SECTION 3

SPECIALIZED BROADCAST RADIO ENGINEERING

TECHNICAL ASSIGNMENT

MICROPHONES

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INTRODUCTION

GENERAL CONSIDERATIONS.—The microphone is at the head end of the broadcast system and its characteristics are of paramount importance in determining the technical performance of the system. It is therefore important that the broadcast engineer have an adequate knowledge of the types of microphones available, their characteristics, and the factors that determine the choice of one microphone over another with regard to the type of program to be broadcast.

Microphones can be classified according to:

1. Acoustical properties, and
2. Electrical properties.

Under acoustical properties come such features as frequency response and directional characteristics; under electrical properties come such characteristics as methods of generating the electrical wave, impedance considerations, output level and the like.

TYPES OF MICROPHONES.—At this point, it will be of value to survey briefly the various types of microphones that are available. A more detailed description will be given later. The first and oldest type is essentially a loudspeaker motor unit that is actuated as a generator by the acoustic wave. It represents the class known as the moving-conductor type. This type is at present used in various forms and is known in one form as the dynamic type.

Moving-Conductor Microphone.—Fig. 1 shows a simplified model of this type of microphone. It will be observed that a dynamic speaker type of permanent magnet is employed in whose air-gap is placed a circular voice coil. The magnetic lines of force in the air-gap are radial and hence perpendicular to the coil. The coil is fastened to a dome-shaped diaphragm which is caused to vibrate by the acoustic wave and in so doing produces a cutting of the magnetic lines of force by the voice coil. An audio voltage is thereby generated by the voice coil and this represents the electrical output of this type of microphone.

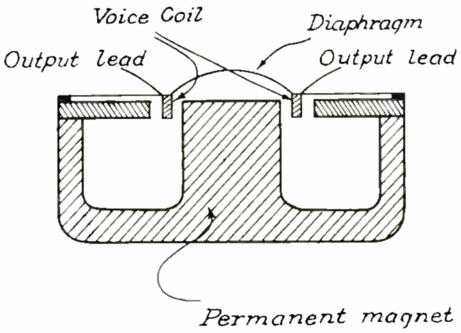


Fig. 1.—Dynamic Type of Moving-Conductor Microphone.

Ribbon Microphone.—Another important moving-conductor microphone is shown in Fig. 2. This also operates on the basic principle of a conductor (in the form of a ribbon) cutting the magnetic flux when actuated by an acoustic wave, and thereby generating an audio voltage. It is known as the ribbon microphone, and while its action electrically is identical to that of the diaphragm type shown in Fig. 1, acoustically its behavior is quite different.

Inductor Microphone.—A further variation on the type shown in Fig. 1 is obtained by having a single straight conductor mechanically fastened to the diaphragm. This conductor is suspended in a narrow straight air-gap of a permanent magnet and generates an audio voltage by cutting the lines of magnetic flux. It is known as the inductor microphone and has characteristics very similar to the dynamic microphone.

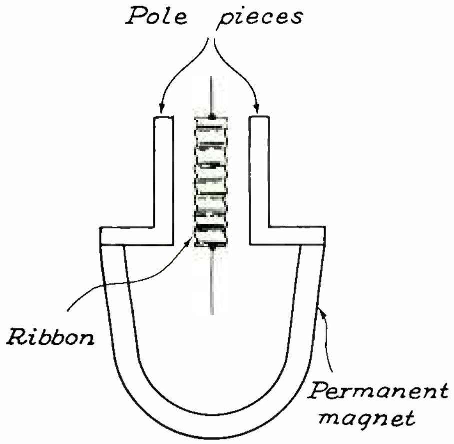


Fig. 2.--Ribbon Type of Moving-Conductor Microphone.

Carbon-Button Microphone.—While the above microphones are the preferred types in use today, their forerunner, namely, the ordinary telephone receiver as employed by Alexander Graham Bell, was so inefficient that early in telephone art a microphone of higher output was developed. This was the carbon-button microphone. A practical, successful model was developed by Thomas A. Edison. A simple schematic form is shown in Fig. 3. Here a brass cup is employed which is filled with carbon granules. Two carbon discs as shown make contact with the granules. One of the discs is actuated by a diaphragm. The complete assembly or button is connected in series with a source of d.c. and the primary of an audio transformer. The variable pressure on the granules produced by the vibrating upper disc varies the electrical resistance of the circuit and thereby produces audio variations in the button current. These are transferred to the secondary of the audio transformer and can be made to actuate an ordinary telephone receiver, or—if desired—an audio amplifier and loudspeaker.

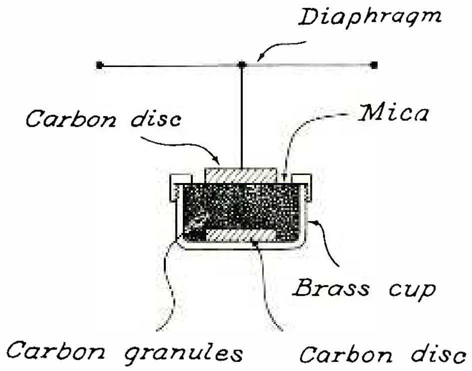


Fig. 3.--Carbon Button Type of Microphone.

This is the well-known transmitter in universal use in telephone systems today. It has the important characteristic of furnishing considerably more electrical output than the acoustical power impinging on its diaphragm, because the latter *controls* the electrical output, which can be of much greater magnitude. It represents one of the earliest forms of audio amplifiers known. Because of this important property, it is still used where quality of reproduction is not as important as economy and simplicity; i.e., in commercial communication systems.

For high quality broadcasting, however, its characteristics are unsatisfactory. An improved double-button model that operates very much like a pushpull amplifier has been developed and will be discussed subsequently. However, even this type is not employed to any appreciable extent in broadcast stations today.

Condenser Microphone.--In Fig. 4 is shown a subsequent type known as the condenser microphone.

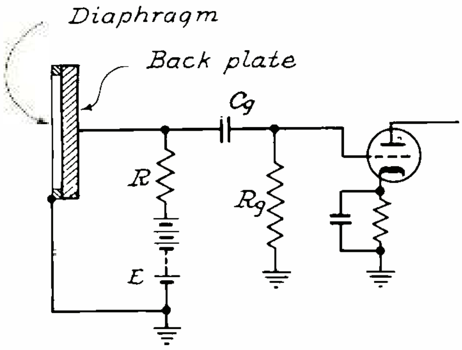


Fig. 4.—Condenser Type of Microphone.

This represented a considerable improvement over the carbon-button microphone but nevertheless has been superceded to a large degree by the moving-conductor types illustrated in Figs. 1 and 2. The condenser microphone as shown in Fig. 4 consists of a very thin duralumin diaphragm placed very close to a metal back plate but electrically insulated from the latter. The two members thus form a small condenser. As shown, this condenser is connected in series with a high resistance (about 10 megohms) and a source of direct voltage E. The impinging sound waves cause the diaphragm to vibrate thus varying the capacity with respect to the back plate. As a result of the variation of the capacity, electrical charges are caused to flow in and out of the two members, and the passage of these electrical charges through R produces an audio voltage across this resistance which is transferred to the grid circuit of a vacuum tube pre-amplifier via condenser C_g and resistance R_g as shown.

Crystal Microphone.—Finally a type of microphone known as the crystal microphone has been developed and is of importance today. Its action depends upon the piezo-electric effect of a Rochelle salt crystal. Piezo-electric effects have been discussed in previous technical assignments with regard to the quartz crystal oscillator. While quartz exhibits the piezo-electric effect, i.e., the variation of a voltage at two opposite faces when the crystal is compressed or extended, the Rochelle salt crystal is superior with regard to the magnitude of the voltage generated, although it is inferior as to mechanical characteristics and frequency stability. Accordingly, quartz crystals are employed to stabilize the frequency of vacuum tube oscillators while Rochelle salt crystals are employed in microphones, phonograph pick-ups, and even loudspeakers (since the action is reversible).

Normally, two or more crystals are employed in an assembly consisting of two crystals fastened or cemented together. There is thus obtained a unit which is more linear in its behavior over a range of sound pressures than the single crystal. The microphone can consist of sound cells in which the crystals are actuated directly by the pressure variations of the sound wave.

In another type, the crystal is operated by a diaphragm which in turn is actuated by the sound wave. This is illustrated in Fig. 5,

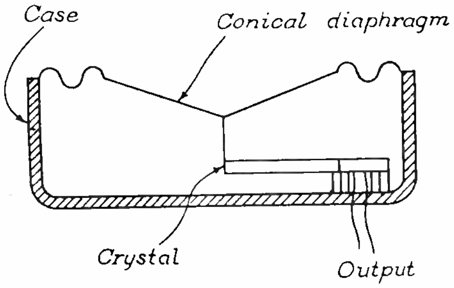


Fig. 5.—Diaphragm Type of Crystal Microphone.

where a conical diaphragm produces a bending or flexing action in the attached crystal. The latter thereupon generates an andio voltage which then can be amplified in the same manner as that from any other type of microphone.

While other principles have been suggested and tried for microphones, the above-mentioned forms appear to be the only successful types in use today. Variations in their construction with particular reference to their acoustical properties are employed, but from an electrical viewpoint they all depend either upon the cutting of magnetic flux by a conductor, the variation of a circuit element, such as its resistance or capacity, or the piezoelectric effect of certain crystals.

ACOUSTICAL CONSIDERATIONS

ANTENNA ANALOGY.—Microphones and loudspeakers are closely analogous to receiving and transmitting antennas. This is not surprising since both types of equipment are concerned with the pick-up and generation of wave energy. It will be found that many of the factors that determine the performance of an antenna are essentially the same as those that determine the performance of a loudspeaker or microphone.

Two important acoustical considerations are frequency response and directional characteristics.

FREQUENCY RESPONSE.—Frequency response can be defined in the following manner. Suppose one has a source of sound which can deliver at some point in free air a sound wave of a certain specified pressure. By pressure is really meant the excess and deficit in pressure of the condensation or rarefaction of the sound wave, respectively, over that of normal atmospheric pressure. Assume further that this variation in pressure is maintained constant as the pitch (frequency) of the wave is changed.

Now suppose that a microphone is set up at this point in space so that it faces the source of sound. If, under such conditions, the open-circuit or generated voltage of the microphone, for example, remains constant in amplitude and merely varies in frequency as the frequency of the sound wave varies, then the microphone may be said to have a flat frequency response, at least in the direction specified; i.e., when it faces the source of sound. Oftentimes the voltage measured is not the open circuit voltage of the microphone but instead is that developed across a specified load impedance. For example, in the case of the dynamic microphone shown in Fig. 1, a load resistance of 30 ohms might be specified and hence connected across the voice coil, and the voltage measured across the 30-ohm resistor. Ordinarily, the frequency response under this condition would be practically the same as for the open-circuit condition; the voltage in this case would merely be less *at all frequencies*. If the internal impedance of the voice coil is 30 ohms, then the voltage across the 30-ohm resistor would be exactly half of the generated voltage *at all frequencies*. In the case of the condenser or carbon-button microphone however, the only voltage that can be measured in practice is that across some specified load since otherwise the microphone would be essentially inoperative. In this case the load impedance must be given specifically.

Practical Difficulties.—While the above suggested test may appear to be straightforward, the particular difficulties encountered in attempting to perform it are very great. One difficulty is that of finding a space sufficiently free of reflecting obstacles. Tests have been conducted in the open air with the source (loudspeaker) and the microphone under test located on wires suspended from spaced poles so as to avoid appreciable reflection from the earth. One difficulty besides the space requirements is that of finding a site outdoors that is sufficiently quiet so as not to introduce erronous readings owing to background noise. A second difficulty is that of building a loudspeaker system that is in itself flat in frequency response. A suggested test setup would be an audio oscillator which excites an audio power amplifier which in turn drives a high quality loudspeaker. Means entailing some form of calibrated microphone would be necessary initially to check the loudspeaker performance. The availability of a calibrated microphone, however, suggests that it may be placed alongside the microphone under test. The loudspeaker system then has merely to be adjusted so that the calibrated microphone reads the same at all frequencies.

Diffraction and Distortion of The Sound Field.--For microphones that are actuated by the pressure of sound waves, it might appear that an equally satisfactory test could be performed by having some mechanical device that fastens to the microphone directly and actuates the latter by direct pressure. An electrostatic device of this sort has been constructed for use in calibrating a condenser microphone. It will be found, however, that the frequency response of a microphone in free space will not necessarily be the same as that obtained by a pressure-actuating device. This is because of an acoustical consideration that enters, namely, that the microphone under test changes the wave pattern in the free space around it compared to the normal pattern when the microphone is absent. This is analogous to the distortion of a radio wave in the vicinity of a receiving antenna and is due to the same reasons: Diffraction (bending) of the wave around the device and re-radiation from the device itself. The latter effect depends upon the electrical or mechanical impedance of the antenna or microphone, as the case may be.

Ultimately the sound will be reproduced from a loudspeaker in the receiver. The listener will form a similar obstruction in his room. Thus there are two obstructions involved: That of the microphone in the broadcast studio, and that of the listener in his home. This is to be compared with the case of one obstruction if the listener is directly in the broadcast studio. It is true that the acoustics of the studio and of the room where the receiver is located have probably a greater effect upon the quality of the reproduced sound but nevertheless the previous considerations indicate an inherent limitation in the use of a microphone.

To obviate the distortion in the sound field by the microphone it is found desirable, when possible, to streamline the microphone casing and, if possible, to make it of a spherical shape. A spherical shape also reduces the effects of diffraction and will be discussed in greater detail with reference to the Western Electric "eight-ball" microphone.

DIRECTIONAL CHARACTERISTICS.—Another equally important consideration is the directional characteristic of a microphone. In the previous discussion the frequency response was tested under the condition that the microphone faces the sound source. More specifically, if, for example, a diaphragm type of microphone is employed, the plane of the microphone is assumed to be normal (perpendicular) to the line joining the microphone and the source of the sound (see Fig. 6). Suppose, however, that the microphone is turned to make some angle θ, Fig. 6, to its previous position. The frequency response in this case will in general show a drooping characteristic; i.e., the higher frequencies will be attenuated.

Effect of Diffraction.—The principal reason for this is diffraction. The microphone constitutes an obstruction to the passage of the sound wave. At low frequencies the wavelength of the sound is large and if the obstruction is small compared to the wavelength, the wave can bend or diffract around the obstruction and produce practically the same pressure on the back of the microphone as on the front. To present it from another viewpoint, if the angle θ of Fig. 6 is increased to 180°, i.e., if the microphone is turned around so that the back of the case faces the source of sound, then at low frequencies the sound wave will be able to bend around the microphone and exert

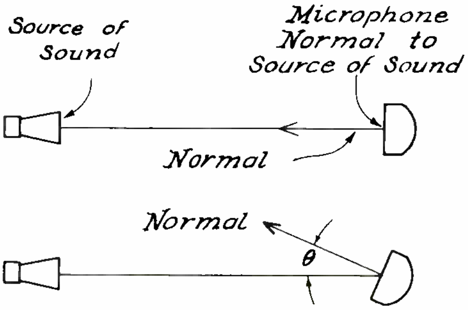
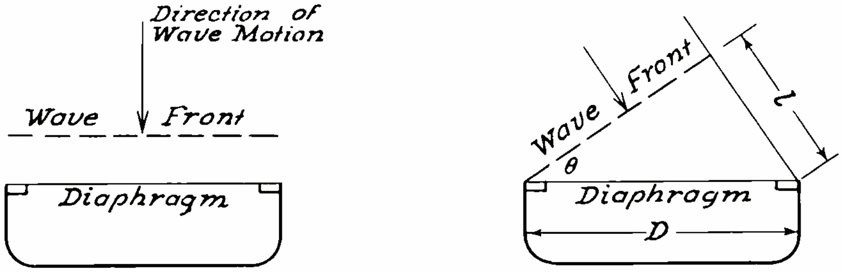


Fig. 6.--Method of Specifying Directional Characteristics of a Microphone.

practically the same pressure on the diaphragm, now in the rear, as it could when the diaphragm faced the sound source.

At high frequencies however, the wavelength is short and the microphone presents a considerable obstacle to the passage of a sound wave. This means that the microphone tends to cast a shadow so that if the sound wave originates to the rear of the microphone it will produce practically no pressure on the diaphragm. For intermediate directions (values of θ between 0 and 180°) the pressure on the diaphragm of the microphone at the higher frequencies will be intermediate in value between the normal amount at 0° and the minimum amount at 180°. On the other hand, for *normal* incidence of the sound wave, there is a tendency for the sound pressure to increase as the frequency is raised. This is due to the fact that as the frequency is raised the microphone becomes more and more of an appreciable obstacle to the sound wave. As a result, the wave energy, instead of diffracting around the microphone, is *reflected* from it. In so doing the wave tends to double the pressure on the diaphragm because in addition to the ordinary pressure there is added that due to the reaction of the air particles as they bounce off the diaphragm. This effect depends upon the shape of the microphone, and is more uniform in its variation and somewhat less for a spherical shape than for a cubical or cylindrical shape. Practical considerations, however, may determine the actual shape employed.

Phase Difference.—Another factor that has a smaller effect upon the directional response of a microphone is that of the phase difference in the pressure at different points of the diaphragm area. This is illustrated in Fig. 7(A) and (B). In (A) the wave direction is normal to the diaphragm; i.e., the microphone is facing the sound source. The wave front is therefore parallel to the diaphragm, as shown, and impinges on all points of its area simultaneously. The instantaneous pressure is the same over the entire diaphragm area and has maximum effect.



(A) (B)

Fig. 7.—**Diagram Showing Phase Difference Effects on a Microphone.**

In (B) it is clear that since the wave front makes an angle θ to the diaphragm, the left-hand side receives the wave front first, and the right-hand side last. The difference in phase at the two ends of the diameter D, depends upon the difference in path length l, and clearly

$$l = D \sin \theta$$

so that the phase difference in degrees is

$$\psi = \frac{360\ l}{\lambda} = \frac{360\ D}{\lambda} \sin \theta \quad (1)$$

The total force on the diaphragm is the sum of the products of the pressures on all the elementary small areas into which the diaphragm may be subdivided, by the small areas themselves. The observant student will note that the diaphragm is thus somewhat like an antenna array occupying an equivalent area, or better still, like the continuous radiating surface of the mouth of a horn. It will be recalled from the assignments on U.H.F. Techniques that the greater the wave capture area of the horn or array, when measured in wavelengths, the more directive the device is.

Examination of Eq. (1) shows that if D is large, θ can be small for the same value of phase difference ψ. This means that the reduction in pickup owing to the variation in phase and hence in pressure over the diaphragm surface, will be large even if the incident wave departs from the normal by a small angle θ, if the diaphragm diameter D is made large. This confirms the previous statement that if D is large, the microphone (or antenna) will be very directional.

For ordinary microphone diaphragms (D = 1 to 2 inches), the above phase difference effect is not important below 10,000 c.p.s., where diffraction rather than phase difference is the important factor in affecting the directional response. On the other hand, large cone and horn loudspeakers exhibit directivity effects at much lower frequencies owing to phase difference effects because their linear dimensions are comparable to the wavelength of even rather low-audio frequencies.

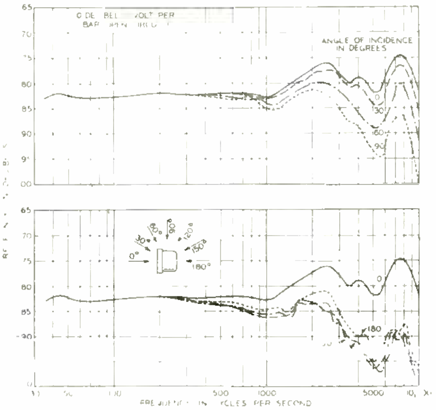
COMBINED FREQUENCY AND DIRECTIONAL CHARACTERISTICS.—From the foregoing it is clear that the frequency response and the directional characteristics of a microphone (or of a loudspeaker, for that matter) are interrelated, so that the complete performance of a microphone must be specified in terms of three quantities (variables): namely, *frequency; direction* of impinging wave; and *output*, usually in volts, either open-circuit or under load conditions.

