HOW SOUND REPRODUCERS OPERATE

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NRI

Study Schedule No. 26

For each study step, read the assigned pages first at your usual speed, then reread slowly one or more times. Finish with one quick reading to fix the important facts firmly in your mind, then answer the Lesson Questions specified for that step. Study each other step in this same way.

☐ **1. Introduction; Types of Loudspeakers; Bi-Polar Magnetic Driving Units - - - - - - - - - - - - - - - - - - - Pages 1-6**

A Complete Loudspeaker has Three Sections; The "Weakest Link" in Radio; What You Will Study; four general groups of loudspeakers; Magnetic Loudspeakers; Dynamic Loudspeakers; Condenser Loudspeakers; Crystal Loudspeakers; Headphone Construction; How a Headphone Works; Why Strong Permanent Magnets are Necessary; Headphone Ratings. Answer Lesson Questions 1, 2 and 3.

☐ **2. Analysis of Vibrating Systems; Mechanical Resonance in Headphones - - - - - - - - - - - - - - - - - Pages 6-11**

Electrical equivalent of mass and compliance; Natural Frequency of Vibration; Velocity of a Diaphragm; Maximum Displacement; Velocity of a Vibrating Mass; Facts to Remember About Vibrating Systems; Why headphone diaphragms must have a high natural resonant frequency. Answer Lesson Questions 4 and 5.

☐ **3. Balanced Armature Type of Magnetic Driving Unit; Dynamic Driving Units; Condenser Driving Units; Crystal Driving Units - Pages 12-19**

Construction of balanced-armature unit; how it works; comparison with other driving units; piston action in a dynamic driving unit; diaphragm construction; how a dynamic driving unit works; voice coil design; factors affecting force upon voice coil; construction of condenser driving units; drawbacks of condenser unit; basic action of a crystal loudspeaker; construction of crystal units; drawbacks of crystal units. Answer Lesson Questions 6 and 7.

☐ **4. Loudspeakers Can Also Serve as Microphones; Action of a Horn as a Loudspeaker Coupling Unit; Design of Dynamic Driving Units for Horn Loudspeakers - - - - - - - - - - - Pages 19-28**

Inter-communicating systems use loudspeakers as microphones; equivalent mechanical circuit of a vibrating diaphragm; Measuring Loudspeaker Efficiency; Loading the Diaphragm; Exponential Horns; Mouth Area; Throat Area; Construction of Horn; Horn Ratings; diaphragm mounting methods; efficiency of horn loudspeakers. Answer Lesson Questions 8, 9 and 10.

☐ **5. Mail your Answers for this Lesson to N. R. I. for Grading.**

☐ **6. Start Studying the Next Lesson.**

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HOW SOUND REPRODUCERS OPERATE

Diaphragm-Type Units

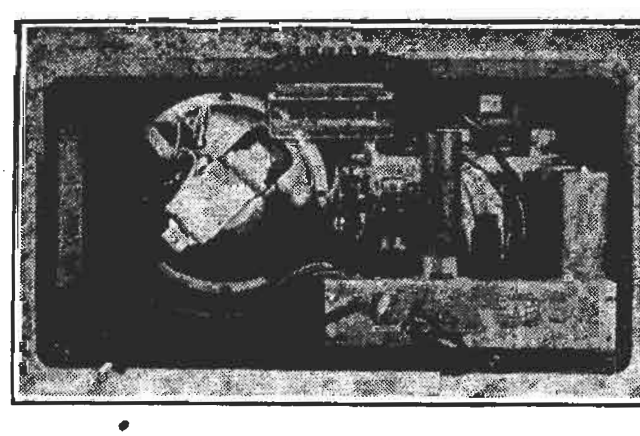
Introduction

IN RADIO receivers and in public address systems the loudspeaker serves to convert audio frequency currents into sounds which can be heard by the human ear. The A.F. currents in the last stage of the audio amplifier are made to set in motion an electro-mechanical system, and this in turn causes the air in the vicinity of the loudspeaker to vibrate in accordance with the variations in the audio signal, thus producing sound having all the characteristics of the original sound.

