon clearance may be reduced, thus increasing sensitivity.

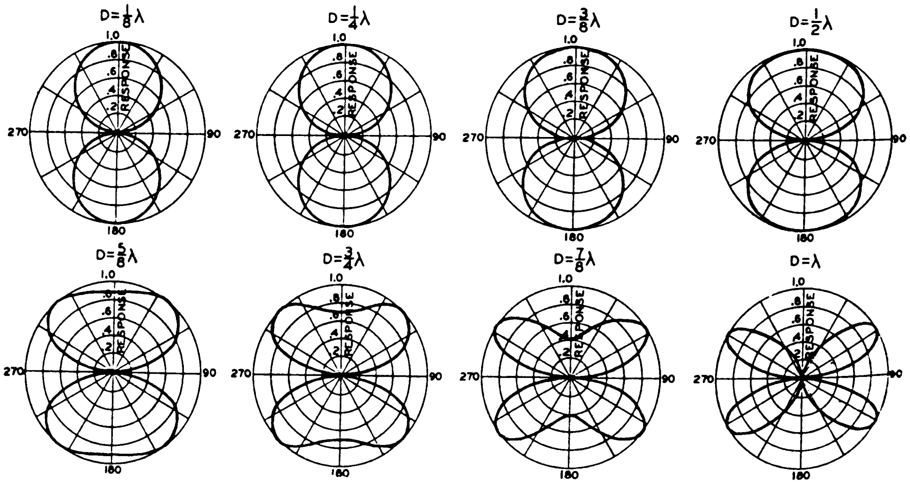


Figure 4.1.13 Directional characteristics of a pressure-gradient microphone as a function of dimensions and wavelength. The polar graph depicts output, in volts, as a function of angle, in degrees. The maximum response is arbitrarily chosen as unity. (*From* [10]. *Used with permission.*)

- 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.
- The longitudinal corrugations may reduce or eliminate transverse resonances, which produce small dips and peaks in frequency response above 8000 Hz.
- The short length of the ribbon makes the polar pattern in the vertical plane more uniform with frequency.

Most ribbon microphones have low magnetic-hum sensitivity because the ribbon circuit is easily designed to be *hum-bucking*. Ribbon microphones have low vibration sensitivity because the moving mass is very low.

4.1.3a Combination Pressure and Pressure-Gradient Microphones

Figure 4.1.14 illustrates graphically how the outputs of a bidirectional and a nondirectional microphone transducer can be mixed to obtain three unidirectional polar patterns. Actually, there are an infinite number of unidirectional patterns that may be obtained. The three patterns shown are hypercardioid, cardioid, and limacon, 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 the cardioid have exactly the same response, but the hypercardioid is superior to both of them in discrimination against random sound. A number of unidirectional microphones produced today are hypercardioids, but the cardioid remains the most popular. The limacon 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

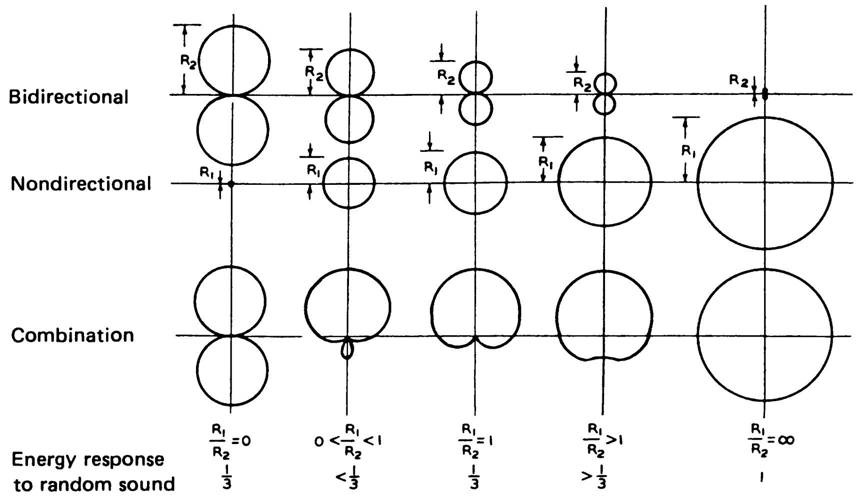


Figure 4.1.14 Directional diagrams of various combinations of bidirectional and nondirectional microphones and energy response to random sounds. (*From* [2]. *Used with permission.*)

single-transducer microphones have a mechanically variable delay system so that the pattern can be varied from bidirectional to cardioid to nondirectional.