Graphs in Three Variables.—The plot of three variables requires three coordinate axes (three dimensions) and hence is a surface in space, instead of a plane curve. However, by keeping one of the variables constant at some arbitrary value (making it a parameter), the other two variables plot as a plane curve. By assigning a series of values to the parameter, a series or family of curves is obtained.

One illustration is that of the vacuum tube, where generally the grid voltage or bias is held fixed at some value and the plate current plotted against plate voltage. By using a number of bias values, a series of curves known as the i_p-e_p family is obtained. On the other hand, the plate voltage could be made the parameter, and the i_p-eg family of curves obtained.

Microphone Family of Curves.— In the case of the microphone, the output voltage or power is generally plotted against the frequency or the direction of the impinging sound wave. Either of the latter may be made the parameter (kept constant), and a curve between the other and the output obtained.

FREQUENCY-OUTPUT CURVES.--In Fig. 8, for example, is shown a family of curves that represents the field response of a Western Electric 618-A diaphragm-type dynamic microphone. Here the angle of incidence of the sound wave is the parameter, and the frequency is the variable that is permitted to change. The direction or angle of incidence takes on values from 0^0 to 180^0 in 30-degree steps, and for each value of the angle, one curve of the frequency-output family is obtained.



(Marshall and Romanow, courtesy of B.S.T.J.)

Fig. 8.--**Directional Characteristics of Western Electric 618-A Dynamic Microphone With Incident Angle as the Parameter.**

It is interesting to note that up to about 200 c.p.s. the microphone is completely non-directional and picks up sounds from all angles with equal facility. This is because such low-frequency waves are able to diffract around the microphone and act upon its diaphragm even when they impinge upon it from the rear ($\theta = 180^0$). At the higher frequencies, particularly above 1,000 c.p.s., the response varies considerably with the angle, and a drop in output of as much as 15 db may be noted for a wave direction 90^0 to the axis or greater.

POLAR DIAGRAMS.--The same information may be presented in the form of polar diagrams, as shown in Fig. 9. In this case the frequency is the parameter, and has been assigned fixed values of 10,000, 5,000, 1,000, and 200 c.p.s. The output is then plotted against direction angle θ, as shown. The values can be taken from Fig. 8 for each frequency. It will be noted that the output at

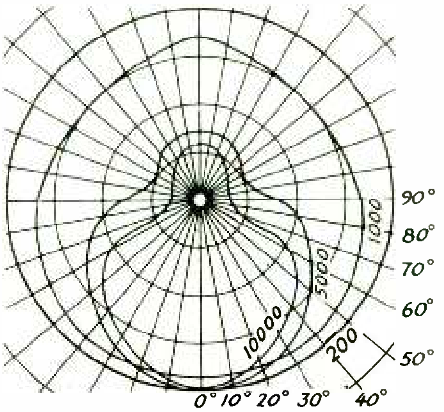


Fig. 9.--**Polar Family of Directional Characteristics of Western Electric 618-A Microphone. Frequency is the Parameter Here.**

5,000 and 10,000 c.p.s. falls off rapidly for directions much more than a few degrees off the axis, whereas for 1,000 and particularly 200 c.p.s., the response is practically the same for all values of θ.

Either family of curves, Fig. 8 or Fig. 9, gives the complete response information for the microphone. Both families are employed extensively in practice. Possibly the polar form is becoming more common. If so, this is because high-grade microphones today have reasonably flat frequency response curves, and hence are chosen mainly on the basis of their directional characteristics and how these fit the pickup problem at hand. This will now be discussed.

SIGNIFICANCE OF COMBINED CHARACTERISTICS.—The previous two families of curves have great significance in evaluating the merit of a microphone for general pickup purposes, such as in a broadcast studio. Consider the following problem:

Example of Pickup of Several Actors.—It is desired to present in a studio a radio play that requires the services of five actors. The problem is how to place them in front of the microphone. Suppose the microphone is of the type whose characteristics are shown in Fig. 9. In order to have sufficient room to turn pages of the script, etc., the actors must be spaced from one another by a reasonable amount of space. In addition, they should all be fairly close to the microphone so that adequate output is obtained from the microphone without their having to speak too loudly. Suppose a distance of five feet is taken as satisfactory, i.e., the actors will form a circle of five foot radius around the microphone. The consideration of freedom of movement will necessitate their being spaced by 30° angles, so that one actor will face the microphone directly ($\theta = 0^\circ$), two others will be $+30^\circ$ and -30° from the first; i.e., on either side of him, and the remaining two will have positions at $+60^\circ$ and -60°. This is illustrated by Fig. 10.

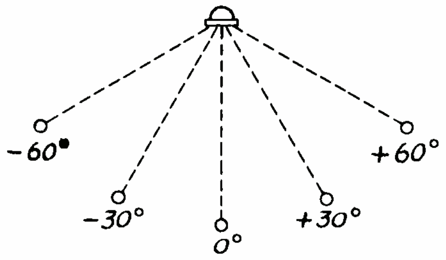
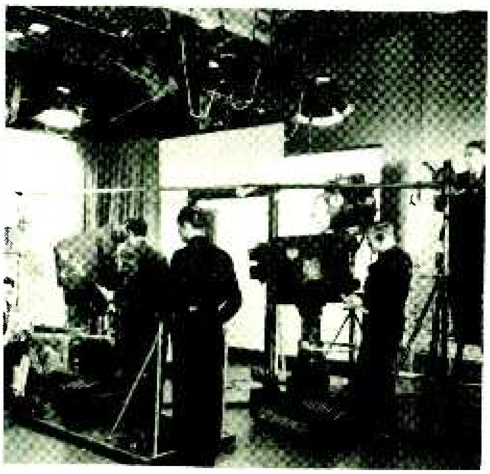


Fig. 10.—Arrangement of Performers in Front of the 618-A Microphone.

From Fig. 9 it is found that for frequencies of 1,000 c.p.s. and below, the pickup is the same for all the five positions within 1 db. For 5,000 c.p.s., however, the pickup drops 2 db at the 30° positions, and 7 db at the 60° positions, while for 10,000 c.p.s. the drop is 4 db and 9 db, respectively. It is clear that the quality and intelligibility of the speech from the actors at the 60° positions will be noticeably poorer than that of the actor directly in front of the microphone. Such variation in quality with position is in general undesirable, even though the curves shown in Fig. 9 are for a high-quality microphone. For a microphone of restricted frequency range, say up to 5,000 c.p.s., the variation would be less objectionable, since 5 db variations in the frequency response are not too disturbing to the ear.

Similar effects will be encountered in the case of one actor, if he is required to move around with respect to the microphone. This is more apt to occur in sound motion picture recording, although the same problem now arises in television. To prevent large variations in microphone output, the microphone is often mounted on a boom, as shown in Fig. 11. The microphone can thus follow the actor and maintain a fixed distance from him. *This does not solve, however, the directional effect*, for if the actor turns away from the microphone, it is usually not so easy to manipulate the boom as to place the microphone in line with the actor. Hence the conclusion is that the microphone should have the same relative response in all directions, even though the output, *at all frequencies*, may be less for one direction than for another.

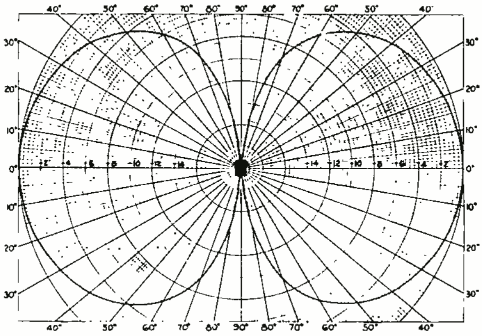


(Courtesy of NBC)

Fig. 11.--Use of Microphone Boom.

Another Example--Velocity Microphone.—This is illustrated by the following example. As will be shown later, the ribbon type microphone is generally constructed so that the velocity of the ribbon is proportional to the velocity of the air particles rather than to the excess pressure that they produce at the microphone location. As a result of the action, the microphone picks up a maximum of sound energy on its axis (the 0°-180° line) and a minimum along the -90°-+90° line perpendicular to the axis. The pickup and hence electrical output of the microphone *is the same at all frequencies, however, so that the quality is unchanged with change in direction of pickup.*

A typical polar diagram is shown in Fig. 12. This diagram is practically identical for all audio frequencies of interest, and is of a figure-of-eight shape. When such a microphone is employed, a speaker off the 0° line or axis will be picked up with the same quality as one on the axis, but at a somewhat reduced volume. For example, for



(Courtesy of RCA)

Fig. 12.—Polar Diagram for Velocity Microphone.

a speaker 60° to either side of the axis, and on either side of the microphone (which is bi-directional), the relative response will be only 6 db down as compared to the axial response. This means that the power output will be one-quarter as great.

However, if the actor *on the axis line* were to step back so as to be twice as far from the microphone as the actor on the 60° line, the pickup from the first-mentioned actor would vary inversely as the square of the distance, or be reduced to one-quarter its original value. In short, by arranging the actors so that those at an angle to the microphone are placed correspondingly closer to it, practically uniform sound pickup from all will be obtained, *and at all frequencies.* This is clearly not possible in the case of a microphone whose frequency response varies with the angle of pickup.

Reverberation Considerations.— Another factor of very great importance is that of reverberation. In an actual room or studio, the acoustic energy picked up is not only the sound coming directly from the source, but also that reflected from the surface of the enclosure. This produces the effect known as reverberation.

The reflected energy is practically the same at all points in the room because it is the result of a large number of random reflections that practically uniformly permeate the room. As a result, while the pickup of reverberant energy is about the same at all points of the room, the pickup of the direct sound is less, the farther away the microphone is from the source. Since the reflected energy or reverberation is a confused jumble of the original sound, it mars the intelligibility of the latter, particularly in the case of speech, and for large distances between the microphone and the source, the total pickup may consist of such a large percentage of reflected-to direct-energy as to be unintelligible. A contributing factor is the presence of ordinary extraneous noise present at the microphone location.

If the microphone is directional, however, then it can be so positioned as to favor the direct sound over the reflected sound and even background noise. Thus, for the directional characteristic shown in Fig. 12 it has been calculated by Olson* that the pickup of reverberation and noise from random directions is reduced to one-third that from a non-directional microphone. This means that for a given satisfactory ratio of direct-to-reflected

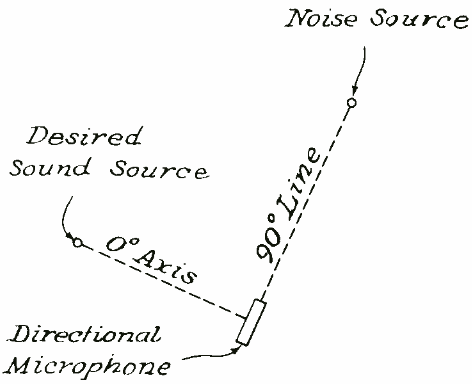


Fig. 13.--Orientation of Microphone to Reduce Noise Pickup.

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*Olsen, H. F., "The Ribbon Microphone, *Journal Soc. of Motion Picture Engineers*, June 1931.

sound the directional microphone can be placed $\sqrt{3} = 1.73$ times as far from the source as the non-directional microphone.

Reduction of Noise Pickup.—Even more marked advantages are obtained in the ratio of desired sound to extraneous noise when the source of the noise is not close to that of the desired sound. An examination of the polar diagram of Fig. 12 shows that if the source of noise is 90° to the microphone axis, then the microphone will not pick up the noise to any appreciable extent, except by multiple reflection from the walls. In this way satisfactory sound pickup can be obtained in noisy locations by proper orientation of the microphone.

This is illustrated in Fig. 13. It is clear from the figure that the desired sound will be picked up to a maximum degree, whereas the noise will hardly be picked up at all, at least not directly. Such characteristics are particularly valuable in sound motion picture and television pickups.

On the other hand, it must not be construed that a non-directional microphone is not desirable for many purposes. Further on in this technical assignment a particularly valuable and important non-directional microphone will be described, namely, the Western Electric 630-A or "eight-ball" microphone. This is very useful for orchestral and similar pickups. What is objectionable, as a general rule, is a microphone whose frequency response is different for different directions. Even this, however, may not be a serious fault for a microphone used in a public address system for close-talking purposes, where the speaker faces the microphone at all times.

ELECTRICAL CONSIDERATIONS

OUTPUT CHARACTERISTICS.—The electrical characteristics of a microphone are of considerable practical importance. This refers particularly to the magnitude or level of the electrical output, and the impedance at the output terminals.

Output Level.—While the output level of a microphone is not ordinarily a matter of paramount importance because generally a pre-amplifier is available to raise the power output to an acceptable level for further distribution, nevertheless, given two microphones having equal frequency response and directional characteristics, the one having the greater output level will clearly be preferred over the other.

Level vs. Band Width.—The output level is closely related to the audio band width or frequency response desired. In general, the greater the band width, the lower is the output level. For example, if it is desired to extend the range of the dynamic microphone from 5,000 to 10,000 c.p.s., so much acoustical damping must be added in that particular design that the output power is $(5,000/10,000)^4$ or 1/16 as great. Expressed in decibels, the output level for a 10,000 cycle band width is 10 log (1/16) = -10 log 16 = -12 db down or below the output level for a 5,000 cycle band width.

Acoustic Reference Levels.—For this reason high-fidelity microphones have rather low output levels. Before the actual values can be presented it is necessary to discuss the various reference levels employed in order that ratings based on two different input reference levels can be compared.

The microphone produces an electrical output that is proportional to the acoustic input; therefore the acoustic input must be specified before the electrical output can be compared with that of any other microphone. The standard acoustic inputs employed are 1 bar and 10 bars. A bar is one dyne force per square centimeter of wave front. It is the pressure developed on the microphone when a person speaks in an average conversational tone about 10 inches from the microphone. A pressure of 10 bars represents $(10)^2 = 100$ times as much acoustic power and would correspond roughly to the average power output of a moderate-sized orchestra, although the output of an orchestra is exceedingly variable.

Effect of Input Transformer.— The microphone is of necessity located in the studio, but the preamplifier is preferably located on a rack in the Control Room or other suitable place. The connecting leads are so short electrically (about 100 feet at the most) that at audio frequencies they need hardly be regarded as a transmission line, and so do not have to be terminated in their characteristic impedance. Instead, they are rated on the basis of the source impedance. For example, if the microphone feeding them has an internal resistance of 500 ohms, then they are called a 500-ohm line. This is sufficient: they do not have to be terminated in 500 ohms; the 500-ohm microphone can thus feed an open circuit at their other end or more generally, a very high impedance. In this case no appreciable current is drawn from the microphone, and the terminal voltage across the line equals the generated or open-circuit voltage of the microphone.

The pre-amplifier requires no appreciable power in the audio range; it merely needs grid signal voltage to actuate it. Hence the open-circuit voltage of the microphone can constitute a measure of the microphone's ability to drive the pre-amplifier. If, however, the microphone is of low impedance it is possible to interpose a step-up input transformer between it and the first grid of the pre-amplifier in order to increase the grid driving voltage and thus cut down the required amount of voltage amplification in the pre-amplifier for a desired output.

The circuit is shown in Fig. 14.

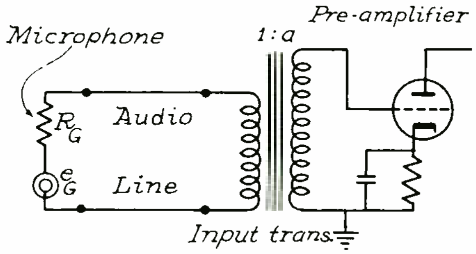

Fig. 14.—Use of Step-up Input Transformer to Increase Voltage Gain.

The input transformer represents a voltage amplifier in effect, and may replace a stage of tube amplification thereby. If the transformer primary has a sufficient number of turns, its inductive reactance will be several times the internal resistance R_G of the microphone even at the lowest audio frequency. In this case it draws a negligible current from the microphone, there is a negligible voltage drop in R_G, and hence substantially e_G, the open-circuit voltage, appears across the primary. Then ae_G (where a is the turns ratio of the transformer), appears across the secondary, so that the voltage gain of the transformer is a. The magnitude of a depends upon two factors:

1). The value of R_G, and hence the necessary number of turns on the primary to provide the desired low-frequency response.

2). The desired band width of the transformer. This determines how many turns can be placed in the secondary coil before the distributed capacity of the latter, as reflected to the primary side, produces too great an attenuating effect at the high-frequency end of the band.

For a given design, the number of secondary turns is fixed, and the primary turns are varied to fit the value of source impedance R_G. For a low value of R_G, few primary turns are required and therefore a is high; whereas for a high value of R_G, many primary turns are required, and a is low. If R_G is about 150,000 ohms, then the primary and secondary turns in the average high-grade transformer are about equal, and a is unity--there is no step up. In this event the microphone may just as well feed the grid directly and thus eliminate the expense and trouble of the input transformer.

In the case just mentioned, a 150,000-ohm resistance connected across the secondary would reflect an equal value across the primary and thus just match the internal resistance of the microphone. It has become customary to designate the secondary as a 150,000-ohm secondary. From what has been just said, it is clear that this does not refer to the actual impedance of the secondary winding (which is a much higher inductive reactance—at least at frequencies below where it tunes with its distributed capacity), but instead refers to the value of load resistance which will reflect on the primary side a matched value to the source impedance.*

If R_G is low, say 500 ohms, then the primary turns will be less. In this case 150,000 ohms across the secondary will reflect 500 ohms across the primary. The number of primary turns must be such that

$$a = \sqrt{150{,}000/500} = 17.3 : 1$$

In this case the transformer has a voltage gain of 17.3; which compares favorably with that of an ordinary audio stage.

High-Impedance Microphones.--Many microphones, such as the crystal and condenser microphones, have such a high internal impedance that no input transformer of the desired audio band width can fit them. Even if the primary could be designed to have sufficient turns, and hence inductance, for the purpose, the secondary number of turns would not exceed those of the primary, and no step up would result. In this case the microphone preferably feeds the pre-amplifier first grid directly, since usually the grid resistor (to provide a d.c. path between the grid and cathode) can be made high enough to draw negligible current from the microphone, so that essentially the

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*Special transformers have been built, such as for photocell work, that have 500,000-ohm secondaries. This does not invalidate the above argument; it merely moves the range of application up into higher impedance levels. The value of 150,000 ohms given above is representative of average high-grade commercial audio transformers.

open-circuit voltage appears across the grid circuit. However, in actual practice the capacity of the audio line represents an appreciable load on the microphone, especially at the higher audio frequencies, and must be taken into account in calculating the voltage delivered to the grid of the tube.

A representative case is shown in Fig. 15. A crystal microphone whose internal impedance is that of a capacity C_G, feeds the pre-amplifier through an audio line whose capacity is C_L. In addition there is the input capacity of the tube, but this is small compared to a line 25 feet or more in length. The resistance R_g provides the d.c. path for the grid circuit. It can be made so high that even at the lowest frequencies its resistance is high compared to the capacitive reactance of C_L and C_G. Representative values are e_G = 1 mv., C_G = .003 µf, C_L = .002 µf, and R_g = 1 to 5 megohms.

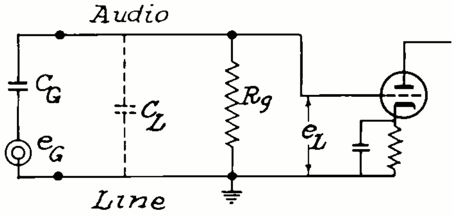


Fig. 15.—Method of Coupling High-Impedance Microphone to Grid of Input Tube.

Under the above conditions C_L and C_G form a capacitive voltage divider, and the voltage delivered to the grid is

$$e_L = e_G \frac{C_G}{C_G + C_L} \qquad (2)$$

Substituting the above values in Eq. (2) there is obtained

$$e_L = 1 \frac{.003}{.003 + .002} = 0.6 \text{ mv.}$$

If a longer audio line is employed, e_L will be correspondingly reduced.