A Complete Loudspeaker has Three Sections. From what you have already studied in this Course and from your own actual experience, you can readily see that a complete sound reproducer or loudspeaker consists of three essential sections: *1,* an electro-mechanical *driving unit,* often called a *motor,* which converts A.F. currents into vibratory motion; *2,* the *diaphragm* or *cone,* which when driven by the motor sets the surrounding air into motion; *3,* the *air coupling system,* consisting essentially of a horn or baffle, which improves the efficiency of the loudspeaker by setting a larger amount of air into vibration and by preventing the reproduced sound components from cancelling each other.

The "Weakest Link" in Radio. Perfection in radio transmitter and receiver design is of little value unless the loudspeaker, the final link in the radio system, is capable of reproducing the entire range of audio signals with true fidelity and is capable of operating at the required maximum loudness level without distorting the reproduced sound. Contrary to general impressions, *the loudspeaker is the weakest link in the entire radio system.* The design of high-fidelity loudspeakers is an intricate and involved task even for the engineer who specializes in this particular branch of radio engineering. Even today, after years and years of research on the subject, engineers are still striving for the perfect loudspeaker.

What You Will Study. Although as a Radiotrician and Teletrician you are not particularly interested in the exact details of loudspeaker design technique, a general discussion of some of the problems encountered in building loudspeakers and a study of the various solutions which have been developed for these problems will



The loudspeaker is the mechanical means of converting electrical signals into sound waves.

serve to make you realize the limitations of loudspeakers. Furthermore, a familiarity with the constructional features of various types of loudspeakers and with their performance under various conditions will be of value to you in any branch of radio. Only the more widely used loudspeakers, which you will be likely to encounter in your practical work, will be considered. Basic principles of loudspeaker construction will be stressed, but enough actual examples of commercial loudspeakers will be taken up to illustrate how these principles apply to all loudspeakers.

Types of Loudspeakers

Although some loudspeaker manufacturers have assigned trade names to their various types of loudspeakers, you will find that technical men in general prefer to describe loudspeakers according to their construction or operation.

Loudspeakers can be divided into four general groups according to the type of motor or driving unit which they employ: *1, magnetic loudspeakers,* in which the moving element is made of iron; *2, dynamic or moving coil loudspeakers,* in which the moving element is a coil of wire; *3, condenser loudspeakers,* in which one plate of a large two-plate condenser is the moving element; *4, crystal loudspeakers,* in which a crystal is the moving element.

Magnetic Loudspeakers. That type of magnetic loudspeaker which depends for its operation upon the attraction of a bi-polar driving unit for an iron diaphragm has long since been superseded by the other types to be discussed. The bi-polar driving unit is still used almost universally in headphones, however, and will therefore be taken up in this lesson. Magnetic loudspeakers in use today are of the *balanced armature type;* when a balanced armature unit is made to drive a diaphragm, we have a *diaphragm type magnetic loudspeaker.* On the other hand, if a balanced armature unit drives a cone, we have a *magnetic cone loudspeaker.*

Dynamic Loudspeakers. When the fixed magnetic field for a dynamic or moving coil loudspeaker is furnished by an electromagnet, we have what is known as an *electrodynamic loudspeaker.* When this fixed magnetic field is provided by a permanent magnet, we have a *permanent magnet dynamic loudspeaker,* often abbreviated as *P.M. dynamic loudspeaker.* Either of these dynamic or moving coil units can be used to drive a small cone, a large cone or a diaphragm. With a small cone or diaphragm, the air coupling unit is usually a horn; with large cones, of the size commonly found in radio receivers employing dynamic loudspeakers, a baffle ordinarily serves as the air coupling system.