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 [2]. Figure 4.1.15 gives curves for velocity and unidirectional microphones. If the curves for 0° are plotted to a decibel scale, the slopes follow linear 6-dB-per-octave characteristics. The unidirectional curves exhibit a corner (+3-dB) frequency that is one octave higher than those of the velocity microphone. 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, which has a reduced proximity effect.

Dual-Diaphragm Condenser Polydirectional Microphone

The dual-diaphragm microphone vibrating system consists of a pair of diaphragms, each spaced a small distance from the backplate, as in the pressure microphones described previously [11]. 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 backplate. The phase shift in this system plus the variable electrical polarizing system make possible a variety of directional patterns.

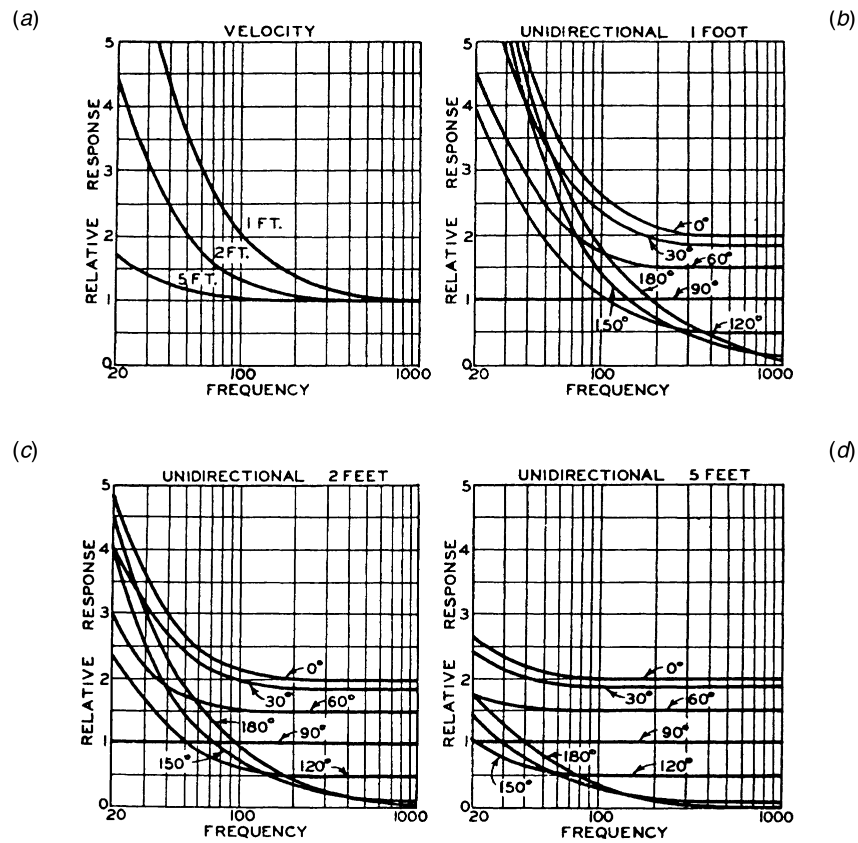


Figure 4.1.15 Microphone characteristics: (*a*) relative voltage output of a velocity (or pressure-gradient) microphone as compared with a nondirectional pressure microphone for distances of 1, 2, and 5 ft; (*b–d*) relative voltage output of a unidirectional microphone as compared with a nondirectional pressure microphone for distances of 1, 2, and 5 ft and for various angles of incident sound. (*From* [2]. *Used with permission*.)