Microphone Ratings.—From the foregoing it will be clear that it is not sufficient to specify merely the open-circuit voltage of the microphone. The internal impedance of the microphone and the characteristics of the associated circuits must also be given before the voltage delivered to the grid of the tube can be calculated.

In the case of a low-impedance microphone, this means that the impedance of the secondary of the input transformer must be specified. However if this is taken at the usual value of 150,000 ohms, then the microphone can be rated on the basis of its db output level *into a matched load*. For example, suppose a velocity microphone is stated to have an output level of -63.7 db per bar (0 db = 6 milliwatts). This corresponds to an output power per bar of $P_1 = 6\cdot10^{-3}\text{anlg}(-63.7/10) = 6\cdot10^{-3}/\text{anlg}(63.7/10) = 2.56\cdot10^{-9}$ watts.

The above assumes that 150,000 ohms is connected across the secondary of the input transformer and that 2.56×10^{-9} watts is dissipated in this resistance. The voltage developed across this resistance is therefore

$$e_L = \sqrt{P_1 \times 150{,}000}$$

$$= \sqrt{2.56 \times 10^{-9} \times 150{,}000}$$

$$= 19.6 \text{ mv.}$$

This is the voltage applied to the grid.

However, suppose the 150,000-ohm resistor is omitted. Then the microphone no longer faces a reflected resistance equal to its internal resistance, so that no longer is half of its generated voltage consumed in its own internal resistance, and half permitted to appear across the primary terminals. The latter voltage thereupon doubles, so that the secondary voltage becomes 39.2 mv. instead of 19.6 mv. The output voltage of the pre-amplifier thereupon doubles, so that the output power quadruples. This represents a 6 db rise in output power level.

Note that it was not necessary to know the internal resistance of the microphone in either case; all that had to be specified was the db output level under matched conditions and the impedance of the secondary. Indeed, had the open-circuit or generated voltage of the microphone been given instead, it would have been necessary to know in addition the internal resistance of the microphone and the secondary impedance From the latter two values the turns ratio could then be calculated as shown previously, and then the voltage across the secondary found.

On the other hand, for a high impedance microphone, the db output level is of little practical significance. This is because such a value represents a logarithmic *power* ratio, and the power consumed in the grid resistor has no direct bearing on the voltage delivered to the grid. For example, if the grid resistor is doubled in value, the power dissipated is one-half, and the level is 3 db lower, yet the delivered voltage remains practically unchanged.

In this case it is more important to specify the open-circuit voltage of the microphone, the internal impedance, and the impedance of the audio line. Then, by means of Eq. (2) or its equivalent, the voltage delivered to the grid can be calculated. Very often the generated voltage is specified on a db basis. The reference level (0 db) is 1 volt per bar. Thus, suppose a crystal microphone is rated as having an open-circuit voltage level of -65 db per bar. The open-circuit voltage is

$$e = 1/\text{anlg}\ (65/20) = 1/1778$$

$$= .563 \times 10^{-3} = 0.563 \text{ mv./bar}$$

Miscellaneous Remarks.—It is unfortunate that microphones are not rated uniformly on the basis described above. In the case of low-impedance microphones, the manufacturer may rightly claim that the input transformer is a component of the pre-amplifier and hence no concern of his. In the case of the high-impedance microphone, the manufacturer may disclaim any responsebility for the audio line.

However, it will be found that a manufacturer of a low-impedance (dynamic) microphone may state that his microphone has an output level of -88 db below 0 db (1 volt) per bar (open circuit), and neglect to state the internal impedance of the microphone. Since it will undoubtedly be used in conjunction with an input transformer, its internal impedance must be known before the step-up ratio of the latter can be calculated (even if the secondary impedance is known).

In another case, a manufacturer of a high-impedance (condenser) microphone may state that the power output level is -116 db per bar (0 db = 6 milliwatts), without stating what the load impedance is. In this case the delivered voltage cannot be calculated until this quantity is specified. In some cases the manufacturer even neglects to state the sound pressure employed (1 bar or 10 bars or possibly some other value). No comparison of microphones, or estimate of the performance of any particular make, can be made until all necessary factors are specified.

NOISE CONSIDERATIONS.--As in the case of antennas there are several sources of noise associated with microphone pickup. Microphone noise pickup has an important bearing upon the design and use of the microphone and is closely tied in with the sensitivity (output level) and impedance of the microphone.

Types of Noise.—First, there is the extraneous background noise as well as reverberation of desired signals present in the studio itself. This corresponds to atmospheric static although it is under greater control. It will be observed that a directional microphone can discriminate against such noise just as directional antennas can discriminate against static.

A second source of noise is the thermal noise owing to the electrical resistance of the microphone and associated circuit. This noise has been described in previous technical assignments on Ultra-High Frequency Techniques. Similar and comparable to this noise is the thermal agitation of the air molecules themselves in the studio. However, this noise can be considered as part of the acoustic static. Its magnitude is such that a person with acute hearing could just about perceive it in an otherwise quiet location, i.e., it is just about at the threshhold of hearing.

The third source of noise is the shot effect in the plate circuits of the pre-amplifier tubes, principally the first stage. In a well-designed amplifier, this can be made less than the thermal agitation noise. This is in contrast to ultra-high frequency operation of a vacuum tube where the shot effect may be relatively great because the amplification of the tube is small owing to input loading.

A fourth source of noise other than thermal agitation may occur in some microphones. Reference is particularly made to the carbon grain hiss of a carbon-button microphone. The exact cause of this noise is not definitely known but it is attributed to arcing between the granules of carbon in the button. This background noise occurring within the microphone itself is generally of a relatively high level and is particularly rich in high-frequency components. A carbon-button microphone can therefore be used only where the sound intensity is relatively high and the band width is limited, at most, to about 5,000 c.p.s.

Finally, a fifth source of noise is that of electrical pickup or coupling from other circuits, particularly power lines. This depends upon the impedance of the microphone audio lines.

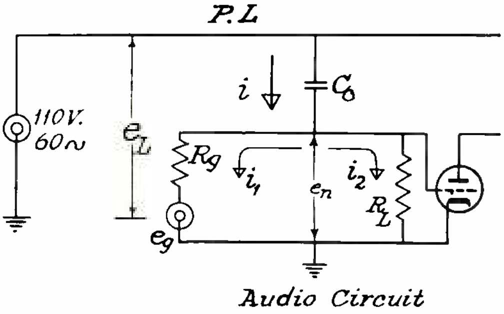


Fig. 16.--Example of Capacitive Coupling.

Electrical Noise Pickup.—The last source of noise will be discussed at this point. Most of the other sources will be covered in the detailed discussions of the various microphones. Electrical noise pick-up may be due to electrostatic or inductive coupling between the two circuits involved. A typical example of electrostatic coupling is illustrated in Fig. 16, wherein, is shown a power line, P.L., which develops a 60-cycle voltage e_L with respect to ground and the audio circuit. There is a certain amount of capacity, C_c, existing between the power line and the audio circuit and this serves to introduce 60-cycle hum and other disturbances into the audio circuit. As shown, P.L. feeds a current i through C_c which then divides into components i_1 and i_2 that flow through R_G and R_L respecively. There is thus developed across the audio circuit the noise or hum voltage e_n which is clearly equal to i_1R_G or i_2R_L.

The magnitude of e_n depends upon the magnitude of e_L, of C_c, and of R_G and R_L in parallel. Ordinarily the reactance of C_c is so extremely high (because C_c is so small) that the current flow i is practically equal to

$$e_L \div \frac{1}{j\omega C_c} = j\omega C_c e_L$$

and is not appreciably influenced by the magnitude of R_G and R_L in parallel.

Normally R_G and R_L are of the same order of magnitude; i.e., if R_G is high R_L is high. For matched impedance conditions, they are actually equal to one another. Assume, for simplicity, that this is the case, then the impedance of the audio circuit is simply $R_G/2 = R_L/2$. The voltage e_n is then clearly equal to $iR_G/2$. Substituting the value for i from the previous equation, there is obtained

$$e_n = \frac{j\omega C_c R_G e_L}{2} \qquad (3)$$

If the load resistor R_L is omitted in order to obtain a better ratio of signal to thermal noise (see next section), then e_n becomes double the value given in Eq. (3). This does not affect the general conclusions derived from the analysis. Eq. (3) is not of direct practical importance since it is extremely difficult in many cases to measure the disturbing voltage e_L and the coupling capacity C_c. However, this equation does point out a very important point, that if the impedance of the audio line R_G is high, then the noise voltage e_n will be correspondingly high. It also shows that the noise voltage is in direct proportion to the frequency, (in view of the presence of ω in the above equation.) Thus high impedance circuits are more prone to electrostatic noise pickup than the standard 500 and 250-ohm lines. However, whether or not the noise is objectionable depends upon the ratio of e_n to the desired signal voltage e_g. Clearly, the higher e_g is, i.e., the greater the output level of the microphone, the greater will be the signal-to-noise ratio for a given audio line impedance R_G, or to put it another way, the greater the output level of the microphone, the higher can be the impedance of the audio line for a given permissible signal-to-noise ratio. Further, if the microphone develops a higher signal voltage (for the same sound pressure) at the higher audio frequencies, than it does at the low frequencies, then the desired signal-to-noise ratio can be preserved at the higher audio frequencies in spite of the presence of the quantity ω in the noise formula.

Electrical pickup is a serious source of noise and generally requires that the microphone output be greater than say -90 db (0 db = 6 milliwatts), particularly if the microphone has a high output impedance. For example, a condenser microphone has a capacitive internal impedance, and the load impedance is on the order of megohms. Thus the audio line will be of high impedance although the fact that the microphone has an internal impedance that is capacitive indicates—as in the case of the crystal microphone—that the signal voltage will not tend to be attenuated at the higher frequencies if a long audio line is employed. However, the power output level per bar of the condenser type microphone is about -116 db. If it is located an appreciable distance from the pre-amplifier, then a correspondingly long audio line will be required. This will tend to have a larger coupling capacity C_c to other electrical circuits so that the noise pickup will tend to be greater and at the same time the capacity of this line will reduce the terminal voltage to the grid to a much lower value, as per Eq. (2). The high impedance of the audio line is favorable for noise pickup anyway, and since the output level of the microphone is inherently low, it is readily apparent that the signal-to-noise ratio, when a long audio line is employed, will be very small. For that reason it is necessary to locate the pre-amplifier within an inch or less of the microphone proper so that the two are generally mounted in one housing. This not only increases the complexity of the device and reduces its maneuverability, but also requires a rather large housing with the accompanying undesirable diffraction effects, particularly at the higher audio frequencies.

On the other hand, a dynamic microphone, for example, not only has a much greater output level, but the fact that it is a low impedance device means that the noise pickup will be correspondingly small so that a reasonable length of audio line can be employed.

Inductive pickup is due to magnetic coupling between the two circuits involved. Ordinarily this does not appear to be as serious a factor as electrostatic coupling. Difficulty arises mainly when an audio line runs parallel to the disturbing line for an appreciable distance. In the case of inductive coupling, the lower the impedance of the audio circuit, the greater the the pickup is in general. However, if a microphone, such as the ribbon type, has a low impedance, it is best to design a suitable step-up transformer as described previously to enable the audio line to be of a higher impedance, such as 250 ohms. Thus it is possible to minimize the effects of inductive pickup more readily than in the case of electrostatic pickup. Shielding of the audio circuit and of the disturbing circuit, for that matter, reduces the pickup very markedly, but in the case of a high impedance circuit the shield should be spaced an appreciable distance from the audio wires in order that the capacity in the audio system be kept within reasonable limits. This, in turn, means a bulky and therefore rather impractical audio line.

It should now also be clear why the microphone dimensions cannot be reduced in order to reduce the effects of diffraction at the higher frequencies. If the dimensions are reduced sufficiently for this purpose, it will be found that the output level will also be reduced to such a point that the desired signal-to-noise ratio will be seriously impaired, at least for the ordinary condenser, dynamic, and ribbon types of microphones.

Thermal Noise.—As stated previously, the thermal noise developed in the microphone is analogous to that developed in an antenna. While this is not normally a very serious source of noise, it can be reduced in many instances in a very simple manner. In Fig. 17 is shown a microphone connected to the tube through a microphone-to-grid transformer. Suppose the secondary were loaded by a resistor R_g, that was matched to the microphone impedance R_G by means of the turns ratio a. Then conversely R_G would appear at the secondary terminals as equal to R_g, and the impedance would be the two in parallel or $R_g/2$. The voltage at the terminals would be $ae_g/2$.

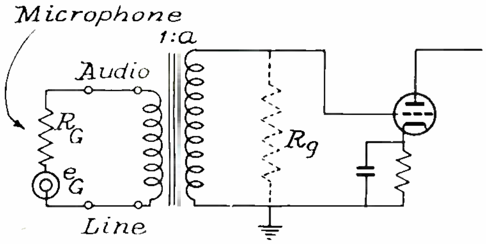


Fig. 17.—Use of Unloaded Input Transformer to Increase Signal-to-Noise Ratio.

If the secondary load resistor R_g is removed, the impedance at the terminals would become double or R_g, and the voltage would also double or be ae_g. It will be recalled that the mean *square* thermal noise voltage and hence noise power is proportional to the resistance, and hence is doubled when the secondary is unloaded. The signal power, on the other hand, is proportional to the square of the signal voltage e_G, and hence is quadrupled when the secondary is unloaded.

It therefore follows that the signal-to-noise *power ratio* is doubled when the secondary is unloaded, or there is a 3 db rise in signal-to-noise ratio. For this reason the audio line is, in general, not terminated in a matched impedance but instead faces an open-circuit. For very low-level microphones the resultant 3 db improvement in signal-to-noise ratio is a worthwhile advantage.

MECHANICAL CONSIDERATIONS

MECHANICAL ELECTRICAL ANALOGIES.—In the previous technical assignment on loudspeakers it was indicated that a mechanical system could often be represented by an electrical circuit counterpart or analogue. In order to do so it is necessary to understand what quantity in the one system corresponds to that in the other system. In passing, it may be mentioned that mechanical and electrical systems are but two examples of the more general topic of circuits. The equations for circuits cover electrical circuits, mechanical circuits, heat flow, radio-active decay, solutions of crystals in water, etc. The fact that the same mathematics applies to all these phenomena indicates that the behavior of a circuit in one field can reveal the behavior of a similar circuit in another field. Since electrical quantities are in general the easiest to measure, the field of electricity has had perhaps the greatest advancement of all similar fields. For that reason it is found desirable to study microphone or loudspeaker behavior in the light of the behavior of an electrical analogue, because the theory of the latter has already been developed and experimentally tested and can now be very easily applied to the new field.

Displacement, Velocity, Force.—Suppose an object, such as a microphone diaphragm, is displaced by a force F through a distance d, as shown in Fig. 18. The displacement can be compared to a displacement of so many electrons from one point of the circuit to another point. The total number of electrons thus displaced represents a certain amount of charge, and is measured in coulombs. The displacement of the diaphragm in inches, or preferably centimeters, is thus analogous to electrical charge, as measured in coulombs.

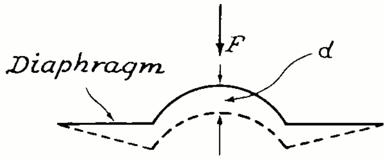


Fig. 18.--Analogy of Mechanical Displacement to Electrical Charge.

The velocity which the diaphragm acquires in moving through the distance d is so many centimeters per second. Corresponding to this is the volume velocity of the electrons, i.e., the total number of electrons passing a given point of the circuit in one second. This is the electrical current and is measured in amperes; it is analogous to velocity measured, say, in cm/sec.

The force F necessary to displace the diaphragm is analogous to electromotive force. A usual measure for F is in dynes, and the measure for e.m.f. is in volts. There is another quantity in mechanical systems that does not quite have its electrical counterpart, and that is pressure. Pressure is force per unit area. In the above case of the diaphragm, the force acting on the diaphragm may be due to air pressure. This might be .1 *dynes per square centimeter* (above or below atmospheric pressure which equals 1.01 x 10^6 dynes/cm^2). If the diaphragm has an area of 5 sq. cm., then the *total force* F acting on the diaphragm is 5 x .1 = 0.5 *dynes.*

Mass, Friction, Compliance.--As was also indicated in the previous technical assignment, the mass of a body corresponds to electrical inductance. It will be recalled from Section II that an inductance opposes any change in current, whether to a higher or lower value. In the same way the inertia of the mechanical body, i.e., its mass, opposes any change in the velocity of the body, that is, acceleration or deceleration of the body. The opposition in an electrical system to change in current is manifest as an induced e.m.f.; in a mechanical system, opposition to acceleration or deceleration of the body (rate of change of velocity) is manifest as a counter force. Inductance is measured in henries; mass, in grams.

In the case of friction, the counter force opposing the motion of the body is proportional to the magnitude of the friction and to the velocity of the body. The magnitude of the friction is measured by the number of dynes force required to move the body against this opposing effect at the rate of one centimeter per second. For example, if a body is slid along a rough floor, and 20,000 dynes are required to move it at the rate of one centimeter per second, then there are 20,000 ÷ 1 = 20,000 units of resistance. A unit is one dyne per centimeter per second.

Similarly in an electrical circuit, if 5 volts are required to circulate electrons through a portion of the circuit at the rate of one coulomb per second (one ampere), then the portion has a resistance of 5 ÷ 1 = 5 volts per coulomb per second or 5 volts per ampere. However, in the electrical circuit it was early found desirable to replace the expression volts per ampere by the term "ohm". Similarly, in a mechanical circuit, the expression one dyne per centimeter per second is now generally replaced by the term "mechanical ohm".

The capacitance of an electrical condenser is a measure of its ability to store charge. The more charge it can store for a given voltage, the higher is its capacity. Thus, a condenser that can store one coulomb of charge when one volt is impressed across its terminals, has one unit of capacitance. The capacitance can be expressed in terms of so many coulombs per volt. However, here, too, a shorter term, namely, the "farad" is employed, and in practice one millionth of this unit, or the microfarad, is used.

In the mechanical system, it is not always so apparent as to what is being stored. The reason is that in an electrical system, current flow is primarily due to the motion of electrons, and charges stored represent electrons forced into an element (storing of negative charge), or electrons extracted from an element (storing of positive charge), and the two types of storage occur simultaneously in an electrical system. In a mechanical system, that which moves and has a velocity and displacement may be anything in the system, and may be either in the gaseous, liquid, or solid state. In the case of a microphone, for example, there is an initial displacement of the air particles in the vicinity of the diaphragm. This in turn produces a displacement of the diaphragm and associated voice coil. The latter then move the air behind them, often through narrow orifices, thereby producing a frictional effect. Thus the displacement and accompanying velocity has been transferred from air to aluminum back to air again. In a more complicated system there is even a greater number of diverse elements involved, and the displacement and velocity must be traced through the entire system.

The mechanical quantity that corresponds to electrical capacity is compliance, or elasticity. It represents a spring action: the force opposing any deflection of the device. Thus, suppose one has a leaf spring, as shown in Fig. 19, and it is deflected through a distance d by the application of a force F. The compliance is defined as

$$C = d/F \qquad (4)$$

that is, as the deflection per unit force. Thus, if 5 dynes deflects the spring a distance of 2 cm, then the compliance is $C = 2/5 = 0.4$ cm/dyne.

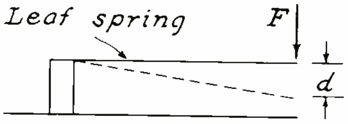


Fig. 19.--Example of Compliance: Leaf Spring.

However, instead of a leaf spring, one can have a compressed air tank, as shown in Fig. 20. Here a force F is applied to a piston, moving it down a distance d. This in turn compresses the air in the tank, and the compliance is again defined as in Eq. (4).

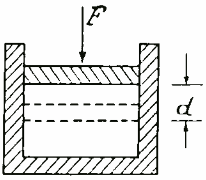


Fig. 20.--Example of Compliance: Air Chamber.

Possibly this second example appears more nearly analogous to the electrical condenser in that air, like electrons, is being crowded into a smaller space, but the main thing to note is that energy is being stored in an elastic medium, and from this viewpoint Fig. 19 is as valid an example as Fig. 20.