Condenser Loudspeakers. These are also known as *electrostatic loudspeakers,* for they depend for their operation upon the forces of attraction and repulsion existing between two charged plates. The moving plate is ordinarily about one foot square, so no cone or diaphragm is required. Condenser speakers are used so seldom today that only the fundamental operating principles will be taken up in this lesson.

Crystal Loudspeakers. The driving units of crystal loudspeakers are all essentially the same, but they may be made to drive either a diaphragm or a cone, and may be used with either a baffle or horn.

Once you become familiar with loudspeaker construction and operation, you will find that practically all of the loudspeaker names or designations which you encounter will be self-explanatory.

Bi-polar Magnetic Driving Units

No discussion of sound-reproducing units would be complete without a consideration of the headphone unit. Aside from the fact that this bi-polar magnetic driving unit was the essential part of all early loudspeakers, headphones are still widely used today by commercial radio operators, by radio amateurs, by experimenters, and by those who are hard-of-hearing.

Headphone Construction. The constructional details of a typical headphone unit are shown in Fig. *1*, the important parts being clearly identified. The operating principle of this bi-polar magnetic driving unit can be more clearly understood by referring to the simplified diagram shown in Fig. *2A*. The permanent magnet *PM*, semicircular in shape and made of hard steel, produces a fixed magnetic flux which flows through the two soft iron pole pieces *P*, and then through two air gaps to the thin iron diaphragm *D* (about .003 inch thick), which is firmly clamped around its edges to the housing and which is accurately spaced away from the pole pieces. The diaphragm is attracted toward the pole pieces; one explanation is that the magnetic circuit always adjusts itself to have the least reluctance (opposition to the flow of magnetic flux), while another is that the north (*N*) pole piece makes the section of the diaphragm directly above it a south (*S*) pole, and the south pole piece makes the diaphragm section above it a north pole. Since opposite poles always attract, the