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. 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

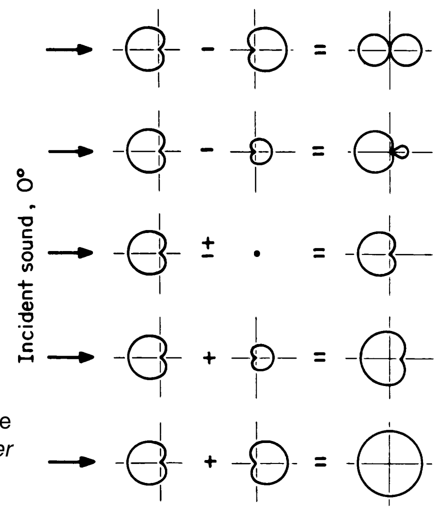


Figure 4.1.16 Condenser polydirectional microphone using two cardioid transducers back to back. (*After* [11].)

the backplate form a phase-shift network similar to the rear sound aperture of a single-element unidirectional microphone.

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. As in the case of 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 obtained with the larger-diaphragm transducers.

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 back to back. Figure 4.1.16 shows how two cardioid capsules placed back to back will function as a polydirectional microphone. As in the case of 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 $+E_0$, the same as in the dual-diaphragm transducer. The same polar patterns are obtained. Likewise, the same effect can 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 to 1.2 in (10 to 30 mm), comes into play, and the polar characteristics at high frequencies become nonuniform.

4.1.3b Single-Element Unidirectional Microphones

The classic single-element ribbon polydirectional microphone (RCA type 77-DX) is shown in Figure 4.1.17. 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 that 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 percent uncovered, which yields a cardioid pattern.

The simplified acoustical equivalent circuit of the microphone (Figure 4.1.17) 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
- 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 capacitive 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. The polar pattern is bidirectional or figure-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 with the impedance of $(M_R + R_L)$; so the volume current U is given by

$$U = \frac{p_1}{R_p} \tag{4.1.8}$$

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

With the shutter set for a cardioid pattern, part of the ribbon volume current U flows through R_P and part through $(M_S + R_S)$. Thus, the ribbon is partly controlled by P_1 and the line resistance