MECHANICAL INDUCTANCE OR MASS.- In electrical systems, especially at ultra-high frequencies, it is quite difficult to obtain an essentially pure inductance, mainly because distributed capacity is unavoidably associated with the coil and makes its behavior with frequency quite different from that of a pure inductance. In the limit, transmission line elements or even cavity resonators must be employed so as to exhibit the desired inductive reactance, at least over the desired range of frequencies.

In mechanical systems the same problem arises at audio frequencies. This is because materials in general have too much compliance or elasticity associated with their mass, and thus refuse to move as one unit even at audio frequencies. For example, suppose a diaphragm, as shown in Fig. 21 is actuated by an alternating force f. The members s-s

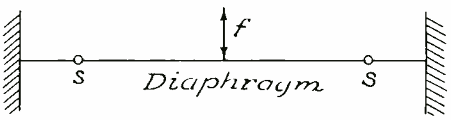
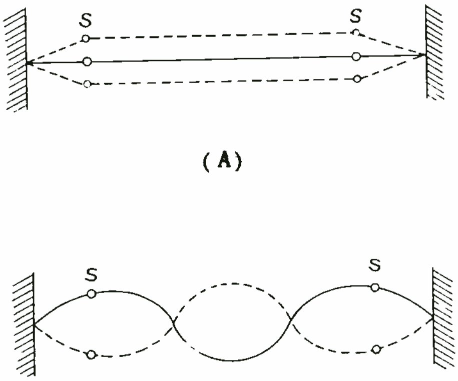


Fig. 21.--Alternating Force Applied to Diaphragm Having Distributed Constants.

represent strings having practically infinite compliance, that merely hold the diaphragm in place, but do not appreciably restrict its motion. If the diaphragm is to move as a unit, all parts must be displaced by the same amount, as indicated in Fig. 22(A). Here the strings s-s merely deflect as shown.



(A)

(B)

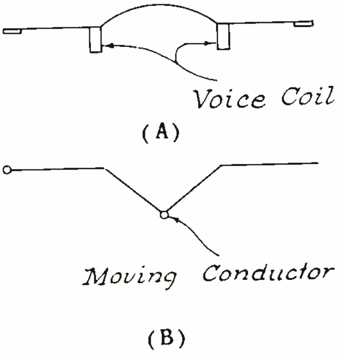
Fig. 22.--Fundamental and Higher Modes of Vibration of Diaphragm.

At higher audio frequencies, however, the diaphragm may refuse to move as a unit, owing to its internal compliance. At some particular high frequency it will move as shown in (B), Fig. 22. This is its first resonant frequency. Since the edge was assumed to be relatively free, the shape at some instant is as shown. For a clamped diaphragm a different instantaneous shape will occur.

The important thing to note is that the diaphragm is no longer flat, but vibrates so that the edge and the center are moving in opposite directions at any instant. This means that the *effective mass* of the diaphragm at and around this resonant frequency will be quite different from its static (at-rest) mass. This changes the behavior from that desired and calculated, and produces marked variations in the frequency response.

The diaphragm is therefore usually designed to function as a rigid unit over the audio band. This could be done by increasing the thickness of the diaphragm, but this would also increase the mass and reduce the band width. Instead, the diaphragm is given the proper structural shape to increase its rigidity without increasing its mass. In addition, it is generally clamped around its edge instead of being practically free at the periphery as indicated in Figs. 21 and 22.

Two preferred shapes for the diaphragm are shown in Fig. 23(A) and (B). In (A) the central portion is made dome-shaped. It thus behaves very much like an arch, and is very rigid for a given thickness and mass. Flexing occurs in the



(A)

(B)

Fig. 23.--Diaphragm Shapes Having Maximum Ratio of Stiffness to Mass.

outer annular flat portion, which is relatively flexible. A typical design employs a 1 mil (.001") thick duralumin sheet, whose center portion is usually a segment of a sphere one inch in diameter. This shape is particularly well suited to fasten to and actuate a voice coil.

In (B) a conical diaphragm is employed. This is also very rigid but is not as well adapted to fasten to a relatively large voice coil as is the shape shown in (A). Instead, it is better adapted to be fastened to a single conductor, as in the inductor type microphone. Such shapes act substantially as a plunger or piston over the main portion of the audio band, particularly since the actuating acoustic wave acts substantially uniformly over the entire surface.

MECHANICAL RESISTANCE.—One of the most difficult things to obtain mechanically is a resistance effect. One reason is that mechanical resistances or frictional effects are usually nonlinear, i.e., variable in magnitude depending upon the velocity of the rubbing member. It is therefore necessary to keep the velocity variations (oscillations) relatively small in order that the *variation* in friction be kept to a negligible value. Another difficulty is that any ordinary vibrating member has very little damping compared to its mass and compliance reactions; i.e., it is like a high-Q resonant circuit. Special means must therefore be employed to enhance the frictional effect.

One method is to employ fine capillary tubes through which air is forced by the diaphragm. A simple example is shown in Fig. 24. When the diaphragm D moves downward, for example, air compressed in the space A moves radially outward around the dome of the center magnet pole piece E and around the voice coil attached to the diaphragm. It then passes out through an annular slit B formed between the annular magnet pole piece F and a brass ring C. The annular slit B is in the neighborhood of 3 mils high. Such a slit affords a large frictional effect to the air flowing through it owing to the viscosity of the air, and thus produces the desired mechanical resistance effect. More recently a simpler method has been developed, namely, by using a small bolt of silk cloth. The latter has very fine openings owing to its weave, and furnishes a much cheaper method of obtaining the same result.

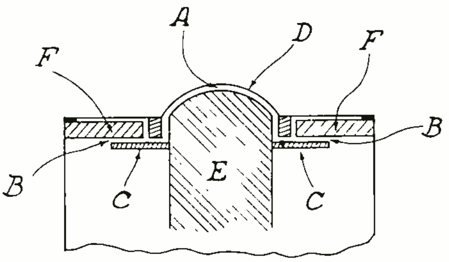


Fig. 24.--Use of Capillary Tubes for Damping Purposes.

Other methods can be employed, such as transmitting the vibrations to a block of rubber, or to an oil chamber. Ordinarily, in the case of a microphone, the above method of air damping appears sufficient and is relatively simple. Another source of damping is the connected electrical circuit. For example, if a load resistance is connected to the voice coil, then currents will flow in this resistor when the diaphragm and voice coil are actuated by the acoustic wave. Thus electrical energy will be dissipated as heat, and this energy clearly comes from the acoustic wave.

Hence the electrical circuit will introduce a reaction into the mechanical system that is essentially a mechanical resistance, provided that the electrical circuit is essentially resistive in nature. However, unless exceptionally high magnetic field intensities are employed in the air gap, the coupling between the electirical and mechanical portions of the system will be small; i.e., the resistive reaction introduced by the electrical circuit into the mechanical system will be small. As a consequence, the electrical reactions ordinarily are not relied upon to produce mechanical resistance; instead, much larger mechanical resistances, as described above, are employed for the purpose.

One point should be noted here. It may have been noticed by the student that unlike a loudspeaker, a microphone does not ordinarily employ a horn or flat baffle (except that the case acts in a sense as an infinite baffle). Instead, the small diaphragm is normally directly exposed to the sound waves. The reason for this is two-fold:

1). The microphone is much smaller and lighter and can be located almost anywhere in the studio, and

2). The smaller bulk of the microphone decreases the diffraction effects and makes it have a more nearly uniform frequency response regardless of the direction of pickup.

On the other hand, the efficiency of pickup would be greatly improved, at least for favored directions, if an adequate horn or baffle were coupled to the microphone. That is why these devices are employed in a loudspeaker, which is the reverse of a microphone. In this way maximum acoustic output is obtained from the loudspeaker for a given amount of electrical input from the power amplifier stage. High conversion efficiency is highly desirable here since the source of the electrical power, namely the power amplifier stage, is expensive both from the viewpoint of first cost and operating cost.

In the case of the microphone, however, it is preferable to operate it in a relatively inefficient manner if thereby its size and directional characteristics can be improved. This is because if the electrical output is thereby reduced, compensation can be had by the use of an additional small voltage amplifier stage of inexpensive design. For that reason adequate mechanical damping is also employed to flatten the microphone's frequency response. Most of the acoustical energy is therefore converted directly into heat energy in the orifices, etc., of the microphone, and very little into electrical energy. As a result the output level is quite low, but as long as it is sufficient to override the various noise components present, the microphone is satisfactory from a commercial viewpoint. As pointed out previously, the wider the audio band width desired, the greater is the damping and the lower is the output level.

COMPLIANCE.—Mechanical capacitance or compliance, as it is called, is obtained by having the force flex a solid spring member, or compress air in a chamber. For example, in the diagram shown in Fig. 24 (reproduced here), there is an air chamber A. Air is compressed here and acts like a spring member to increase the stiffness of the diaphragm. Another compliance is that of the annular edge of the diaphragm--the portion that is clamped to the casing.

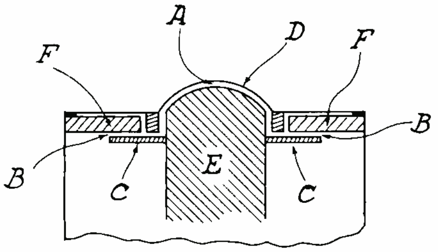


Fig. 24.--Use of Air Chambers as Compliances in a Dynamic Microphone.

When the diaphragm is flexed, this clamped portion flexes, and acts as a spring member. A third compliance is that of the air chamber formed by the microphone itself. Thus air that is forced out of the annular slit B by a downward motion of the diaphragm rushes into the bottom portion of the casing, where it acts to increase the compression of the normal air there. The casing acts like a large compliance, i.e., like a large electrical condenser. More will be said about this in the detailed discussion of the 630-A non-directional microphone.

EXAMPLE OF MECHANICAL ANALOGY.--The microphone discussed above furnishes an excellent example of a mechanical system for which there is an electrical analogy. It is reproduced once again in Fig. 25 with the proper annotations. The diaphragm (plus the voice coil) has a certain amount of mass, M_d, compliance C_d, owing to the edge of the diaphragm being clamped, and internal molecular friction R_d. (This is very small.)

The small air space between the inside of the diaphragm dome and the top of the center pole piece E represents a compliance, denoted in Fig. 25 by C_s. The annular slit approximates very closely a mechanical resistance and mass (that of the enclosed air) in series. Finally, the air within the microphone casing can be regarded as another compliance, C_c.

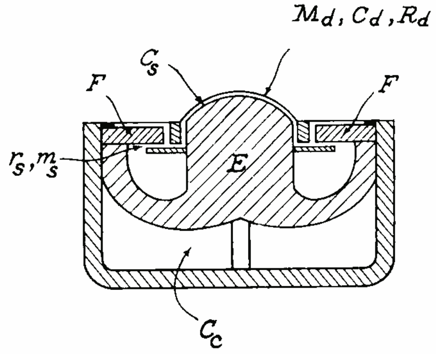


Fig. 25.--Analysis of Dynamic Microphone as a Mechanical Analogy of an Electrical Circuit.

In analyzing the behavior of the microphone, it must be noted that if the applied force is consumed in part across each of two or more of the above components, then these components are in series. On the other hand, if the force on two or more components is the same, but the velocity of motion divides between them, then the components are in parallel. This is exactly analogous to the electrical circuit, and its application will be clearer by drawing the electrical cir-

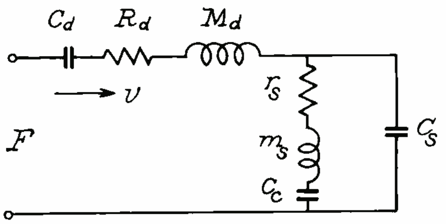


Fig. 26.--Electrical Circuit Analogy for Dynamic Microphone.

cuit analogous to the microphone. This is shown in Fig. 26. The force F is that of the acoustic wave acting on the microphone. Some of this force is consumed in flexing the diaphragm (across C_d); some in overcoming the internal friction of the diaphragm (across R_d); and the rest in moving the diaphragm's mass (across M_d) as well as the remaining components of the circuit. Hence C_d, R_d, and M_d are shown as a condenser, resistance, and inductance in series. A further check that they are in series is that all parts of the diaphragm move in phase, so that there is one common velocity for all parts. (In a series circuit the current is the same throughout the circuit.)

Next consider the air space C_s and the slit r_s, m_s. Suppose the slit were closed so that no air could flow through it. If it were in series with C_s, then no air could flow in C_s, since if a series circuit is opened at any point, no current (velocity) can flow in any portion of it. An inspection of Fig. 25, however, shows that this is not the case; if the slit is blocked, the diaphragm can still force air into the space C_s. Indeed, if the slit is opened, it relieves the air pressure in C_s, i.e., r_s and m_s act as a shunt to C_s. Hence r_s and m_s must be drawn in parallel with C_s. However, the air issuing from the slit does not empty into free space (which can be regarded as an infinite condenser), but instead empties into the volume within the microphone casing, namely C_c. Hence r_s, m_s, and C_c are shown in series, and the three are in parallel with C_s, as shown in Fig. 26.

Thus the electrical circuit analogous to the microphone has been worked out. An analysis of the behavior of the electrical circuit indicates the behavior of the microphone mechanical circuit. For example, inspection of Fig. 26 indicates several resonant circuits coupled together. These will give a response curve showing several resonant peaks, something like the double-peaked response of an i.f. amplifier. By the use of sufficient damping, such as r_s, the peaks can be reduced so that the response does not vary say, more than 1.5 db from 100 to 5,000 c.p.s.

By response is meant the output electrical voltage for a force F that is fixed in magnitude but variable in frequency. The output voltage is proportional to the rate at which the voice coil cuts the field flux, i.e., the voice coil velocity. This is denoted by v in Fig. 26. Hence what is desired is that v be constant in amplitude over the frequency range. By the proper choice of C_d, R_d, M_d, r_s, m_s, C_c, and C_s, i.e., by the proper choice of the masses, damping, and elasticities in the mechanical system, the velocity v can be kept relatively constant.

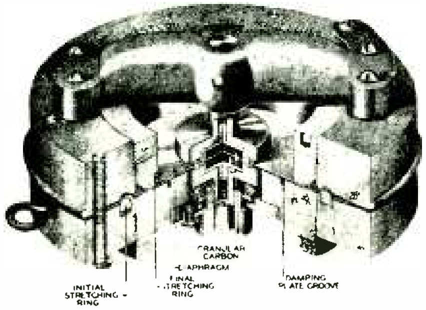
This is done by solving the equivalent electrical circuit by the usual methods of circuit analysis. Thus the force F is assumed to have some representative amplitude and various frequencies, in turn. At each frequency f, a compliance, such as C_d, has a *mechanical capacitive reactance* of $1/j2\pi fC_d$; a resistance, such as r_s, has a value of so many mechanical ohms: and a mass, such as M_d, has a *mechanical inductive reactance* of $j2\pi fM_d$. The equations for the various meshes can then be written, and—by the application of Kirchoff's

Laws--the mechanical current v can be found at various frequencies. If v varies too much over the frequency range, other values of the masses, compliances, and resistances can be chosen, by a cut-and-try method, until a combination is found that yields a substantially constant v over the frequency range.

REPRESENTATIVE TYPES OF MICROPHONES

The foregoing analysis of the acoustical, electrical, and mechanical behavior of microphones in general permits a better understanding of the representative types of actual microphones to be discussed here.

DOUBLE-BUTTON CARBON MICROPHONE.—In Fig. 27 is shown a photograph of a double-button carbon microphone, and in Fig. 28 is shown a cross-sectional view. This type is rarely employed in broadcast work today, but is still used in some special services.



(Terman, courtesy of Radio Engineering)

Fig. 27.--Double-button Carbon Microphone.

Construction.—A thin duralumin diaphragm is stretched by an arrangement similar to a pair of embroidery hoops between a pair of carbon buttons until it is resonant at about 5,700 c.p.s. or higher.

The air in the 1 or 2 mil clearance space between it and the damping plate adds to the stiffness of the diaphragm and raises its resonant frequency above that produced by simple stretching alone. At the same time the air, when set into radial motion by the movement of the diaphragm, sets up damping reactions in the small clearance space as it flows into the damping groove and thus prevents an undue displacement of the diaphragm at its resonant frequency. The displacement with and without damping is illustrated in Fig. 29.

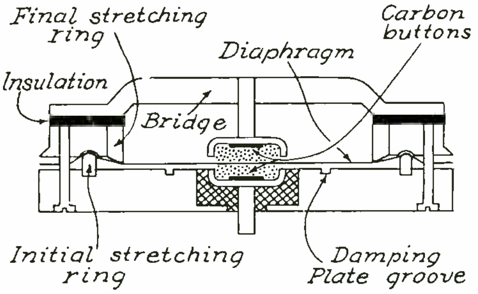


Fig. 28.--Cross Section of Double-button Carbon Microphone.

The motion of the diaphragm in either direction decreases the pressure on the carbon granules in one button and simultaneously increases the pressure on the granules of the other button, so that the resistance of the first increases, and that of the second decreases. This produces a push-pull action and aids in cancelling even harmonic distortion. The change in resistance is approximately proportional to the diaphragm displacement, hence the displacement and not the velocity should be proportional to the pressure on the diaphragm. This will be the case for frequencies below resonance of the diaphragm, for its mechanical impedance will be a capacitive reactance (spring action), and under such conditions the deflection, or displacement, is proportional to the force on the diaphragm.

It is further to be noted that seals, in the form of stacked rings of paper of great compliance, are interposed between the diaphragm and the rim of each button to prevent the carbon granules from sifting out, without the seals hindering the motion of the diaphragm. The latter is also usually gold-plated in the center to prevent corrosion and poor contact with the carbon granules.

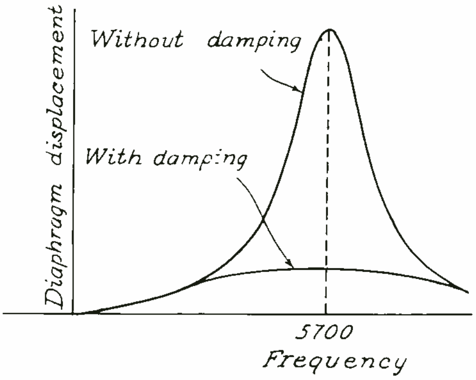


Fig. 29.--**Showing Effect of Damping on Frequency Response of a Diaphragm.**

Electrical Characteristics.--The method of connection to the input transformer, or alternatively to a microphone-to-line transformer, is shown in Fig. 30. This is perhaps the original push-pull circuit. The function of the r.f. coils and condensers is to prevent arcing of the granules and their fusing together when the circuit is suddenly opened. Such arcing will cause the buttons to "pack" and prevent subsequent variations in their resistance.

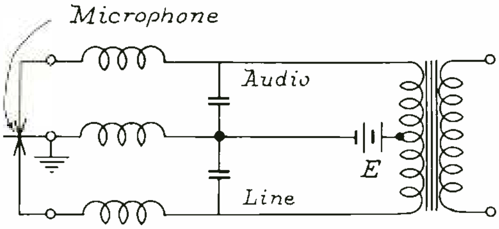
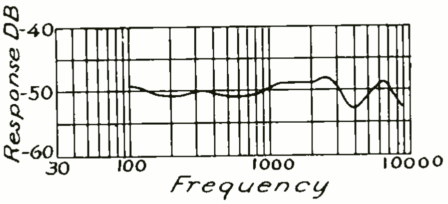


Fig. 30.--**Electrical Circuit for Double-button Carbon Microphone.**

The output is about -40 db per bar (0 db = 6 mw.) and the internal (button) resistance can be made anything from 100 to 500 ohms, total, depending upon the size of granules employed. The combination of the relatively high output level and low impedance makes it possible to employ quite long audio lines and at the same time reduces the amount of subsequent amplification required. Hence this microphone is well adapted for cheap public address systems and communication purposes of moderate fidelity requirements, such as telephone and radio telephone services.

A typical frequency response curve is shown in Fig. 31. It must not be overlooked that considerable hissing and "frying" noise is developed in the carbon granules, and prevents any appreciable extension of the high frequency response.