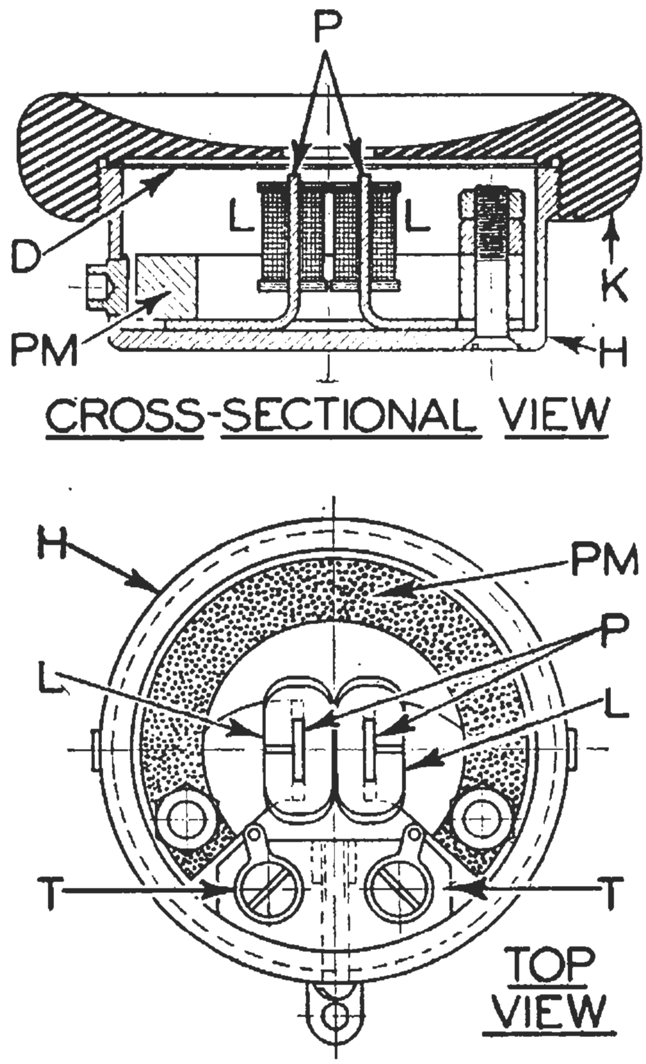


FIG. 1. These two diagrams show the important constructional details of a typical bi-polar magnetic driving unit as used in a headphone. The parts are: *PM*—hard steel permanent magnet; *L*—coils; *P*—soft iron pole pieces; *D*—soft iron diaphragm; *H*—metal housing; *K*—ear cap; *T*—headphones terminals, connected directly to the coils.

diaphragm is bent toward the pole pieces.

The diaphragm is made stiff enough and is originally separated far enough from the pole pieces so that it cannot actually touch the pole pieces under any normal conditions of operation.

How a Headphone Works. Observe that around each of the pole pieces in Fig. *2A* is a coil of wire, with the two coils connected together in series in such a way that the magnetic flux due to each will be in the same direction through the permanent magnet. When a current is sent through these coils, it will produce an additional magnetomotive force which either aids or opposes the magnetomotive force of the permanent magnet (depending upon the direction of current flow) and therefore either increases or decreases the amount of magnetic flux flowing through the magnetic circuit of the headphone. Any change in this total magnetic flux naturally changes the attraction of the pole pieces for the diaphragm; when the current flowing through the coil is varying at an audio frequency, the diaphragm will move toward and away from the pole pieces at the same frequency. With proper design of the entire headphone unit, the movement or displacement of this diaphragm will correspond exactly to the variations in the audio frequency currents, and this diaphragm will produce sound waves which correspond in wave form to that of the A.F. signals.

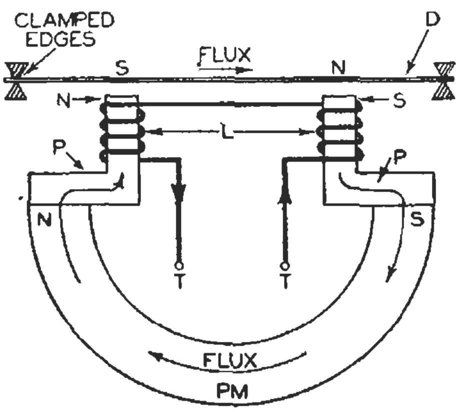


FIG. 2A. Simplified diagram of a bi-polar magnetic headphone unit, showing coil connections and flux paths.

Why Strong Permanent Magnets are Necessary. One of the most important factors affecting the performance of a magnetic loudspeaker is the permanent magnetic field. Let us see what would happen if this field were not used. Assume that we are sending a pure sine wave alternating current through the coil of the bi-polar driving unit in Fig. *2A,* with permanent magnet *PM* temporarily replaced by a soft iron piece of similar shape. When this alternating current is zero there will be no magnetic field and no pull on the diaphragm. As the current swings positive, the two poles will become magnetized with opposite polarity, and the diaphragm will be pulled toward the pole pieces. This attraction will continue until the current again reduces to zero. As the current reverses for the negative half of the cycle, the polarity of each pole will reverse, but the poles will again attract the diaphragm. As a result, the diaphragm will vibrate at twice the frequency of the current passing through the coil. Clearly this is an undesirable condition for sound reproduction.

The use of a strong permanent magnetic field eliminates this undesirable frequency-doubling effect in a bipolar headphone unit, for the permanent field provides a continuous attraction for the diaphragm which is merely varied by the alternating current. The change in the attraction of the pole pieces for the diaphragm depends upon the original magnetization and upon the change in flux caused by the signal current flowing through the coils (the change in attraction actually depends upon the product of these two factors). Increasing the strength of the permanent magnet and increasing the strength of the signal currents are thus possible ways of increasing the sensitivity of a headphone unit.