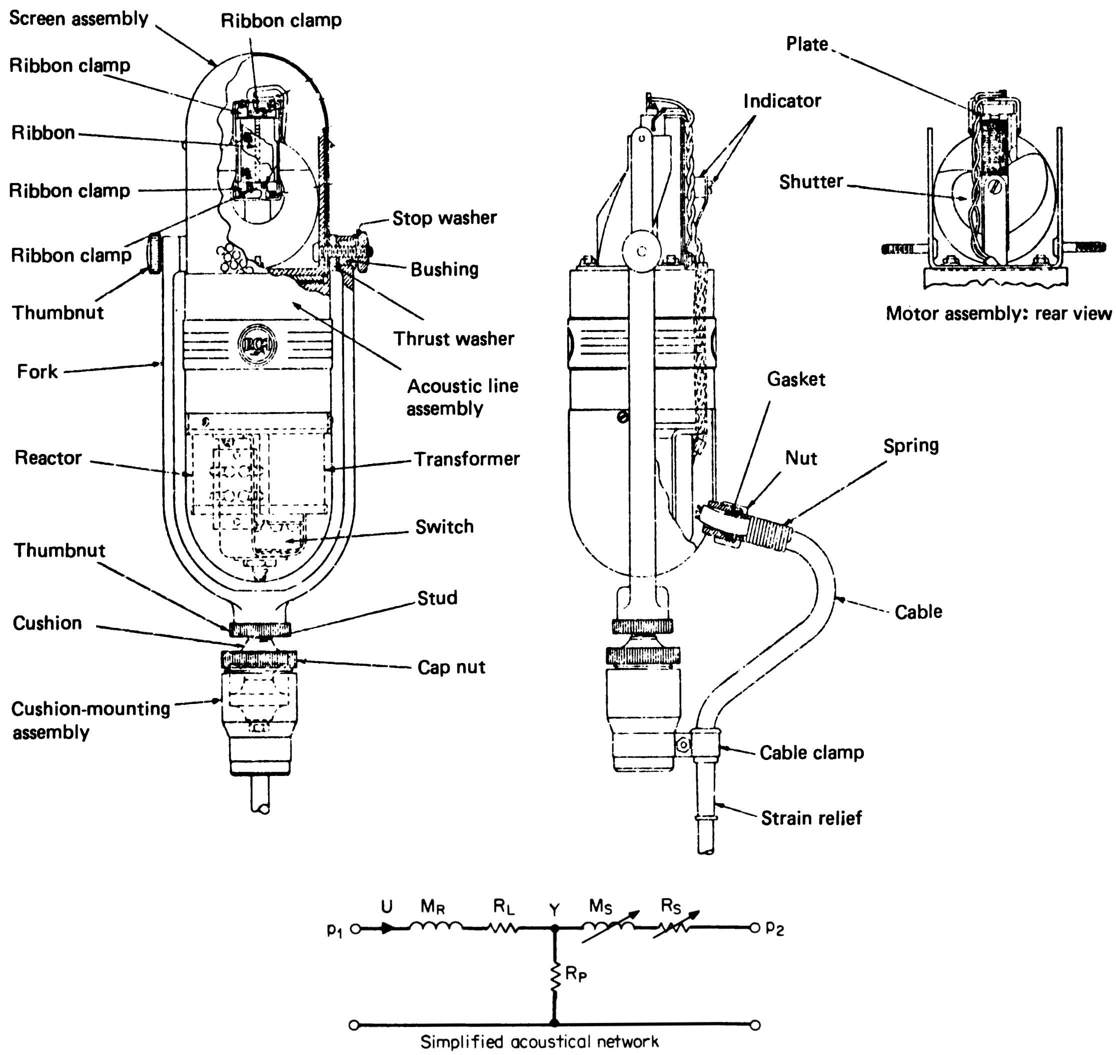


Figure 4.1.17 Ribbon polydirectional microphone and acoustical network (RCA type 77-DX).

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 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 the bidirectional set-

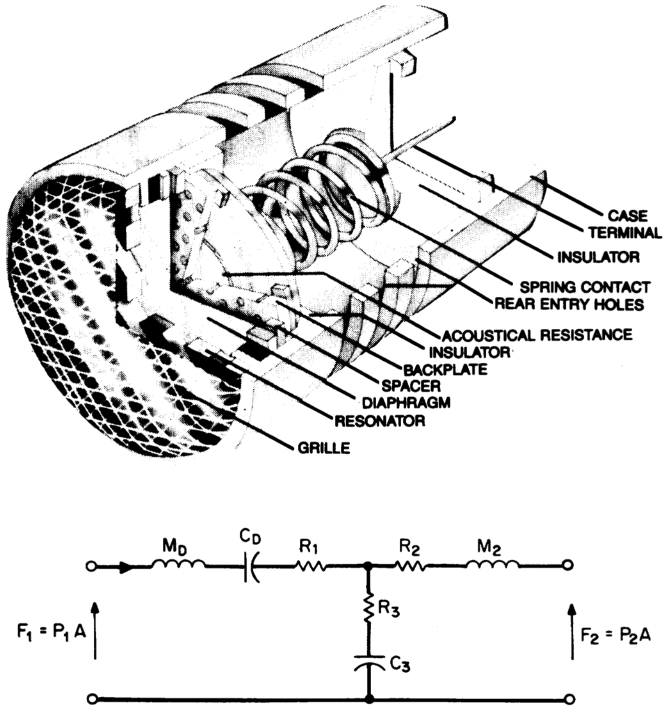


Figure 4.1.18 Unidirectional condenser microphone mechanical layout and simplified mechanical network. (*From* [4]. *Used with permission.*)

ting slopes downward with frequency, whereas the response at the nondirectional setting slopes upward. This is a limitation of the ribbon polydirectional microphone.

Unidirectional Condenser Microphone

The unidirectional condenser microphone incorporates a prepolarized capsule where the electret is on the backplate [4] and [12]. The unidirectional capsule backplate 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 can be determined from a consideration of the simplified mechanical network. (See Figure 4.1.18.) 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 backplate; R_3 is the resistance of the screen, which connects to the case volume C_3; and R_2 and M_2 represent the holes and screens at the rear sound entry.

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

$$\dot{x} = \frac{F_D}{Z_M} = \frac{j\omega KPA}{Z_M} \tag{4.1.9}$$

Where:
Z_M = mechanical impedance of vibrating system, mechanical ohms
F_D = force on diaphragm, N
K = transducer
P = sound pressure, N/m^2
A = area of diaphragm, m^2
$\omega = 2\pi f$
f = frequency, Hz

and the displacement is given by

$$x = \frac{\dot{x}}{j\omega} = \frac{KPA}{Z_M} \tag{4.1.10}$$

The output voltage is given by Equation (4.1.2).