Acoustical Characteristics.--Owing to the relatively large diaphragm employed, pressure-doubling at the higher frequencies occurs for axial waves, and attenuation of the higher frequencies owing to diffraction effects occurs for waves off the axis. The poor directional response characteristics. coupled with the high internal noise characteristics, precludes the use of this microphone for ordinary broadcast pickup, and restricts its use mainly to close-talking applications.



(Olson, courtesy of Elements of Acoustical Engineering)

Fig. 31.—Frequency Response, Double-button Carbon Microphone.

In addition, the tendency of the buttons to become unbalanced as to resistance owing to aging and packing effects, together with the fact that a low-voltage d.c. polarizing source is required, has aided in rendering obsolete this type of microphone.

THE CONDENSER MICROPHONE.—The condenser microphone supplanted the carbon-button type because of its negligibly low noise level, its greater electrical stability, and more extended frequency response. However, its poor directional characteristics, together with its extremely low output level, which necessitates its pre-amplifier being located at the microphone, has caused it to be supplanted by newer types to be described farther on in this technical assignment.

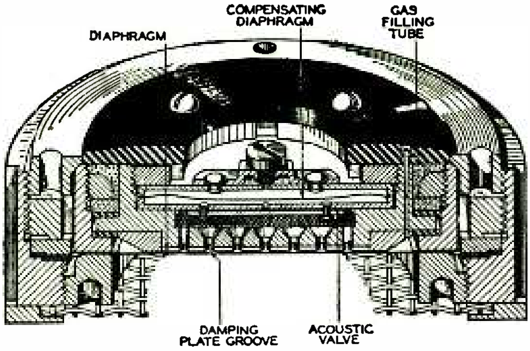
Nevertheless, it may still be found in use in some of the smaller broadcast stations for close-talking purposes, such as where the announcer sits at the console and reads his script directly in front of the microphone.

A minature model of the condenser microphone has been employed in the past as a kind of acoustic probe to measure, for example, the pressure at various points in an exponential horn. The same principle has also been employed in a phonograph pickup: the variation in capacity in this case is usually employed to frequency modulate an r.f. wave.

Construction.—A cross-sectional view is shown in Fig. 32. The fundamental action was described earlier in this lesson. Similar to the carbon-button microphone, a stretched duralumin diaphragm about 1 mil in thickness and 1-5/8 inches in diameter, is spaced about 1 to 2 mils from an insulated back plate and forms in conjunction with the latter a small condenser of from 400 to 200 μμf capacity. The acoustic wave varies this capacity about 0.01% of the static value.

The change in capacity is proportional to the displacement of the diaphragm, and since this is compliance-controlled below its resonant frequency (about 9,000 c.p.s.), it follows that a flat frequency response will be obtained for constant acoustic pressure, just as in the case of the carbon-button microphone.

Damping is produced in a manner similar to that for the carbon-button microphone, but is more elaborate. As may be noted from Fig. 32, a series of grooves are cut in the back plate so that they intersect each other at right angles. At each intersection a hole is drilled to act as a vent for the escape of the air from the clearance space.



(Terman, courtesy of Radio Engineering)

Fig. 32.--Cross Section of Condenser Microphone.

A further point to be noted from Fig. 32 is the means to provide equalization of the inside and outside pressure owing to variations in barometric pressure. A flexible diaphragm of thin brass or rubber can be moved by a change in external pressure so as to vary the internal pressure to the same extent. At the same time the acoustic variations in pressure are not transmitted to the inner side of the duralumin diaphragm owing to the mass (inertia) of the equalizing diaphragm. In many models the inside is filled with pure dry nitrogen to prevent corrosion of the internal parts. The gas-filling tube shown in Fig. 32 enables this to be accomplished.

Electrical Characteristics.--The microphone must be coupled directly to the pre-amplifier, as shown in Fig. 33. Recommended values for R and GL are 20 and 25 megohms, respectively, and R should not be less than 10 megohms if good low-frequency response is to be obtained. The resistors should be exceptionally constant in value if background noise is to be avoided.

For a polarizing voltage of 180 volts, the open-circuit voltage is 0.5 mv. for 1 bar pressure (RCA). This is sufficient for a close-coupled pre-amplifier. Suppose however an audio line about 35 feet long, and having a capacity of .001 µf, were employed. The internal capacitance of the microphone can be taken as 400 µµf. Then, by Eq. (2), the terminal voltage at the grid of the first tube will be

$$e_g = 0.5 \frac{400}{400 + 1000} = 0.143 \text{ mv./bar}$$

This is too small, particularly

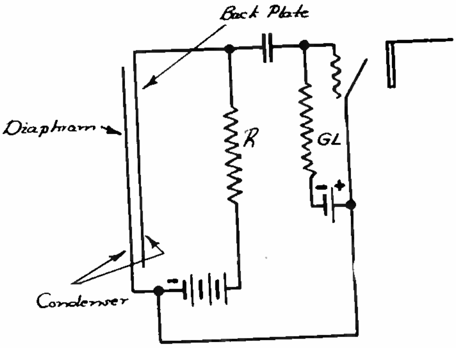
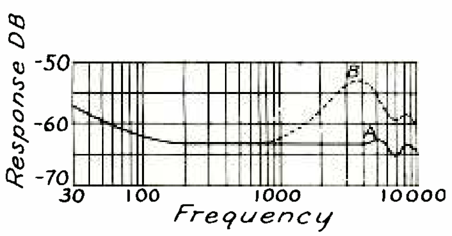


Fig. 33.--Electrical Connections, Condenser Microphone.

when the high impedance of the circuit is taken into consideration. At the very most, a 12-foot cable-run has been employed in sound motion picture work.

Acoustical Characteristics.—The pickup characteristics of this microphone are practically the same as for the carbon-button microphone, since the diaphragms are comparable in size. The frequency range is greater, however, and is shown in Fig. 34. The peak around 4,000 c.p.s. is due in part to the pressure-doubling effect that occurs at the higher frequencies, and in part to the acoustic resonant effect (like that of an organ pipe) owing to a shallow cavity produced by the diaphragm clamping ring.



(Olson, courtesy of Elements of Acoustical Engineering)

Fig. 34.—Frequency Response, Condenser Microphone.

Off the axis, diffraction causes an attenuation of the higher frequencies, so that the directional characteristics are poor. In addition, the microphone and pre-amplifier are bulky and fragile, and unsuited for remote pickup work—as in night clubs, etc. Although the microphone may become noisy in time owing to insulation leakage, defective tubes, etc., it is normally quite free of internal noise and can be located a considerable distance from a large sound source, such as a symphony orchestra. In this way a more uniform pickup of the various instruments can be obtained with a single microphone. This is not possible with the noisier carbon-button microphone, which must be placed quite close to the sound source.

THE VELOCITY MICROPHONE.—This type of microphone was developed by Dr. H. F. Olson around 1930, and has proved to be one of the most important types available for

(Courtesy of RCA)

Fig. 35.—Velocity (Ribbon) Microphone.

sound motion picture recording and for broadcasting. Its outstanding features are simplicity of design and construction, excellent frequency response, and highly desirable directional features.

Construction.--In Fig. 35 is shown a velocity microphone of the ribbon type. Its internal construction is illustrated in Fig. 36.

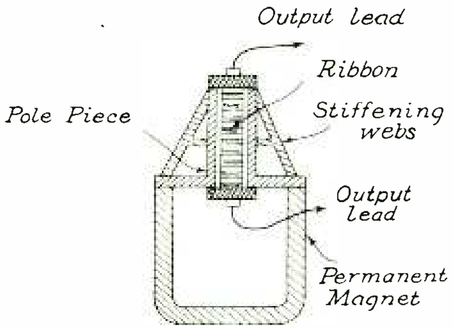


Fig. 36.--Cross Section, Ribbon Microphone.

A permanent magnet with two long pole pieces sets up a magnetic field across and in the plane of the ribbon situated between the pole pieces. The sound wave causes the ribbon to vibrate to and fro, and the voltage generated by the ribbon is proportional to its velocity, (rate of cutting of magnetic lines of force).

The ribbon is made of very thin duralumin about 0.2 mil thick, 1/4 inch wide, and about 2 inches long. It is corrugated as shown to give it some lateral stiffness, but it is very flexible along its length, so that even when clamped at its two ends it has a very high compliance. It also has mass (although this is very small), so that the equivalent electrical circuit, as shown in Fig. 37, is that of a series resonant circuit, in which M_r is the ribbon mass, plus that of a certain amount of air associated with the ribbon, C_r is the ribbon compliance, and F is the actuating force of the impinging sound wave.

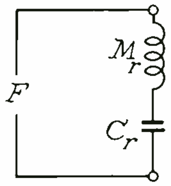


Fig. 37.--Electric Circuit Analogy for Ribbon Microphone.

So large is C_r that the ribbon is resonant at a frequency below the audio range. Hence, in the audio range the inductive or mass reactance, $j\omega M_r$, exceeds the capacitive or compliance reactance $1/j\omega C_r$ to such an extent that the mechanical reactance of the ribbon is essentially inductive, and practically equal to $j\omega M_r$. The ribbon's motion is said to be mass- or inertia-controlled in the audio frequency range. This is important to an understanding of the microphone's behavior.

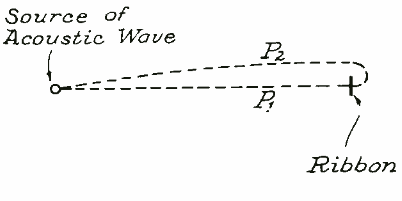


Fig. 38.--Action of Acoustic Wave on Ribbon Microphone.

Now consider an acoustic wave proceeding along the axis of the ribbon, as shown in Fig. 38. (This is a top view of the ribbon.) The path to the front face of the ribbon is P_1, and the path to the back face of the ribbon is P_2. Path P_2 is longer than path P_1 by an amount depending upon the shape and construction of the pole pieces. Normally the difference in path length $(P_2 - P_1)$ is made short enough by cutting holes in the stiffening webs of the pole pieces (Fig. 36) so that it is less than half a wavelength at the highest audio frequency to be picked up.

The difference in path length causes the pressures and hence forces on the two sides of the ribbon to be out of phase so that the two do not cancel. There is thus a net force acting on the ribbon that causes it to vibrate and generate and e.m.f. In Fig. 39 is shown the phase relationships. Suppose that at the instant under consideration the sinusoidal acoustic wave impinging upon the front face of the ribbon is at a positive maximum. This is shown as AD in Fig. 39.

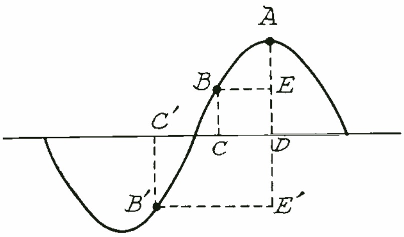


Fig. 39.--Showing How Pressure Differential is Produced on Ribbon.

Owing to the greater path length P_2 to the back of the ribbon an earlier instantaneous value of the wave, BC has just reached the back of the ribbon. The net or differential pressure is then AD - BC or AE, and this develops the net force that actuates the ribbon.

Suppose that the frequency of the wave is higher. Then corresponding to the *same path lengths* the phase difference will be greater. Thus, if AD corresponds to the instantaneous pressure on the front face, B'C' will be represent the instantaneous pressure of the back face, and AE' will represent the net or differential pressure acting on the microphone. As is clear from Fig. 39, the differential pressure is now greater, so that the force actuating the ribbon is greater at the higher audio frequency. The same effect could be obtained at the original audio frequency if the path length difference $(P_2 - P_1)$ were correspondingly increased, such as by putting a baffle around the ribbon.

A mathematical analysis shows that the net or differential force ΔF acting on the ribbon *is directly proportional to the frequency*, i.e.,

$$\Delta F = k\omega \qquad (5)$$

where k is a constant of proportionality and ω is the angular velocity = $2\pi f$. Recall that the mechanical reactance of the ribbon in the audio range is essentially $j\omega M_r$. In an electrical circuit having an inductance, *the current* is given by

$$i = e/j\omega L$$

Similarly, in this mechanical circuit, *the velocity* is given by

$$v = \Delta F/j\omega M_r = k\omega/j\omega M_r = k/jM_r$$

$$= \text{constant} \qquad (6)$$

This shows that if the force

acting on the ribbon is directly proportional to frequency, and if in addition the ribbon's motion is controlled by its mass or inertia, *then the velocity of the ribbon will be the same at all frequencies.* The significance of this is that *the voltage generated by the ribbon is proportional to its velocity* or rate of cutting of the magnetic lines of force, so that if the velocity is independent of frequency, *the generated voltage will be independent of frequency;* in short--a flat frequency response can be expected, at least for an axially directed wave. The microphone is usually called a velocity type because the motion of the ribbon corresponds to the velocity of the air particles through which the sound wave is passing.

Acoustical Characteristics.—The same flat frequency response is fortunately possible for waves impinging at an angle to the microphone axis. In Fig. 40 is shown a sound source S_1 making an angle θ to the ribbon axis, as well as a source S_2 making a 90-degree angle with the ribbon axis. In the case of S_1 *the difference* in path length $(P_2 - P_1)$ is less than for a source on the axis. The reduction in the quantity $(P_2 - P_1)$ is in proportion to cos θ, hence the actuating force ΔF is proportional to cos θ.

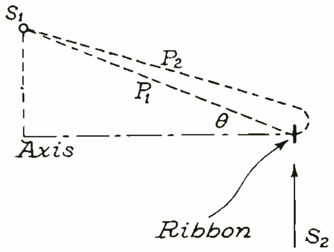


Fig. 40.--Directional Effects of Oblique Wave on Ribbon Microphone.

More specifically, if $\Delta F_{(\max.)}$ is the net force for an axial direction, and ΔF_θ is the net force for a direction θ, then

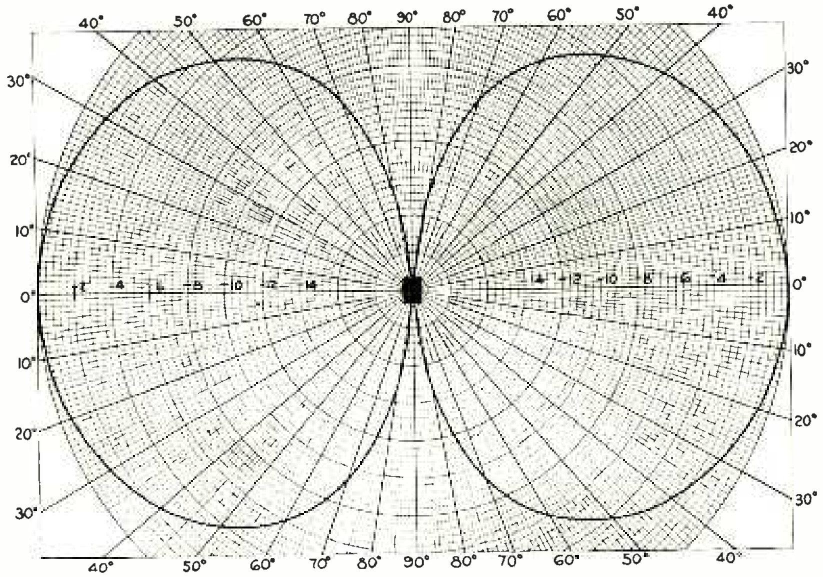
$$\Delta F_\theta = \Delta F_{(\max.)} \cos\theta \qquad (7)$$

It is clear from Eq. (7) that if $\theta = 90^\circ, \Delta F_\theta = 0$, *or the microphone has no pickup for sounds originating in the plane of the ribbon.* This can be seen directly from Fig. 40. If the source is S_2 at right angles to the axis, then clearly the path length to both sides of the ribbon is the same, and hence there is no difference in pressure on the two sides.

The important thing is that this reduction in actuating force with θ is a geometrical effect, *and is independent of the frequency.* Hence, if the microphone has a flat response for axial waves, it will have a flat response for waves off the axis, the only change being that the output level will be reduced.

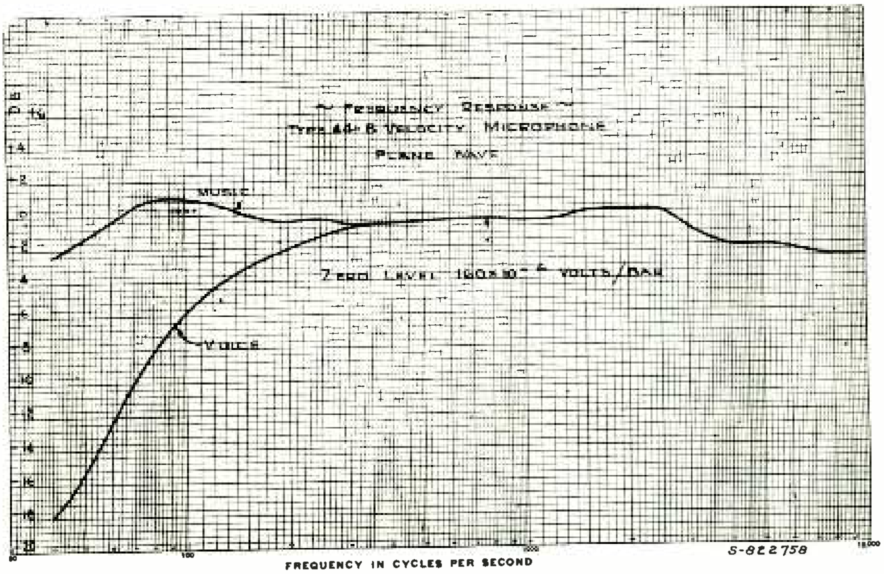
A typical polar response curve is shown in Fig. 41, and the frequency response for an axial wave in Fig. 42. The polar diagram is the familiar figure-of-eight pattern obtained from the cosine relationship, and is similar to the polar diagram for a loop antenna. The frequency response is essentially flat over the audio range for the "MUSIC" connection. (This will be explained farther on.)

An inspection of Fig. 41 shows that for sound originating say 45° off the axis the response is -3 db below that for an axial sound. This corresponds to a power ratio of $1/\text{anlg}\,(3/10) = 1/2$, or a voltage ratio of $1/\sqrt{2}$. Con-



(Courtesy of RCA

Fig. 41.--Polar Response Ribbon Microphone.



(Courtesy of RCA)

Fig. 42.--Axial Frequency Response of Ribbon Microphone.

sequently, if one person stands on the axis at a distance from the microphone of $\sqrt{2}$ times as far as another person 45° off the axis, the sound pickup from either will be about the same (at all frequencies). Thus the directional effect can be compensated by the distance from the microphone because the frequency response is the same off the axis as on it. (This has been discussed earlier in this technical assignment.) Furthermore, it will be observed that the microphone picks up sounds from the rear just as from the front, i.e., it is bi-directional and both sides of the microphone can be employed.

Practical Applications.--The directional characteristics, particularly the null positions, can be utilized to advantage in practice. Suppose there is a source of noise that it is desired to avoid picking up. By a proper orientation of the microphone this can be accomplished. The method is shown in Fig. 43. The microphone is so located and turned that the plane of its ribbon contains the noise source. Since this represents a null region, no noise will be picked up. At the same time the desired sound source is on the axis of the microphone and is picked up with maximum effect.

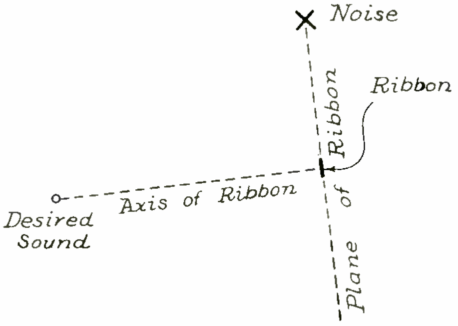


Fig. 43.--Method of Eliminating Noise Pickup by Ribbon Microphone.

Such placement is very effective in recording operations. The noise source may be the motion picture camera. This is therefore located in the plane of the ribbon of the microphone to capitalize on the latter's null characteristic. The sound stage and actors are directly in front of the microphone, and sounds from this region are picked up with maximum effect.