Modern headphone units have permanent magnets made of chrome or tungsten steel, which produce a strong permanent flux and thereby give a highly sensitive unit with a minimum of frequency doubling. Permanent magnets made of Alnico produce even greater magnetomotive forces, and this recently developed alloy may therefore be found in new high-quality headphones. Placing the diaphragm as close as possible to the pole pieces increases the amount of permanent flux and thus increases the sensitivity of the unit, but at the same time this procedure reduces the maximum available volume; the practical headphone unit is therefore based upon a compromise between sensitivity and volume.

If the coil current in a bi-polar magnetic driving unit is to produce a large A.C. magnetic flux, many turns of wire are needed on the coils, and the A.C. magnetomotive force produced by these turns must develop a large A.C. flux. You know that in a magnetic circuit the amount of flux produced for a given magnetomotive force depends upon the reluctance of the flux path, just as the current for a given voltage depends upon the resistance of the path for current in an electrical circuit. The first essential of a low-reluctance flux path is a small air gap between each pole piece and the diaphragm, but on the other hand, the air gap must be long enough to permit the diaphragm movements which are necessary for maximum required volume. With the arrangement shown in Fig. *2A,* however, the A.C. flux produced by the coils must flow through the permanent magnet; unfortunately this has a high reluctance because it is made from a hard, tempered steel or steel alloy rather than from soft iron.

A simple solution to this difficulty is shown in Fig. *2B;* it involves placing a short-cut path for A.C. magnetic flux across the bottoms of the pole pieces. The air gap *R* which is placed in this path has a low enough reluctance to make the *alternating* magnetic flux prefer it to the path through the permanent magnet, but at the same time this air gap offers considerably more reluctance to the *permanent* magnetic flux than does the desired path through the pole pieces and the diaphragm.

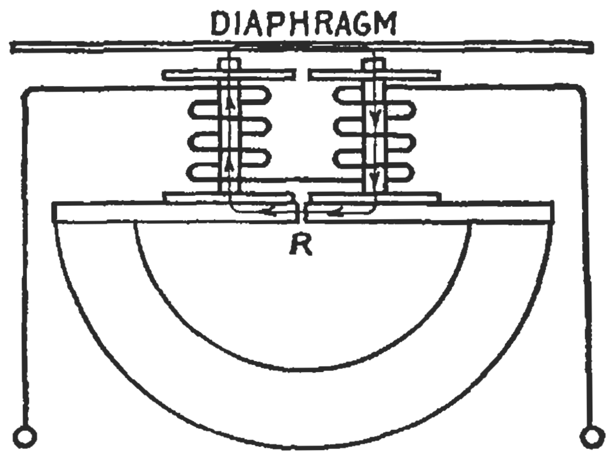


FIG. 2B. Simplified diagram of a special type of bi-polar magnetic headphone unit in which a leakage reactance path *R* for magnetic flux is purposely introduced to improve performance.

Headphone Ratings. Headphones are commonly rated according to their D.C. resistance, even though the impedance value gives a far better considerable *force* is required to set it into motion, but once the auto is moving at a definite speed, it can be kept at that speed with little additional effort. In order to set such a heavy object into motion, we must overcome the inertia of its *mass;* the heavier the object, the greater is its mass and inertia, and the more we must push to set it into motion. We have the same situation in an electrical circuit; an inductance has an electrical inertia which serves to limit the initial flow of current. *Mass in a mechanical vibrating system therefore corresponds to the inductance of a coil in an electrical circuit.*

Now let us consider an ordinary steel coil spring. Experience has taught us that force is required to stretch the spring, and now we learn that this ability of a spring to stretch under the application of force is referred to by engineers as its *compliance.* The greater the compliance of a spring, the more it will stretch when a given force is applied. This compares very closely to a condenser, where greater capacity means that we can store more electricity in the condenser.