Thus, for the 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 on a variety of configurations similar to the various networks in ribbon and dynamic microphones.

Moving-Coil Unidirectional Microphone

Figure 4.1.19 shows the basic mechanical cross section and acoustical network of the moving-coil unidirectional microphone. 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. The lowest attainable resonance is limited by the stiffness of the plastic-film diaphragm material.

The moving-coil system is mass-controlled above resonance as in 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.

Variable-Distance Unidirectional Microphone

Figure 4.1.20 shows a sectional view and the acoustical network of the variable-distance unidirectional microphone. The distance from front to rear sound entry varies approximately inversely with frequency [2]. 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

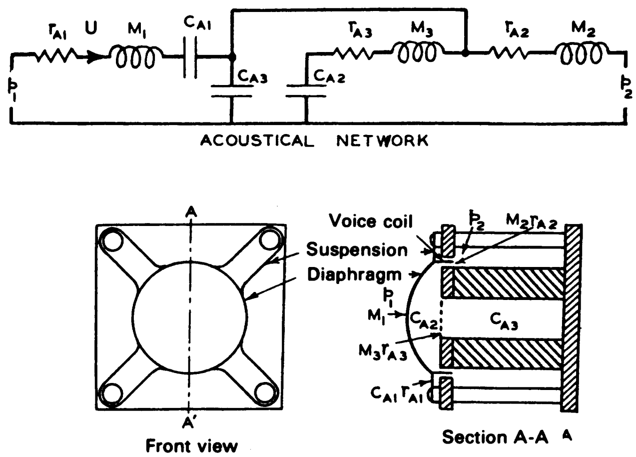


Figure 4.1.19 The basic acoustical network and mechanical construction of the moving-coil unidirectional microphone. (*From* [2]. *Used with permission.*)

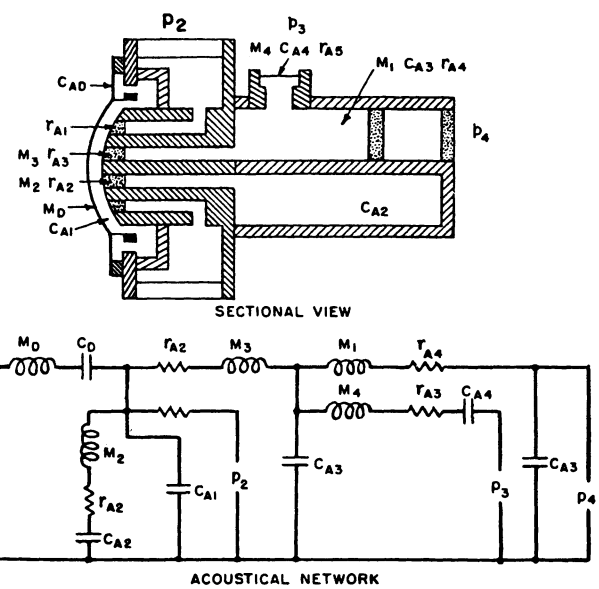


Figure 4.1.20 Sectional view and acoustical network of the variable-distance unidirectional microphone. (*From* [2]. *Used with permission.*)

is that accentuation of low frequencies due to the proximity effect is reduced. As with the moving-coil unidirectional microphone, the moving-system resonance is in the region of 100 Hz and is mass-controlled at higher frequencies.

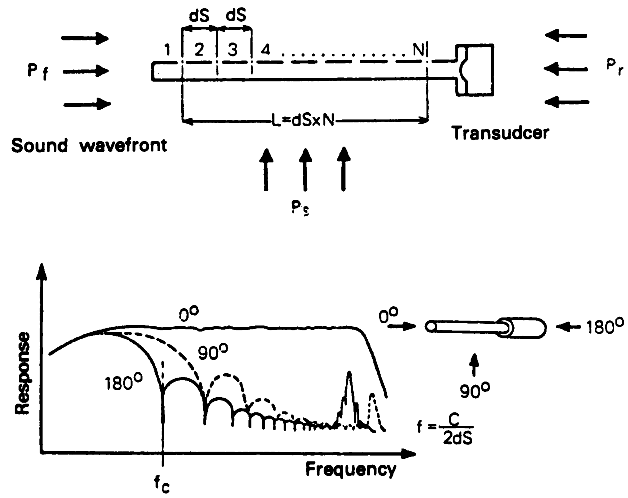


Figure 4.1.21 Operating principles of the line microphone. (*Courtesy of Sony.*)

4.1.4 Ultra-Directional Microphones

For the purpose of this discussion, an *ultradirectional microphone* is defined 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. The value of 0.25 is the random energy efficiency of a hypercardioid, which represents the highest directivity obtainable with a first-order gradient microphone [13]. 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 high-noise environments.