Another valuable feature of such a microphone is that its directional characteristic favors direct pickup of the sound source located on its axis over reverberation that comes from all directions in the room in about the ratio of 3 to 1.

This is often an important consideration. In the case of direct pickup by a human being, the two ears are sensitive to phase and intensity differences in the sound waves impinging upon them and thereby serve to locate the sound source and focus the mind's attention on it in spite of the presence of appreciable reverberation. In the case of the microphone, only one pickup unit is involved. This is known as "monaural" as compared to "binaural" pickup. An equal amount of reverberation in the case of monaural pickup is much more objectionable than for binaural pickup. For this reason the reduced pickup of reverberation by the ribbon microphone tends to make the reproduced sound seem more like that which would be heard directly at the scene.

Another advantage occurs if the microphone must be located at a point remote from the source. In this case the reverberation in the enclosure is about the same at all points owing to the complete filling of the space with sound energy by means of multiple reflections from the walls of the enclosure. The desired sound picked up, however, is greatly reduced by the large seperation between the source and the microphone. Hence the ratio of direct sound to reverberation may too low. In the case of a directional microphone, however, the reverberation pickup is reduced, hence the distance from the sound source may be correspondingly increased. As was mentioned previously, if the reverberation pickup is reduced to one-third, as is the case for a velocity microphone compared to a non-directional microphone, then the distance can be increased to $1/\sqrt{1/3} = \sqrt{3} = 1.73$ over that of a non-directional microphone.

Another example of the use of the directional characteristics of the velocity microphone is illustrated in Fig. 44. The loudspeakers may be employed to reinforce the sound for an audience located in a large studio. The arrangement indicates how the microphone may be oriented to avoid direct pickup of the loudspeaker acoustic energy and thus obviate acoustic feedback. This method is also useful for public address systems. While the microphone can pick up energy reflected from the walls of the studio, this effect is minimized by the absorption material on the walls and also by the reduced pickup effect for reverberation mentioned above.

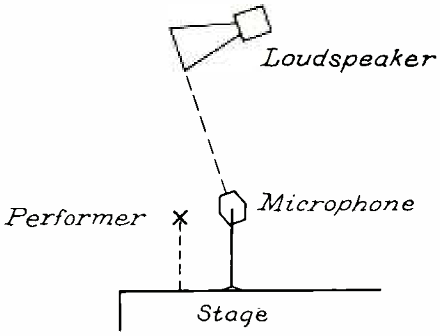


Fig. 44.--Method of Eliminating Acoustic Feedback from Loudspeaker to Ribbon Microphone.

Electrical Characteristics.--The electrical characteristics have been discussed earlier in this technical assignment and will be briefly reviewed here. The ribbon represents a very low impedance electrical generator. Hence it is necessary to step up its impedance to a standard value, such as 250 ohms by means of a matching transformer located directly in the microphone case. By this means the voltage drop in the leads running to the pre-amplifier is minimized. Such voltage drop is due not only to the resistance in the leads, but to the inductance. The latter effect is greater at the higher audio frequencies and would attenuate them more than the lower frequencies, thus spoiling the response curve. The arrangement is shown in Fig. 45. As far as the voltage delivered to the grid is concerned, it is immaterial whether the voltage step-up occurs in one step or two, hence the previous calculations based on the db power level apply here; it is merely necessary to know this and the impedance of the line-to-grid transformer secondary.

Most sound sources, like the human mouth radiate waves having essentially a spherically wave front. At sufficiently large distances from the source, the small section of the wave front intercepted by the microphone is essentially plane (flat), but when the microphone is located close to the speaker, say about 2 feet, the curvature of the wave front cannot be ignored. The effect of a spherical wave front is to accentuate the low-frequency response. It is therefore necessary to compensate electrically for this. The method employed is shown in Fig. 45. A reactor L is shunted across part of the secondary winding by placing the jumper V across the two terminals marked "M" (music) in Fig. 45. This shunt is of lower reactance at the lower audio frequencies and reduces the voltage applied to the pre-amplifier line-to-grid input transformer. As a result the frequency response labelled "VOICE" in Fig. 42 is obtained. For a speaker located one foot from the microphone, however, the low-frequency pickup is sufficiently greater to compensate for the above attenuation characteristic, with the result that the overall response is essentially as flat as for the MUSIC position (for which jumper V is

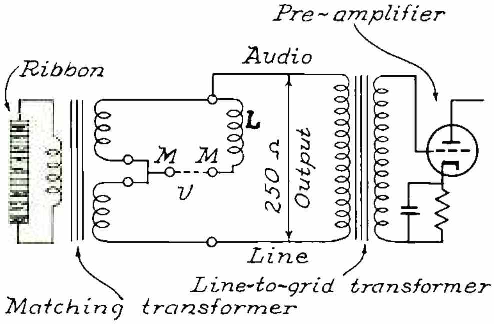
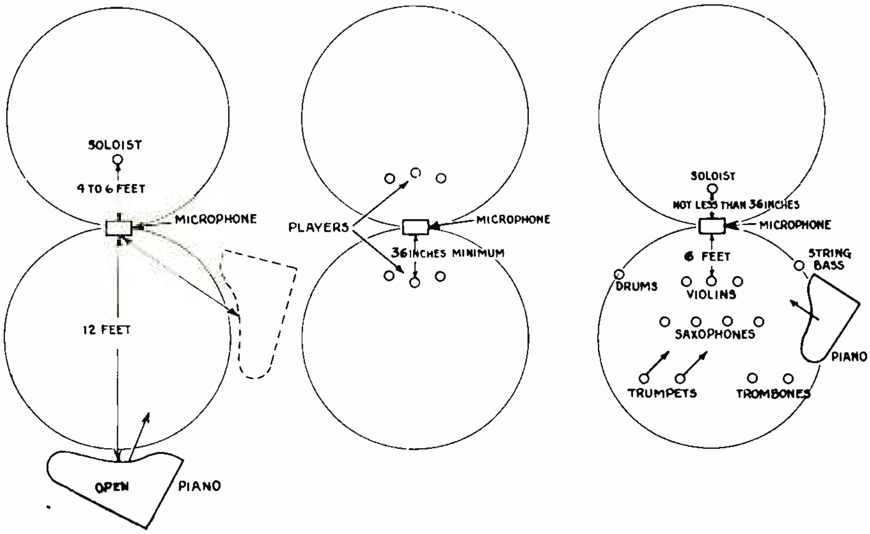


Fig. 45.--Circuit Connections for Ribbon Microphone.



—Soloist with piano

Plays

Dance orchestra

VARIOUS MICROPHONE ARRANGEMENTS

(Courtesy of RCA)

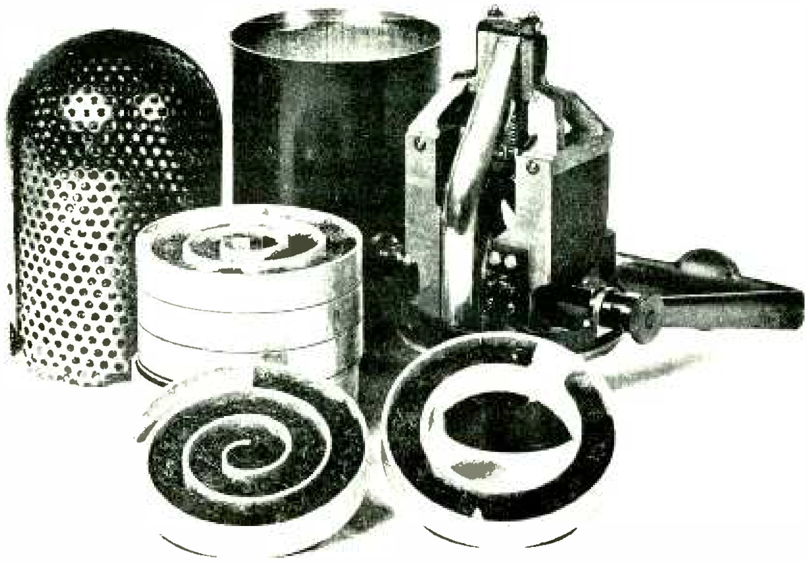
Fig. 46.--Placement of Velocity Microphone and Performers.

removed).

Finally, in Fig. 46 is shown three suggested arrangements for broadcast or similar pickup. In the first example (to the left) the dotted line position for the piano gives a greater ratio of reverberation to direct pickup for the piano. This may produce a desirable effect upon the musical accompaniment, particularly in a "dead" studio.

The center diagram illustrates the bi-directional pickup qualities of the microphone. This has been discussed previously.

The third illustration shows how instruments of a dance orchestra should be placed with regard to their loudness. As will be observed, the violins, being the weakest in-instruments of the orchestra, are placed closest to the microphone, whereas the trumpets and trombones, being the loudest, are placed farthest away. It will also be observed that the drums and string bass are acoustically remote from the microphone in that they are located considerably off the axis.



A disassembled view of the Type 77-A Microphone. Note particularly the pipe which encloses the rear of the upper (pressure-actuated) half of the ribbon, and the ingeniously arranged labyrinth which furnishes the proper acoustic termination for the pipe.

(Courtesy of RCA)

Fig. 47.--RCA Type 77-A Uni-Directional Microphone.

One further point to note is that the microphone should not be placed closer than 3 feet from any solid reflecting surface, unless the latter is covered with thick felt or similar absorbing material. Such material attenuates the reflected sound and thereby prevents accentuation or attenuation of the resultant sound by interaction of the direct and reflected waves at the microphone position.

THE UNI-DIRECTIONAL MICROPHONES.--For many applications a microphone is desired that picks up sound from directions in front of it, and none to the rear. For this purpose the uni-directional or cardiod microphone has been developed by several manufacturers. There are two major types: one in which the directional pattern is obtained by a suitable combination of electrical and acoustical means, and the other by means that are purely acoustic in nature.

RCA Type--Construction.--The uni-directional microphone manufactured by RCA has a ribbon arranged so that the bottom half is exposed on both sides, whereas the top half is enclosed in the rear by a tube of rectangular cross-section in order to fit the ribbon. It thus is essentially two microphones acting as a unit. The construction is made clearer by an inspection of Fig. 47, which shows a disassembled view of the microphone. The tube covering the back of the top half of the ribbon leads to a tube coiled up in the form of six sections, each of spiral form, in the circular base of the microphone. The coiled-up tube or labyrinth is filled with tufts of felt, which acts as a sound absorber. Thus, if the top half of the ribbon is vibrated, such as by pressure from a sound wave on its front side, an acoustic wave is radiated from the back side of the ribbon into the tube, where this energy is absorbed by the felt. The lower half of the ribbon is actuated by the difference in pressure of a sound wave on its two sides, and therefore operates as a velocity microphone described previously.

The ribbon is clamped at the center as well as at the two ends so that the two halves vibrate independently, although electrically they are in series. The top half has a certain amount of mass and a large amount of clamping compliance.* However, when a force is applied, most of it is consumed in overcoming the air frictional effects in the tube and labyrinth, and very little in overcoming the inertia of the ribbon or its compliance. Hence in its electrical representation, shown in Fig. 48, C_r is very large, M_r is very small, and R_t is relatively large. The mechanical impedance is

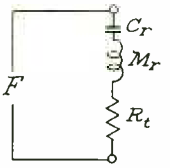


Fig. 48.--Electric Circuit Analogy for Damped Half of Ribbon in Unidirectional Microphone.

$$Z_m = R_t + j\omega M_r + 1/j\omega C_r \qquad (8)$$

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*This means that it has little stiffness, i.e., very little force is required to flex it.

In view of the relative magnitudes of R_t, M_r, and C_r as discussed above Eq. (8) for all practical purposes reduces to

$$Z_m = R_t \qquad (9)$$

or the top half of the ribbon is said to be *resistance-controlled* and independent of frequency.

The significance of this is that if an actuating sound wave develops the same pressure and hence force F on the front face of the ribbon at all frequencies, then the velocity of the top half of the ribbon will be

$$v = F/Z_m = F/R_t \qquad (10)$$

and will be the same at all frequencies. From this it follows that the voltage generated by the top half of the ribbon will be the same for all frequencies, i.e., the frequency response will be flat.

The lower half operates as a velocity microphone and has a flat response because the differential force ΔF varies directly with frequency and the mechanical impedance of the ribbon varies directly with frequency too, so that the velocity and hence generated voltage is independent of frequency. (This was explained in the previous section.) Since the generated voltage of each half of the ribbon is independent of frequency, the total voltage, which is the sum of the two, is also independent of frequency.

Directional Response.--However, the directional response of each unit is quite different, so that the combined response differs from either. The pressure-operated (top) element behaves like an ordinary diaphragm type of microphone, except that the diaphragm here (top half of ribbon) and the tube enclosing its rear are so small that diffraction effects are negligible in the audio range. It therefore has equal pickup in all directions at practically all frequencies, and its polar diagram is as in (b), Fig. 49. The polar equation is

$$\rho_1 = a_1 \qquad (11)$$

where ρ_1 is the radius vector, and a_1 is a constant (the length of the radius). Note that ρ_1 represents the magnitude of the generated voltage at any specified angle to the ribbon axis. Eq. (10) states that this voltage is the same, a_1, for all directions.

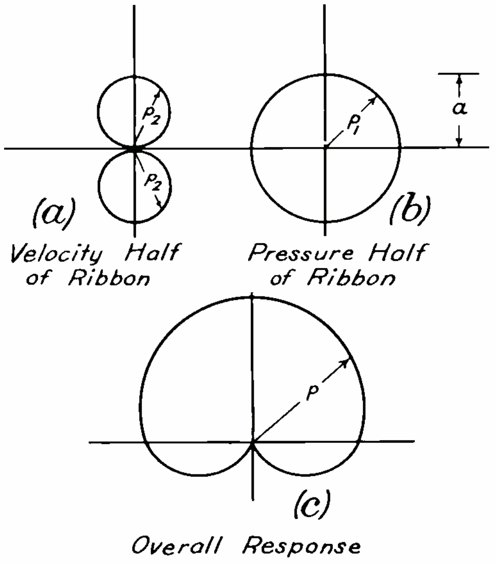


Fig. 49.--Directional Response of the Components of a Uni-directional Microphone.

The bottom half of the ribbon acts as a velocity microphone. The polar response curve is shown in (a), Fig. 49. The polar equation has been developed previously on the basis that the response falls off as the cosine of the angle θ off the axis. If a_2 is the axial response or generated voltage, then the polar equation is

$$\rho_2 = a_2 \cos \theta \qquad (12)$$

The total response is the sum of the two voltages, or

$$\rho = (\rho_1 + \rho_2) \simeq a_1 + a_2 \cos \theta \qquad (13)$$

It is customary so to adjust the sensitivities of the two sections that their generated voltages on the axis are equal, i.e., $a_1 = a_2 = a$, their common value. Hence Eq. (13) becomes

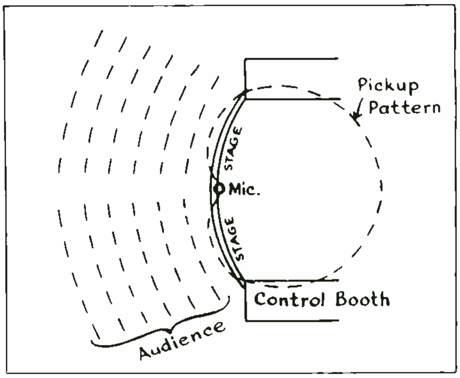
$$\rho = a(1 + \cos \theta) \qquad (14)$$

This is the equation of a cardioid, or heart-shaped figure, and is shown in (c), Fig. 49. It indicates that for sounds originating to the rear of the microphone, the voltages generated in the two halves of the ribbon are 180° out of phase and thus cancel, whereas for sounds originating in front of the microphone the voltages are in phase and add directly.

Actually, owing to the finite length of the labyrinth, it acts like a transmission line of high loss but yet not of sufficient length at the lower audio frequencies to prevent some reflection from the far end. As a result, its impedance is not purely resistive at the lower frequencies, and this in turn causes the velocity of the upper half of the ribbon to lead the pressure in the sound wave instead of being in phase with it. By placing a silk cloth around the lower half of the ribbon, a resistance reaction produces a leading phase shift in this section so that the two generated voltages will remain in phase. At the high audio frequencies equal phase shifts are obtained by giving the field structure a suitable shape.

This microphone has a wider front pickup than the velocity type, that is, the pickup for angles as great as 60° is only about 3 db below that on the axis. Hence, even if the pickup from the rear is very small (about 20 db less than for the front), the total pickup of reverberation is about the same as that for the velocity microphone, or about one-third that for a non-directional microphone.

Applications.--This type of microphone is particularly well suited for use where audience noise is a problem. By having the back of the microphone face the audience, as shown in Fig. 50, such pickup can be obviated. Note how uniform the pickup is of the artists on the stage.

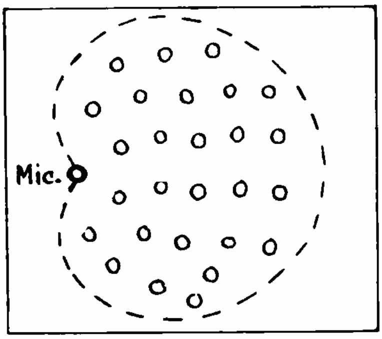


(Courtesy of RCA)

Fig. 50.--Placement of Uni-directional Microphone to Avoid Audience Noise Pickup.

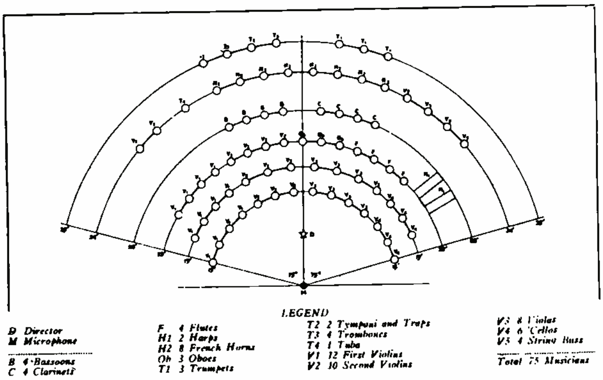
Another application is that

to small studios, where the microphone must be placed near one wall of the studio by having its back face the wall, as shown in Fig. 51.



(Courtesy of RCA)

Fig. 51.--Placement of Uni-directional Microphone in Studio.



(Courtesy of RCA)

Fig. 52.—Uni-directional Microphone and Orchestra Arrangement for Symphony Orchestra.

The wall does not require as much dead-end absorption as would be the case if a non-directional or even a velocity microphone were employed. In connection with this, it is well to note that this microphone is less sensitive to the shape of the wave front. For example, it does not boost the low frequencies in the case of a spherical wave front (performer within 2 feet of the microphone) nearly as much as a velocity microphone will.

Finally, in Fig. 52 is shown the arrangement for picking up a symphony orchestra, where a wide angle stage is employed. Note that pickup over 75° to either side of the axis is possible with this microphone.

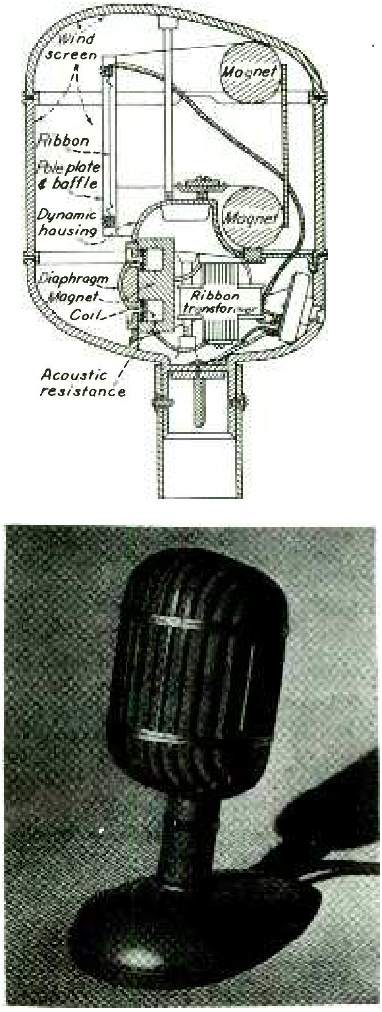
Electrical Characteristics.— The ribbon impedance is stepped up to 250 ohms by means of a matching transformer located in the transformer casing just as it is done in the case of the velocity microphone.