As you well know, motion of any object involves friction. It is far more difficult to move an automobile from which all four wheels are removed than a car having wheels, for without wheels there is a great deal more friction between the chassis and the pavement. You know also that friction can be reduced by making the sliding surfaces perfectly smooth and by lubricating the sliding surfaces with grease. Friction of the type which exists when one object rubs against another is quite familiar to you, but in loudspeakers it is the friction produced by an object moving in air which is of importance. An example will illustrate the nature of this friction.

Suppose we take a mass, as shown in Fig. *3A*, and a spring, as shown in Fig. *3B,* and connect them in series as shown in Fig. *3C*. When both the spring and the mass are stationary, pull down on the mass and then release it. The spring stretches when you pull down, but since it is under tension it immediately starts to pull the mass up again after you have released it. Having reached its original position, the mass continues moving upward because it has acquired momentum. The mass stops moving upward when it has lost this momentum; the mass then drops downward, moving past its normal stationary position again because of momentum, and continues to bob up and down in what we call mechanical vibration. This vibration continues until all of the original energy imparted to the spring and mass by pulling it down is wasted in friction. This friction occurs in two different ways here, between the mass and the air particles, and internal friction produced

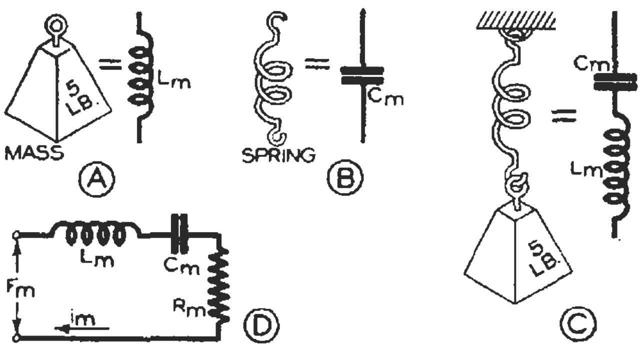


FIG. 3. These diagrams will help you to remember that mass can be considered as a mechanical inductance, that springiness or compliance of any kind (a spring) can be considered as mechanical capacitance, and that a complete mechanical vibrating system acts in much the same way as a series-resonant electrical circuit.

by bending of the spring. If this entire system were in water or in a thick oil, there would be even greater friction between the water or oil particles and the mass than in the case of air, and the vibration would stop sooner.

We need not necessarily have five-pound weights and large, stiff springs in order to secure a mechanical vibration; the weight or mass need be only a fraction of an ounce, and the spring can have far more compliance than that shown in the illustration. No matter how small the mechanical structure happens to be, vibration can be secured if there is mass and compliance in the system.

Now you can readily see that the diaphragm in a bi-polar magnetic driving unit has mass and compliance. It will therefore vibrate. Radio engineers have found that its exact behavior during vibration is far easier to understand if the mechanical system is replaced by an equivalent mechanical circuit which has all the appearances of an electrical circuit. Figure *3D* shows such a circuit for the diaphragm of the headphone unit; it will make the mechanical action of a headphone considerably easier for you to understand. Remember, however, that this is not the actual electrical circuit in the headphone; it is simply an imaginary series-resonant circuit which acts in the same way as the mechanical system.

Natural Frequency of Vibration. Notice that we have mechanical force F_m acting upon mechanical inductance L_m, upon mechanical capacitance C_m and upon mechanical resistance R_m. When this force is applied for a short instant of time and then removed, the system goes into vibration and mechanical current i_m, which you can think of as the *velocity* at which the diaphragm moves back and forth, is the result. The natural frequency of vibration of the diaphragm (or of any other physical object) will be determined by the mechanical inductance (mass) and the mechanical capacitance (compliance) of the diaphragm or other object. When a continuously vibrating force is applied, the vibration of the assembled parts will follow this force, and the amount of mechanical current will depend upon the mechanical reactance of L_m and C_m