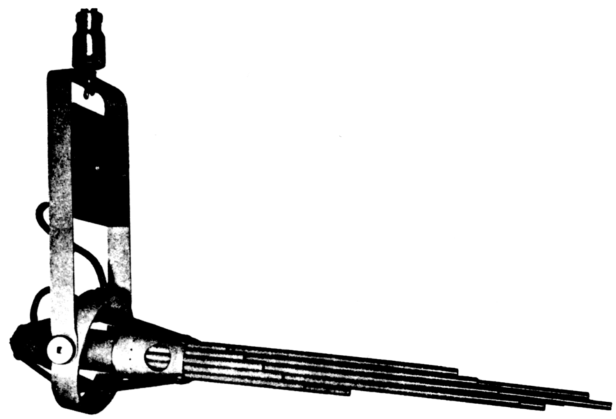
Of the many types of ultradirectional microphones developed, only the line-type microphone remains in common use. It employs high-sensitivity condenser or moving-coil electrodynamic transducers.

4.1.4a Line Microphone

A simple line microphone is shown in Figure 4.1.21. 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. 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 [14]

$$f_c = \frac{C}{2L} \tag{4.1.11}$$

(*a*)



(*b*)

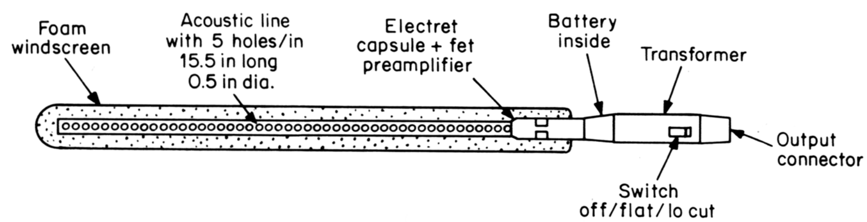


Figure 4.1.22 Line microphones: (*a*) bundled pipes, (*b*) single pipe with holes and electret condenser.

Where:
f_c = frequency, Hz
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*

$$f_n = \frac{C}{2dS} \tag{4.1.12}$$

where *dS* is the hole spacing, m.

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.

Figure 4.1.22 shows an electret condenser line microphone with a small-diameter line and a transducer capsule 0.6 in (16 mm) in diameter. The capsule and line are made as an assembly that 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 [15].

4.1.4b Wave Microphones

A parabolic reflector may be used to concentrate distant parallel rays of sound at a microphone placed at the focus. This concept is illustrated in Figure 4.1.23*a*. As in all wave-type microphones, the reflector must be large compared with a wavelength of sound to obtain a high order of directivity.

An acoustic lens microphone is a lens-like device made of sheet metal that can focus sound waves onto a microphone in a manner similar to the parabolic reflector (Figure 4.1.23*b*). The directivity follows the laws of wave-type microphones in much the same way as the parabola [2].

A large-surface microphone consisting of a large number of pressure-microphone elements arranged on a spherical surface is shown in Figure 4.1.23*c*. The polar pattern is similar to that of a curved-surface sound source, which emits uniformly over a solid angle subtended by the surface at the center of curvature. The microphone shown in Figure 4.1.23*c* is 4 ft (1.22 m) in diameter and has an angular spread of 50°. The pattern is reasonably uniform above 300 Hz [2].

4.1.5 Miscellaneous Types of Microphones

A two-channel microphone such as the one shown in Figure 4.1.24 is a convenient tool for sound pickup in the *x-y* or *M-S* stereophonic modes where coincident microphone transducers are required. The example device shown utilizes two dual-diaphragm condenser transducers, which are mounted on top of each other and in adjacent capsules sharing a common axis; 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.