The output level is given as -68 db (0 db = 6 milliwatts) across a matched load for 10 bars sound pressure. This is only 4 db lower than that of the velocity microphone, and in consideration of the low output impedance--250 ohms--represents a satisfactory level for overriding noise pickup in shielded leads up to possibly 50 feet in length between the microphone and the pre-amplifier. As in the case of the other moving-conductor microphones, no internal noise--other than thermal agitation--is generated in the device, in contrast to that produced in a carbon-button type of microphone.

A variation on the uni-directional microphone is to have a switch whereby either half of the ribbon or both halves in series may be employed. Thus a bi-directional (velocity) type of microphone, a non-directional type--similar to a diaphragm type--and a uni-directional type of microphone may be had from the same instrument. The output for the first two modes of operation is only about 3 db below the uni-directional mode of operation.

Western Electric Type.--The Western Electric 639A Cardioid microphone is similar to the RCA Uni-directional type in its theory of operation, but employs a ribbon type and a diaphragm (dynamic or moving coil) type combination in one housing. A simplified cross-sectional view as well as an external view is shown in Fig. 53. The diaphragm unit (to be described in a following section) is sufficiently small so that diffraction effects over the major portion of the audio range are not serious, i.e., the diaphragm unit is essentially non-directional over most of the frequency range.

The ribbon unit is similar to the RCA velocity type and is bi-directional in response. Owing to the different electrical characteristics of the two units suitable equalizers must be employed to produce the same amplitude and phase relationships in the two. Provision is also made to operate either unit independently, thus obtaining essentially three types of microphones in the same housing. The remarks as to applications of the RCA uni-directional microphone apply here too. The output level is given as -84 db below 1 volt per bar. Assuming a voice coil impedance of 30 ohms, the output level is -84 db below 6 milliwatts, or



(Courtesy of Henney's Handbook and W.E.)

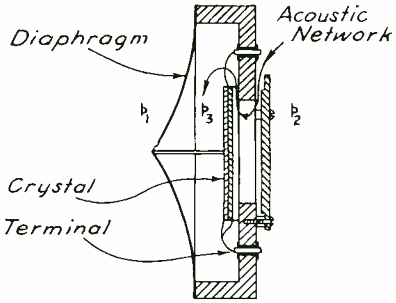
Fig. 53.--Cross-sectional and External Views of Western Electric 639A Cardioid Microphone.

-64 below for 10 bars pressure. Its output is thus about the same as for the RCA uni-directional type.

Shure Brothers Type.*—As stated previously, it is possible to obtain a uni-directional response with only one unit by means of an acoustical phase-shifting arrangement. The arrangement is shown in Fig. 54. A light duralumin diaphragm actuates a Rochelle salt crystal through a pin connector. Let the difference in path length between the front and back of the microphone casing be d. Then an axial wave coming from the front will strike the diaphragm earlier than the back of the casing. The pressure P_1 on the diaphragm will therefore lead the pressure P_2 on the back of the casing by an angle

$$\phi = 2\pi d/\lambda \qquad (15)$$

where ϕ is in radians, and λ is the wavelength measured in the same units as d.



(*Olson, courtesy of Elements of Acoustical Engineering*)

Fig. 54.—Method of Obtaining Uni-directional Characteristic by Acoustic Means.

As shown in Fig. 54, the wave impinging on the rear of the microphone can enter the casing through an opening marked "ACOUSTIC NETWORK" and build up a pressure P_3 in the interior. By proper design the path length and hence the phase angle in the acoustic network can be made the same as that for distance d. By this means P_3 will lag P_2 by the same angle ϕ that P_2 lags P_1.

Hence for an axial wave (directional angle $\theta = 0$), the vector relations between P_1, P_2, and P_3 are as shown in Fig. 55(A). Pressure P_2 lags P_1 by ϕ, and P_3 lags P_2 by ϕ, and hence lags P_1 by 2ϕ. Since P_3 acts on the inside surface of the diaphragm, it must be *subtracted* from P_1 to get the net or resultant pressure P_r on the diaphragm. This is accomplished by reversing P_3 to obtain $-P_3$, which is then added vectorially to P_1 to give P_r.

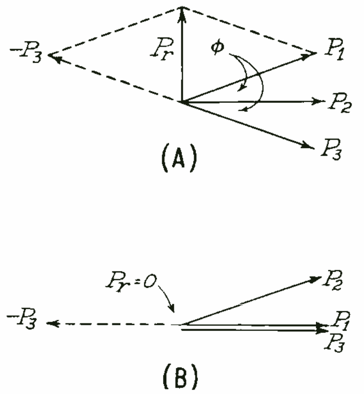


Fig. 55.—Vector Diagrams for Acoustic Type Uni-directional Microphone.

Now consider a wave having the direction $\theta = 180^\circ$, i.e., impinging upon the rear of the microphone.

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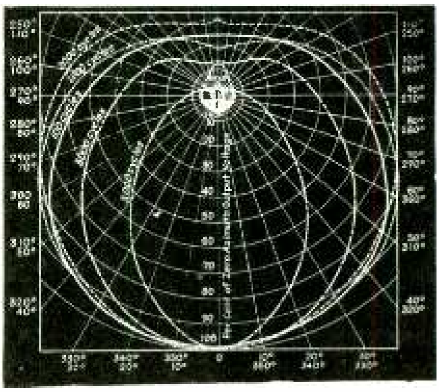
*See "A New Uni-directional Microphone", by Benjamin Baumzweiger, *Electronics*, Feb. 1939, page 62.

In this case P_1--the pressure on the diaphragm--lags P_2 by the angle ϕ, and P_3 also lags P_2 by the angle ϕ, so that P_1 and P_3 *are in phase*, as shown in (B), Fig. 55. Upon reversing P_3 to obtain $-P_3$, and adding this to P_1, a resultant P_r equal to zero is obtained. Hence the response from the rear is eliminated.

In actual practice the response from the rear can be made about 15 db below that from the front. The polar diagram is approximately that of a cardioid at frequencies up to about 2,500 c.p.s., but at higher frequencies the polar diagram is much narrower owing to the relatively large physical size of the microphone. The polar characteristics are shown in Fig. 56. Another factor is apparent from Eq. (15) and Fig. 55(A). As the frequency goes up, λ decreases, and hence ϕ increases. This in turn makes the net pressure P_r increase with frequency. To avoid having a rising response with frequency, electrical equalization is necessary.

NON-DIRECTIONAL DYNAMIC MICROPHONE.--In many cases there is a need for a microphone that is completely non-directional. For example, if an orchestra is situated in a small studio, it may be necessary to place the performers all around the microphone in order to arrange them properly with respect to it, whereupon pickup must be made from all angles.

The Western Electric 630-A or "Eight Ball" microphone, as it is sometimes called, shown in Fig. 57, has been designed to meet this need. It is characterized by three distinguishing features: The diaphragm is normally in a horizontal rather than in a vertical position, so that—from symmetry—it is inherently non-directional in the horizontal plane of the diaphragm; the casing is essentially spherical in shape, (with the top portion sliced off where the horizontal diaphragm is located), so that diffraction effects owing to the casing are not appreciably greater than that of the diaphragm itself; and finally, the microphone has a specially designed acoustic screen mounted directly above the diaphragm for the purpose of equalizing the response in



(Baumzweiger, courtesy Electronics)

Fig. 56.--Polar Diagram for Acoustic Uni-directional Microphone.

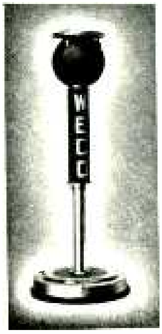
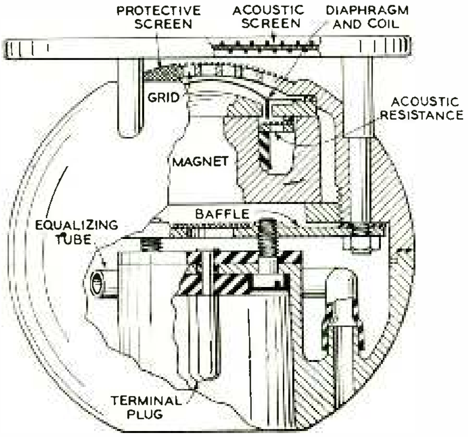


Fig. 57.--Western Electric 630-A "Eight-Ball" Microphone.

a vertical plane.

Constructional Features.--The constructional features of this microphone are illustrated in Fig. 58. A dome-shaped duralumin diaphragm is located at the top of a spherical casing. It has a voice coil on its under side, that vibrates in a radial magnetic field produced by a permanent magnet. Underneath the voice coil is an acoustic resistance made of silk fixed in a brass ring, which in turn is held in place by rubber gaskets.



(Courtesy of Bell Labs Record)

Fig. 58.--Rubber Gaskets.

The spherical chamber is divided into two parts by a baffle in which is placed an opening covered with another acoustic resistance. Communication between the two portions of the baffle is by means of this opening containing the resistance material, and the latter tends to damp out any resonance effects between the two parts.

A final feature is the equalizing tube, which not only affords contact with the outer air and thus serves to compensate for variations in barometric pressure, but also improves the low-frequency response and maintains it substantially flat to about 40 c.p.s.

The diaphragm is about 1 inch in diameter for the domed portion, which acts as a unit for frequencies up to 15,000 c.p.s. The outer annular portion has tangential striations or creases in it, as shown in Fig. 59.

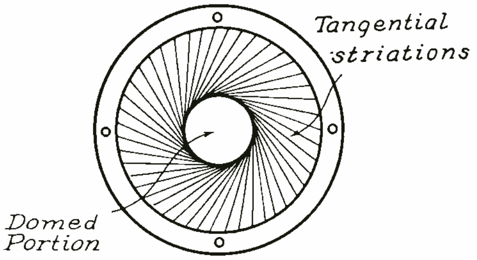
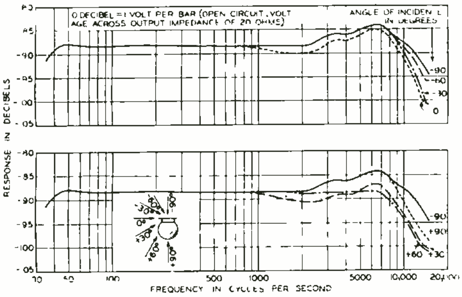


Fig. 59.--Tangential Striations to Reduce Clamping Stiffness of a Diaphragm.

These striations reduce the stiffness (increase the compliance) of the outer portion and thus enable the center domed portion with the attached voice coil to vibrate more freely. At the same time the stiffness must not be reduced to too great an extent or the microphone will be unduly sensitive to wind in outdoor locations. This is a troublesome feature for the ribbon-type microphone, and necessitates a silk screen enclosure to be placed around it.

In the case of the above diaphragm, the residual stiffness in the diaphragm to prevent effects from the wind, impairs its low-frequency response. To offset this the equalizing tube is provided. It permits the acoustic wave--at low frequencies--to impinge upon the under surface of the diaphragm in such phase relationship to the wave on the upper surface as to increase the force on the diaphragm at 40 c.p.s. and thereabouts, and thus serves to maintain the output practically constant down to 40 c.p.s.

The acoustic resistances depend upon the viscosity of the air in flowing through the fine holes in the mesh of the silk; in this way precision machining of fine air passages is avoided, and as a result, the expense of manufacture is considerably reduced. The damping obtained by the use of the silk disc is utilized to prevent undue response at frequencies at which the various masses and compliances in the microphone would resonate. The action is exactly analogous to that of resistance in a resonant electrical circuit. As a result of the careful proportioning and coordination of the various elements in this microphone, the frequency response is essentially flat from about 40 to 10,000 c.p.s., and the useful range (over which the output still has a satisfactory signal-to-noise ratio), exceeds this by an appreciable amount, particularly at the high end. The response curve of output versus frequency, for various directions as the parameter, is shown in Fig. 60.



(Marshall and Romanow, courtesy B.S.T.J.)

Fig. 60.--Frequency Response for Various Directions-Western Electric 630-A Microphone.

Acoustical Characteristics.--It is clear that if the microphone diaphragm is placed in a horizontal position, the pickup will be the same for all directions in the horizontal plane. (These are all denoted as 0° in Fig. 60.) However, the pickup at an angle to the horizontal plane will not necessarily be the same as in the horizontal plane owing to diffraction. As was pointed out earlier in this text, the use of a spherical casing tends to minimize such effects, but not to eliminate them entirely. Hence an acoustic screen 2-1/2 inches in diameter is employed and spaced approximately 1/8 inch above the diaphragm. It is made of a material that has a high ratio of resistance to mass. For sounds coming downward, the screen intercepts the wave motion and attenuates some of the energy, but also permits a portion of the wave to diffract around it (especially at low frequencies) and thus reach the diaphragm. The total amount of energy reaching the diaphragm is thus the fraction that is transmitted through the screen plus the fraction that diffracts around it, and is just about sufficient to hold up the response for this direction (-90° in Fig. 60).

If the screen were not employed, all the energy would strike the diaphragm and would produce at the higher frequencies the pressure-doubling effect mentioned earlier, thus peaking the high-frequency response. In conjunction with this, it should be noted that the grid-like structure above the diaphragm (Fig. 58) is also designed to control the cavity resonance effect in front of the diaphragm and thus aids in improving the response in the range from 8,000 to 15,000 c.p.s.

For sounds originating below the microphone (+90° direction) the response would drop off at the higher frequencies owing to the inability of these shorter waves to diffract around the spherical housing and produce a pressure on the diaphragm. Here, too, the acoustic screen proves to be of value. It not only partly attenuates, partly diffracts, and partly transmits acoustic energy, but it also reflects about as much energy as it transmits. This is illustrated in Fig. 61. The heavy line I represents the incident wave, and the lighter lines marked R and T represent the fractions of the wave that are reflected and transmitted, respectively. For a wave coming down, the fraction transmitted to the diaphragm is just sufficient to equal that coming from any side, while for a wave coming up, the portion reflected onto the diaphragm is about the same as that transmitted in the former case. In this way substantially equal output is obtained regardless of the direction of the wave.

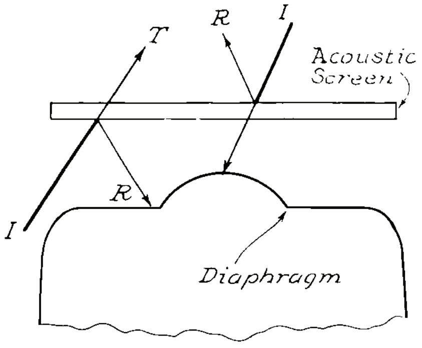


Fig. 61.--Use of Acoustic Screen to Equalize Directional Response.

Electrical Characteristics.—The voice coil impedance is about 30 ohms. This is a sufficiently high impedance for the audio line connecting the microphone to the pre-amplifier that no additional matching transformer is required in the microphone casing to raise the impedance to a higher value.

The output level for 1 bar pressure is about -88 db (0 db = 6 milliwatts). This level, in conjunction with the reasonable value of output impedance, enables the audio line to be as much as 50 feet long or more.

CRYSTAL MICROPHONE.—The acoustic design of a crystal microphone, particularly of the diaphragm type, depends upon the same factors as that of any other type of microphone. The essential difference is in the electrical action, i.e., the manner in which mechanical motion is translated into electrical voltage. Accordingly, the electrical behavior will be taken up first.

Piezo-Electric Effect.—If a wafer be cut from a crystal of Rochelle salt at the proper angle to the crystal axes, a device is obtained such that if it be bent or flexed, electric charges of opposite polarity will appear on its two faces. Conversely, if a potential be applied to the opposite faces so as to place opposite charges on the two faces, the wafer will bend. In short, the action is reversible, just as the ordinary moving conductor in a magnetic field can act as a generator or as a motor.

In Fig. 62 is shown a crystal wafer to whose top and bottom faces are fastened thin sheets of aluminum foil, terminating in connections as shown. If a force A is applied as shown, and the other edge B is held rigid, so that the force (of reaction) is opposite to A, then the wafer will be compressed, and a voltage e will be developed between the two foils. If the voltage e is applied to the two foil electrodes, the wafer will contract as shown. Upon reversing the voltage, the wafer will expand.

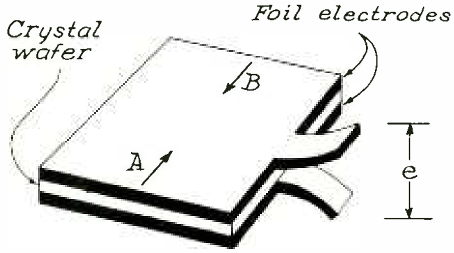


Fig. 62.—Crystal Wafer.

However, the voltage is in direct proportion to the compression or elongation up to a certain point, beyond which a saturation as well as hystersis effect sets in. To eliminate this undesirable characteristic, it is now usual to take two similar wafers and cement or clamp them together so that opposite faces are next to each other, i.e., for a given applied voltage, one wafer contracts, and the other expands. Such a combination is known as a bimorph element.

Bimorph Unit.--Its important characteristics are illustrated in Fig. 63. In (A) is shown such a bimorph element. The two wafers can either be cemented or clamped together. In the latter case frictional contact between the adjacent faces and the intervening foil causes the two to behave as if cemented together, i.e., as a unit. The foil electrodes on the upper and lower faces are connected together as shown and constitute one terminal, while the foil between the adjacent faces constitutes the other terminal.

When a voltage is applied between the two terminals, suppose its polarity is such as to make the upper wafer to contract and the lower one to expand. The action will be similar to that occurring in a bimetallic strip, or thermostat, and the combination will bend, as shown in (B), Fig. 63.

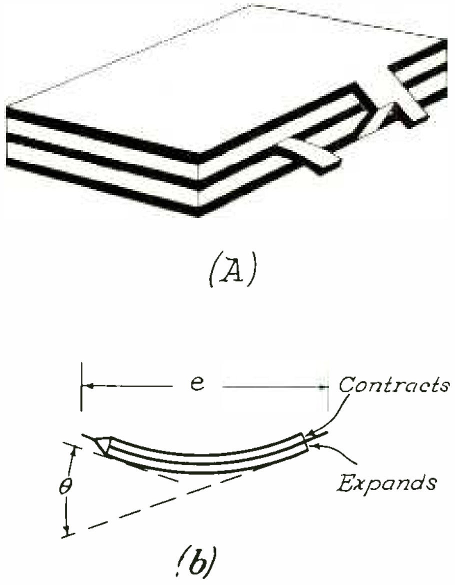


Fig. 63.--Construction and Action of Bimorph Crystal Element.

The important point to note is that for a very small contraction of the upper wafer and correspondingly small elongation of the lower wafer, the angle θ through which the crystal will bend will be relatively large.

Conversely, if a small force is applied to one edge of the bimorph unit, while the other edge is held rigidly in place, for a given amount of bending produced thereby, relatively large compressive and tensile forces will be set up in the two wafers. As a result relatively large charges will be produced in the two electrodes.

This is important in microphone work, since the crystals are very rigid (small compliance) and the air acting upon them is of relatively low mechanical impedance. Hence if the air sound wave was called upon directly to compress or elongate a single wafer, the effect would be very small because of the mechanical impedance mismatch between the two elements. In the case of the bimorph unit, the sound wave produces a bending effect, which in turn is multiplied into much higher compressive and tensile forces in the wafers. There is of course no gain in energy; there is merely a gain in force or mechanical advantage just as in the case of a lever.

The other very important reason for the bimorph form of construction is that it is essentially a push-pull construction and the hysteresis effect mentioned above, as well as variation in mechanical and electrical constants with changes in temperature, are reduced. As a result, the voltage output is a more faithful copy of the impressed acoustic variation in pressure. In passing, it may be noted that if the wafers are cut parallel to the crystal axes, they move so as to tend to shear, and if a bimorph unit is made of these wafers, it will twist rather than bend under the impress of an electrical voltage. The "bender" type is more commonly employed in microphones, whereas the "twister" type is more often used in phonograph pickups and loudspeaker units.