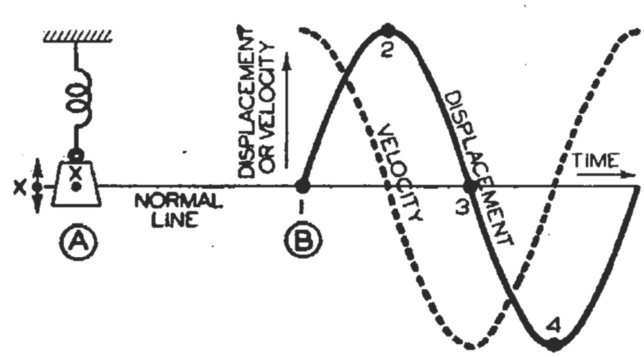
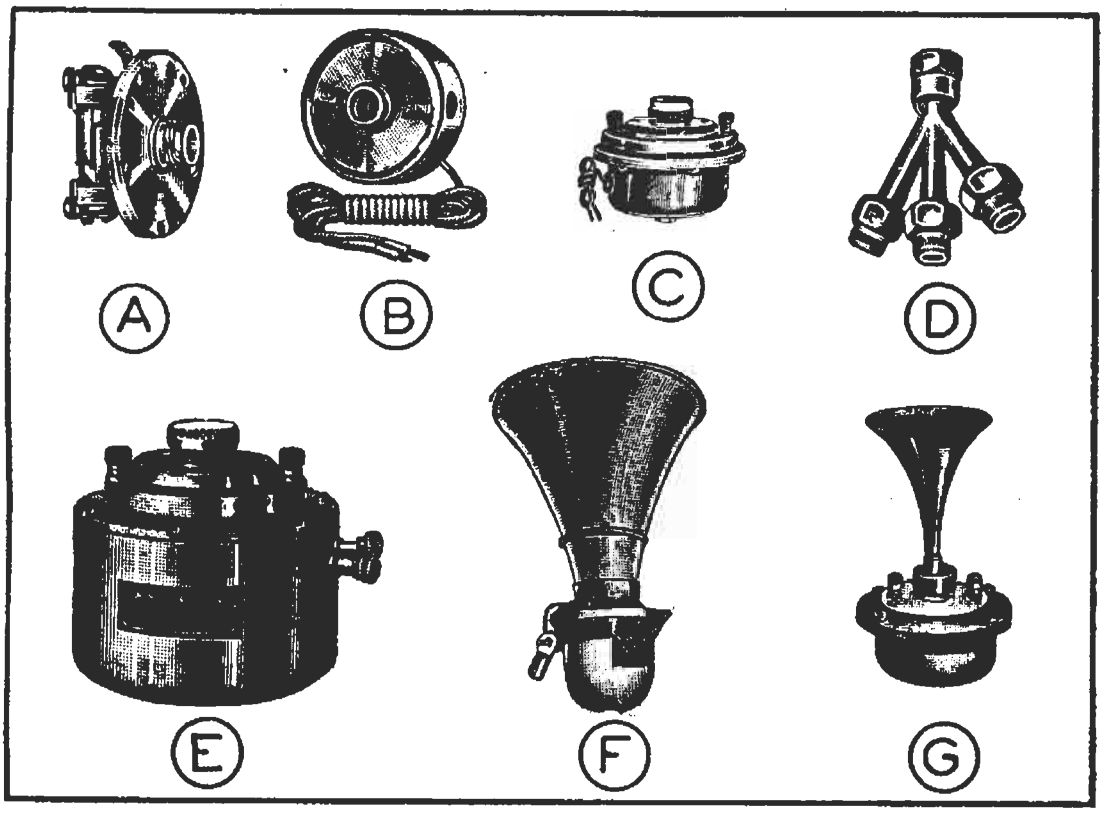


FIG. 4. A careful study of this simple diagram will help you to understand the meaning of *velocity* or *mechanical current* in connection with a loudspeaker.

and the mechanical resistance of R_m, just as in any series resonant circuit. By adjusting the frequency of the vibrating force or by changing L_m and C_m mechanically, you can make the mechanical circuit act either as a mechanical resistance, a mechanical inductance, or a mechanical capacitance.