4.1.5a Sound-Field Microphone

The original sound-field microphone was developed for the *ambisonic* surround system patented by the United Kingdom National Research Corporation and was produced by Calrec Audio Limited. This system was a form of quadraphonic sound. A later version of the device became 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 moved fore and aft as the ratio of direct to reverberant 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.

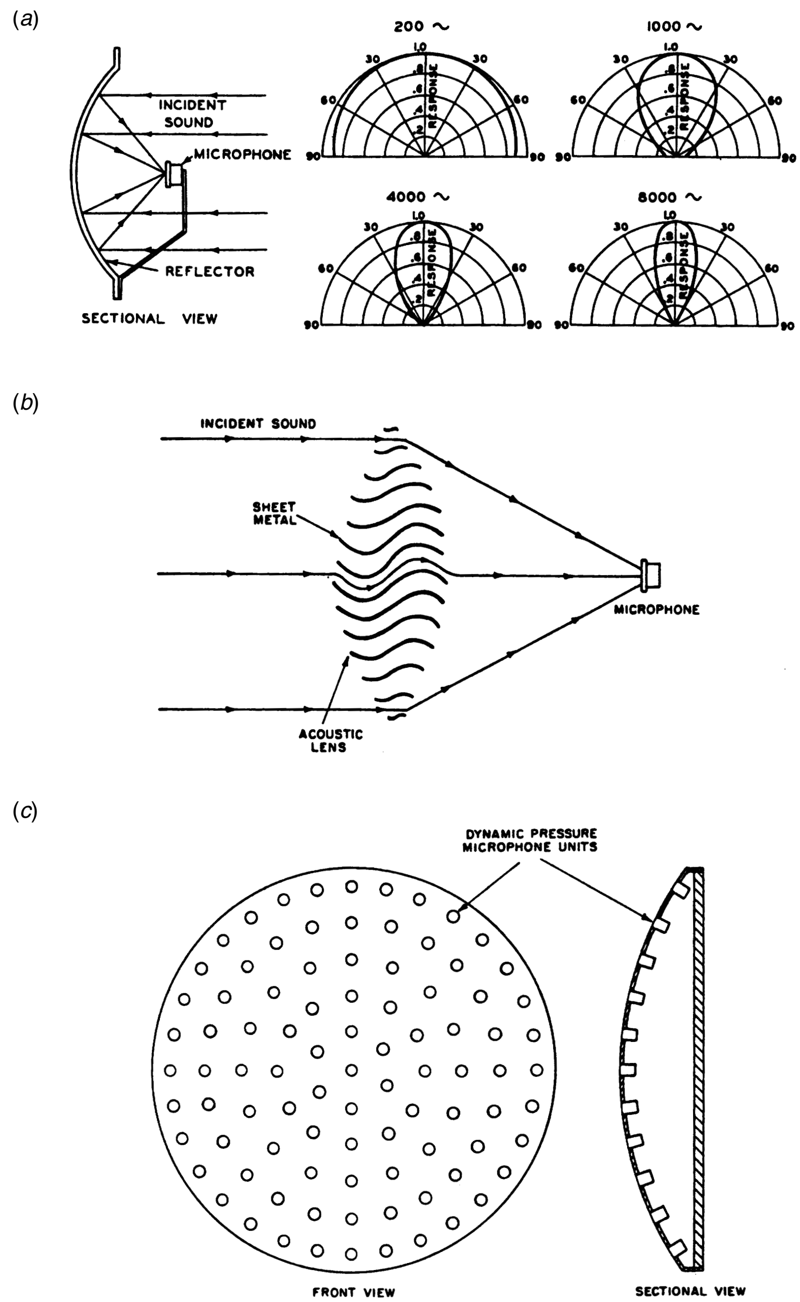


Figure 4.1.23 Wave microphones: (*a*) parabolic reflector, (*b*) lens, (*c*) large-surface. (*From* [3]. *Used with permission.*