Direct-Actuated Microphone.--A typical sound cell is shown in Fig. 64. It consists of two bimorph units connected in parallel. The space between the two bimorph units is sealed to the outside air, and usually contains acoustic damping material, as well. A condensation in an impinging sound wave tends to squeeze the two units together so that the centers approach one another; a rarefaction tends to bow them apart. By the proper orientation of the two units, the output voltage is equal to that of each cell.

Such a cell can be very small[*] so as to have negligible diffraction over the audio range. It is therefore practically non-directional; and also has an essentially flat frequency response

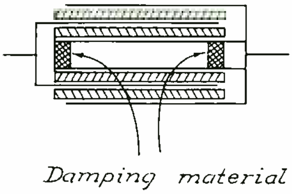


Fig. 64.--Crystal Sound Cell.

Electrical Characteristics.— The internal impedance of a crystal microphone is capacitive, just like the condenser microphone. The capacity varies with the size of the crystal and number of units in parallel. The ordinary sound cell has an internal capacity of .0033 µf; at 100 c.p.s. the reactance is 478,000 ohms. Suppose it is coupled to the grid of the first stage as shown in Fig. 65. Let the capacity C_L of the cable be .0015 µf, corresponding roughly to about 50 feet of cable.

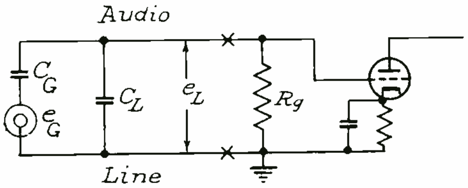


Fig. 65.--Coupling of Crystal Microphone to a Vacuum Tube.

To calculate the response, break the circuit at the X points and apply Thevenin's theorem. The impedance looking to the left is clearly C_L and C_G in parallel, or $(C_L + C_G)$. The voltage at the break is, by Eq. (2)

---

[*] A representative size for a wafer is 3/8" x 3/8" x 0.03".

$$e_L = e_G\left(\frac{C_G}{C_G + C_L}\right) \qquad (16)$$

The microphone and cable therefore appear as an equivalent source whose internal capacity is $(C_G + C_L)$ and whose generated voltage is e_L, and the load is R_g. This is shown in Fig. 66. The voltage e_g delivered to the grid is then

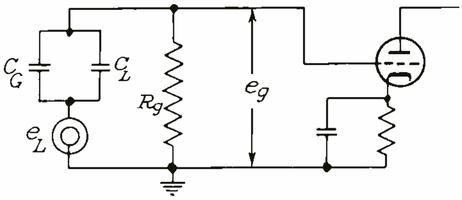


Fig. 66.--Application of Thevenin's Theorem to Crystal Microphone Circuit.

$$e_g = e_L\frac{R_g}{R_g + 1/j\omega(C_G + C_L)}$$

$$= e_L\frac{j\omega R_g(C_G + C_L)}{1 + j\omega R_g(C_G + C_L)}$$

If the value for e_L be substituted from Eq. (16), there is finally obtained

$$e_g = e_G\frac{R_g C_G}{R_g\,(C_G + C_L) - (j/\omega)} \qquad (17)$$

At very low frequencies, (small values of ω), the quantity $(-j/\omega)$ in the denominator will be large and comparable to the other term $R_g(C_G + C_L)$ and hence the fraction and e_g will be small. At sufficiently high frequencies $(-j/\omega)$ becomes negligible compared to $R_g(C_G + C_L)$ and Eq. (17) reduces to

$$e_g = e_L = e_G\left(\frac{C_G}{C_G + C_L}\right) \qquad (2)$$

which is the equation given earlier in the text.

Hence, to maintain a flat response down to very low frequencies, $R_g(C_G + C_L)$ should be large compared to $(-j/\omega)$. This can be accomplished either by making R_g or $(C_G + C_L)$ large. Usually R_g is made as large as possible, up to 5 megohms in value, but some tubes cannot accommodate such a high grid resistance on account of grid-gas currents. Usually 1 megohm is a preferred value.

If this is the case, then $(C_G + C_L)$ should be made large. If C_L is increased, then Eq. (2) shows that the delivered voltage e_g will be decreased compared to the generated voltage e_G, hence C_G should be increased. This means that several cells should be connected in parallel, and this is very often done. Before discussing this it will be instructive to calculate the response at 50 c.p.s. for the above microphone. Assume Rg is 1 megohm and e_G is 2 mv. Then, by Eq. (17)

$$e_g = \frac{2(10^6)\,(.0033)\,(10^{-6})}{10^6(.0033+.0015)\,10^{-6} - (j/2\pi 50)}$$

$$= \frac{(2)\,(.0033)}{.0048 - j.00318}$$

$$= \frac{2 \times .0033}{\sqrt{(.0048)^2 + (.00318)^2}} = 1.145 \text{ mv.}$$

At 5,000 c.p.s.

$$e_g = (2 \times .0033)/(.0048 - j.0000318)$$

$$= 1.375 \text{ mv.}$$

Thus at 50 c.p.s. the voltage gain

is 1.145/1.375 = 83.3% of that at 5,000 c.p.s. or about 1.6 db down. A higher value of R_g or a larger value of C_G would reduce the db attenuation at 50 c.p.s. The frequency response for the values assumed is shown in Fig. 67, as well as the effect on the response curve of increasing R_g, and of increasing C_G, the internal capacity of the microphone.

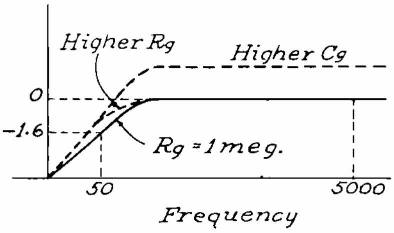


Fig. 67.--**Effect of Grid Resistance on Frequency Response of Crystal Microphone.**

Multi-cell Crystal Microphone.- The advantage of increasing C_G is evident from Fig. 67; the output level for a given generated voltage is greater and the low-frequency response is improved. It is therefore common to employ several units, (each containing two bimorph elements) in parallel or in series-parallel. From 2 to 24 units are employed. In addition, the units can be made larger as well. In Fig. 68 is shown a group of four units in parallel. Each unit is essentially of the form shown in Fig. 64. The sound pressure acts on both faces of each unit. By having openings only on the sides of the casing, the sound wave can strike the cells only as shown. This makes the phase difference between units very small for horizontally directed waves, and since the diffraction effects are also small, the microphone is non-directional over most of the audio band. If it is desired to obtain non-directional effects in a vertical plane, then the cells are stacked so that their faces are in a vertical plane, and holes in the top and bottom of the casing are provided. In this case the horizontal pickup is adversely affected to some extent. Usually, the arrangement in Fig. 68 is preferred.

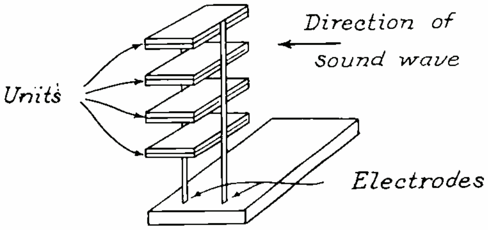


Fig. 68.--**Combination of Sound Cells into a Crystal Microphone.**

The advantage of placing several units in one assembly is not only that the internal capacity C_G is increased, so that a lower value of grid resistor R_g can be employed, (in the neighborhood of one megohm), but the output power is increased. As a result the signal can be routed a greater distance through an audio line before it is amplified.

This is further aided by the fact that the direct-actuated type employs crystal wafers that are *mechanically* self-resonant from 8,000 to 14,000 c.p.s., and in some special cases as high as 30,000 c.p.s. Although damping is employed to hold down the displacement to a reasonable value, it is possible to obtain a rising characteristic in the audio band. Just as in the case of the condenser and carbon-button microphones, so here too the generated voltage is proportional to the displacement, and hence by having the microphone compliance-controlled (below its resonant frequency) a flat frequency response under constant acoustic pressure operation is obtained.

But at the high end of the audio band, where resonance is approached, the displacement, hence generated voltage, will tend to increase. The extraneous electrical noise pickup also generally becomes greater at the higher frequencies because the capacitive coupling to the disturbing circuit increases. The result is that the signal-to-noise ratio remains more nearly constant over the frequency band instead of decreasing with frequency, as in ordinary circuits. Suitable high-frequency attenuation in the pre-amplifier will make the overall response flat, and reduce the noise to a lower level. It is thus possible to run longer leads before the signal-to-noise ratio becomes too low. Another means is to employ stepdown and stepup transformers, as shown in Fig. 69. Such transformers are feasible when a multi-unit microphone of lower internal impedance is employed. The high impedance winding of either transformer is at least 100,000 ohms in value. T_1 steps down the impedance to say, 500 ohms, and T_2 steps the impedance up to 100,000 ohms once again. Thus, neglecting the small losses in the two transformers, the voltage appearing at the grid is substantially that generated by the microphone, and the capacity in the 500-ohm audio line, as well as the noise pickup therein, is very small. This arrangement has been recommended for lines greater than 30 feet in length.

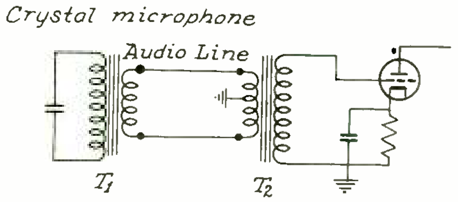


Fig. 69.—Use of Transformer-Coupling for Crystal Microphone.

As a representative example, the Brush Model BR2S microphone is shown in Fig. 70. This is of the floating-crystal sound cell construction. It is flat from 60 to 2,000 c.p.s., then rises slightly (4 db max.), and is non-directional. It employs four bimorph cells, and has an output impedance of approximately .0095 µf. The output level is given as -65 db (based on 1 volt per bar reference level).

Diaphragm Type Crystal Microphone.—The diaphragm type of crystal microphone was explained earlier in this technical assignment. It has a much greater output than the sound cell type—about -48 db (based on 1 volt per bar reference level) and the load impedance is about 250,000 ohms. Owing to the diaphragm, however, the resonant frequency is in the middle of the audio range, and sufficient damping must be employed to level the response, which can be made flat from about 100 to 5,000 c.p.s. Owing to the appreciable size of the diaphragm, the directional response varies with frequency; at low frequencies it is practically non-directional. This does not refer, however, to the Cardioid crystal microphone described previously.

Fig. 70.—Brush Model BR2S Crystal Microphone.

Physical Characteristics.—The mechanical and electrical characteristics of the crystal wafer are unfortunately dependent upon the temperature of the wafer. While the bimorph construction minimizes such effects, nevertheless, for temperatures in excess of 130° F the crystal loses its piezo-electric effects permanently. The crystal is also sensitive to humidity, and tends to lose moisture from its surface in dry air. This is obviated by varnishing the surface so as to protect it from the atmosphere.

While its characteristics may vary with temperature, the crystal microphone is satisfactory where extreme climatic conditions are not encountered. It has the advantage of being reasonably sensitive and relatively inexpensive, and the disadvantage of having a rather high impedance output. However, output transformers are available to transform this impedance into the standard 250- or 500-ohm line, at least for the multi-cell units.

CONCLUSION

This concludes the technical assignment on microphones. The factors stressed have been frequency response, directional response, and methods of rating the microphones. The methods of operation have been described, as well as sufficient acoustical and mechanical information to permit the action of each type to be understood.

Finally various representative types have been discussed and their characteristics and applications described. While it is manifestly impossible to discuss all types commercially available, sufficient information has been presented to enable the student to form an intelligent opinion of the relative merits and applications of such microphones as he may encounter in his work.

MICROPHONES

EXAMINATION

1. (A) With reference to the carbon-button, condenser, ribbon, dynamic, and crystal microphones, in which is the electrical energy merely *controlled* by the acoustic energy, and in which is the acoustic energy, at least in part, directly transformed into electrical energy?

   (B) Which, at least theoretically, can function as audio amplifiers, and which cannot?

2. (A) What causes the response of a microphone to increase at the higher frequencies for an axial sound wave?

   (B) What happens if the microphone is increased in size?

3. (A) What causes the high-frequency response of the microphone to decrease for sound waves directed at an angle to the axis?

   (B) Why is this effect negligible at the lower frequencies?

   (C) What effect has the shape of the microphone housing on this and on the effect mentioned in 2(A)?

4. (A) A diaphragm has a diameter of 5 cm. A sound wave approaches it from the left at an angle of 45° to the axis. At what frequency will the pressure at the righthand side be 90° out-of-phase with that at the left-hand side?

   (3) At what frequency will the phase difference be 60°, and 180°?
   NOTE: Take the velocity of sound to be 34,400 cm/sec.

5. Plot the polar diagram for the microphone whose frequency response is given in Fig. 8, for 7,500 c.p.s. and for 3,000 c.p.s. Hand in the set of tabulated values as well as the two curves. Take the response for 200 c.p.s. as -82 db. In Fig. 9 this corresponds to the fourth heavy circle.

6. Refer to Fig. 41 which gives the polar diagram for a velocity microphone. It is desired to accommodate a total of 10 actors, all spaced an equal radial distance r from the microphone and four feet between centers. The maximum permissible variation in pickup of the various actors is 4 db.

   (A) What should the value of r be?

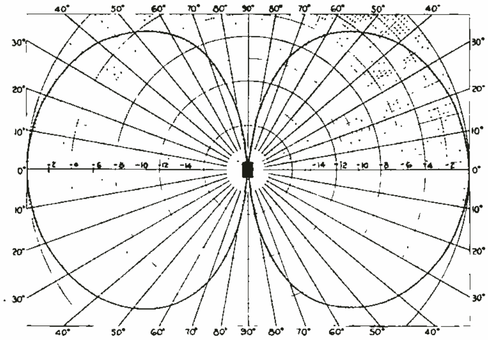
6. 

Fig. 41

(B) How much should the radial distance be increased from the above value for those actors for which the pick-up is greater?
HINT: The db ratios must be converted into *voltage* ratios.
NOTE: Use diagrams to illustrate the solution.

7. The ribbon of a velocity microphone has an impedance of 0.5 ohms, and the output level into a matched load is -84 db for 1 bar pressure. (0 db = 6 mw.) Tabulate your results.

(A) What is the impedance ratio of the transformer in the microphone casing that changes the impedance level to a 50-ohm audio line? To a 250-ohm audio line?

(B) The pre-amplifier input transformer has a 150,000-ohm secondary. What is its impedance stepup from a 50-ohm audio line? From a 250-ohm audio line?

(C) What is the voltage delivered to the grid (across the secondary) for 3 bars pressure across the microphone when 150,000 ohms is connected across the secondary?

(D) Under the above conditions, what is the voltage *generated* in the ribbon?

(E) Under the above conditions, what is the voltage developed in the 50-ohm and in the 250-ohm audio lines?

8. A crystal microphone has 48 bimorph elements. Two bimorph elements form a cell, and are connected in parallel. The cells are arranged into four groups. In each group the cells are in parallel. The four groups are in series. Each bimorph element generates 0.1 mv./bar, and has an internal capacitance of 0.0016 µf.

(A) What is the generated voltage per bar for one cell?

(B) What is its internal capacitance (per cell)?

8. (C) Draw a block diagram for the cells, using a rectangle to represent each cell, and show how they are connected to form the complete microphone.

   (D) What is the generated voltage of the microphone?

   (E) What is its internal capacitance?

9. The crystal microphone feeds the amplifier through a 40-foot cable that has a capacity of .003 µf per 100 feet. The cable is terminated at the grid in a 1-megohm resistor

   (A) Calculate the voltage delivered to the grid at 30 c.p.s.

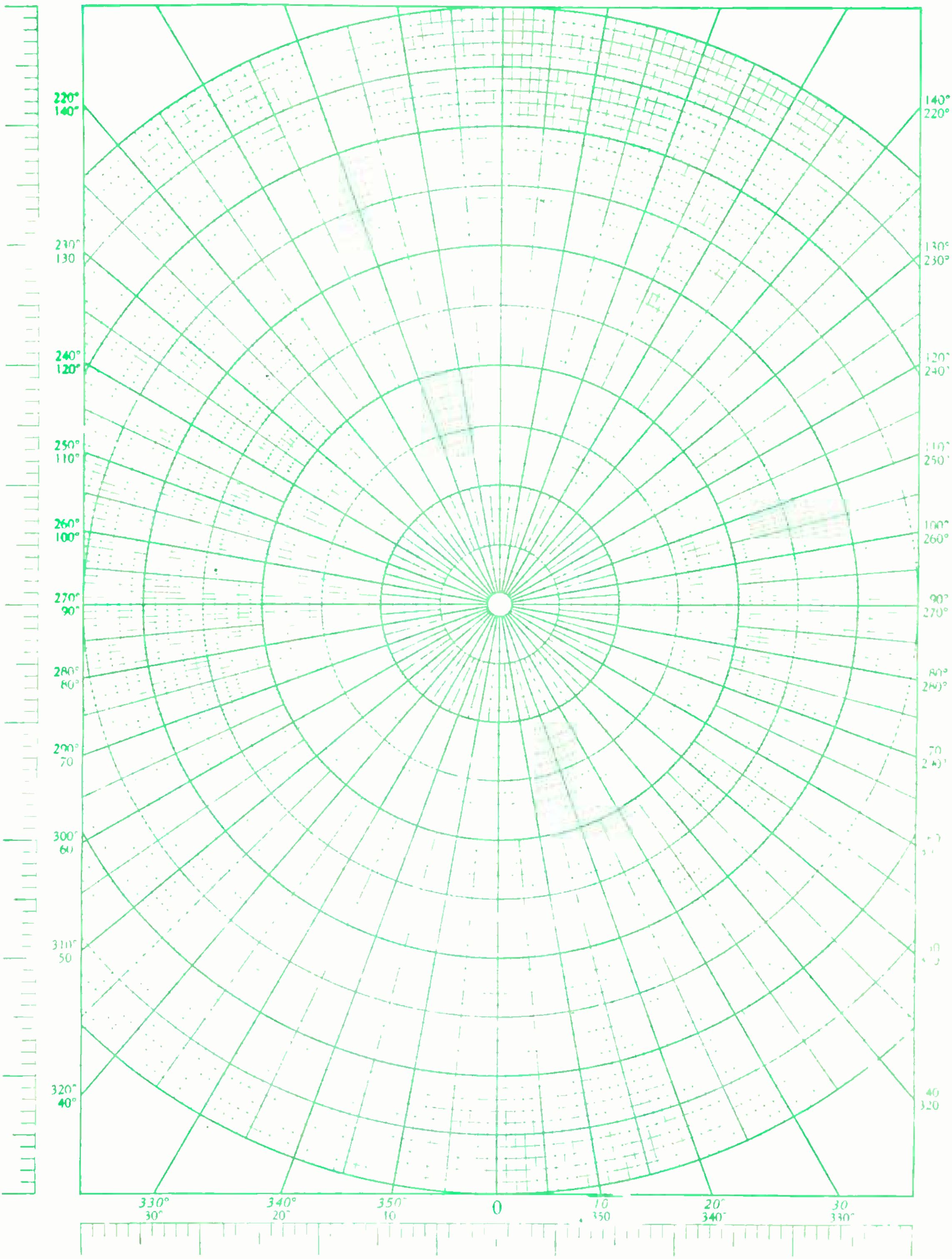
   (B) Calculate the voltage delivered to the grid at 5,000 c.p.s.

   (C) Calculate the power dissipated in the 1-megohm resistor and the db level (0 db = 6 mw.) at 30 c.p.s. and at 5,000 c.p.s.

10. (A) Explain briefly why the response of a velocity microphone is a maximum on the axis, and zero for a direction of 90° to the axis.

    (B) Why is the ratio of pickup of direct sound to reverberation or random sound, the same for a velocity as for the normal cardioid (uni-directional) microphone?

    (C) What are two fundamental advantages of the bimorph over the single wafer type of Rochelle salt crystal for piezo-electric applications, such as in the crystal microphone?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