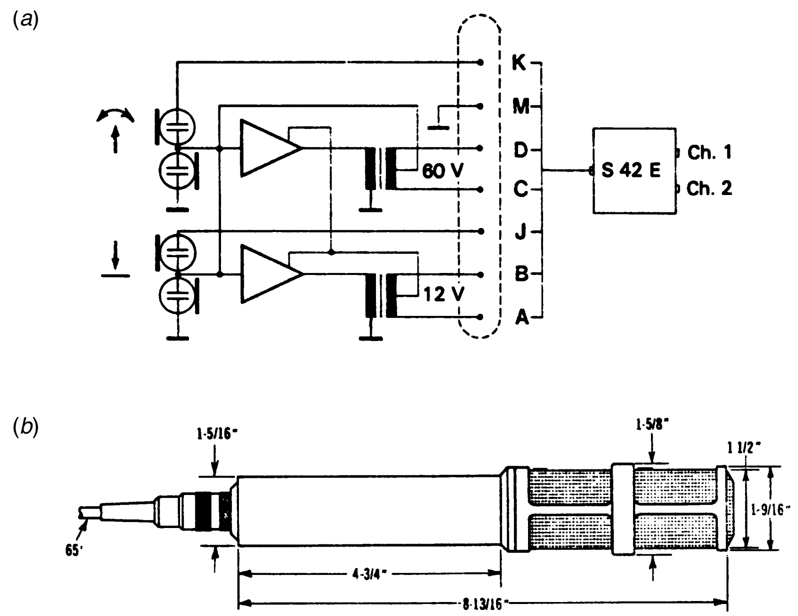


Figure 4.1.24 Stereophonic condenser microphone: (*a*) wiring diagram, (*b*) shell construction.

4.1.5b Lavaliere Microphone

The term *lavaliere microphone* refers to a small microphone that is typically fastened to the clothing of the speaker. When resting on the chest, the microphone requires rising high-frequency response compensation to adjust for the loss in response due to its location off the axis of the mouth. Very small electret condenser models available today utilize a subminiature pickup element. They are light enough so that they may be fastened to the clothing by means of a small clip attached to the cable below the microphone.

4.1.5c Wireless Microphone

A variety of wireless microphones are available today, usually either in a hand-held style or as a lavaliere microphone connected to a separate body-pack transmitter. These systems are widely used in television broadcasting and in professional entertainment.

4.1.6 Selecting Microphone Types

The hand-held microphone, probably the most popular type of mic, is available in many shapes and sizes. Manufactured in both directional and non-directional versions, the hand-held mic provides wide frequency response, low handling-noise and a wide choice of characteristic "sounds."

Because adequate space is available, a shock-mount system is incorporated into most professional hand-held microphones. Just holding a microphone or dragging the cable across a floor can cause low-frequency noise to be transmitted to the pickup element. A shock-mount system minimizes such noise.

The lavaliere microphone is also in high demand today. Its small size and wide frequency response offer professional users what appears to be the best of all worlds. Small size translates into minimum visual distraction on camera or before an audience. Wide frequency response assures good audio quality. There are other points to consider, however, before a lavaliere microphone is chosen for a particular application.

The smallest lavalieres available are omnidirectional. This makes the talent's job easier because staying *on mic* is less of a problem. However, extraneous noise from the surrounding area can result in a generally poor pickup. The omnidirectional lavaliere microphone can pick up unwanted sounds just as easily as it captures the talent's voice. In an indoor, controlled environment, this is usually not a problem. However, outside the ambient noise can make the audio track unusable.

Directional lavalieres are available, but they too have performance tradeoffs. The most obvious is size. In order to make a lavaliere directional, a back entry usually must be added to the housing so that sound can reach the back of the microphone. This translates into a larger housing for the microphone capsule. Although not as large as a hand-held microphone, a unidirectional lavaliere is noticeably larger than its omnidirectional counterpart.

In order to minimize the physical size, shock-mounting of the directional capsule is usually kept to a minimum. This results in a microphone that exhibits more handling noise than a comparable omni.

Windscreens for lavaliere microphones are a must on any outdoor shoot. Even a soft breeze can cause the audio track to sound as if it was recorded in a wind tunnel. The culprit is turbulence, caused by wind hitting the grille or case of the microphone. The sharper the edges, the greater the turbulence. A good windscreen helps to break up the flow of air around the microphone and reduce turbulence.

Windscreens work best when fitted loosely around the grille of the microphone. A windscreen that has been jammed down on a mic only serves to close off part of the normal acoustic path from the sound source to the diaphragm. The end result is attenuated high-frequency response and reduced wind protection.

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