Velocity of a Diaphragm. Let us get a clearer picture of this mechanical current or velocity, for it is extremely important in connection with our study of loudspeakers. Suppose we have a mass and compliance arranged as shown in Fig. *4A;* we set this mechanical system into vibration. Under this condition, any particle on this mass, such as point *X*, will be moving continually above and below its normal position or normal line. If we plotted from instant to instant the position of particle *X* with respect to this normal line, we would secure the

When particle *X* is moving across the normal line at point 1, it has a greater mile-per-hour speed than at any other point along its path; in other words, the particle has maximum velocity when it crosses the



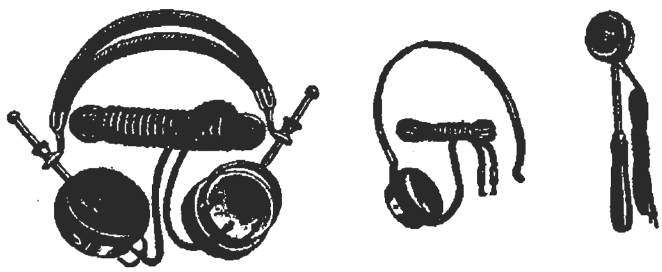
These diagrams illustrate a number of interesting features of horn loudspeakers. *A*—Low-power magnetic driving unit of the balanced armature type, with diaphragm feeding into a standard ⅝-inch throat for use with horn loudspeakers; *B*—balanced armature magnetic driving unit in its housing, with connecting leads clearly visible. Units like this can handle up to 2 watts of input power; *C*—electrodynamic driving unit for horn loudspeakers. Note the two field coil leads coming out of the side of the housing or pot; *D*—special three-way connecting throat which permits the attachment of three separate driving units to a single trumpet or horn; *E*—another electrodynamic driving unit for horn loudspeakers. Size and weight are general indications of power-handling ability in units of this type. A 20-pound unit will handle approximately 25 watts of input power continuously and 50 watts on peaks, while a 6-pound unit will handle about 5 watts continuously and 10 watts on peaks. If more than the rated continuous power is fed to a unit, overheating and failure may occur. If more than the rated peak power is fed at any instant of time, the unit may rattle because of excessive diaphragm displacement. The knurled protective cap on the throat is removed when the unit is installed; *F*—dynamic driving unit employing a large diaphragm which is coupled to a trumpet horn; G—horn loudspeaker designed specifically for high frequencies, from 3,000 cycles to 15,000 cycles. The trumpet horn used on this unit is spun from a single piece of aluminum.

solid line curve shown in Fig. *4B*. Yes, this plotting of displacement against time for a vibrating mechanical system results in a pure sine wave; this is why mechanical vibration of a simple mass and compliance has a simple sine wave motion.

normal line. A quarter of a cycle later, when particle *X* is at point *2*, its highest position above the normal line, it actually comes to a standstill for an instant, and its velocity is zero. As particle *X* drops down toward the normal line again, its velocity in-

indication of operating characteristics. For a given type of headphone construction, having a given size of bobbin for each coil, we can use a large number of turns of very small wire, thereby securing a high D.C. resistance and a high impedance, or we can use a small number of turns of larger wire to secure a low D.C. resistance and low impedance. Since headphones ordinarily serve as plate loads in amplifier stages, it is the impedance value (generally measured at the average voice frequency of 1,000 cycles) which is of importance; the designer will choose a headphone impedance value which best matches the required plate load of the amplifier tube. In general, the impedance of a headphone unit at 1,000 cycles will be from five to ten times its ohmic value for direct current.

When headphones are being used primarily to convert low intensity signals into audible sounds, they should be rated on the basis of how much A.F. power in milliwatts is required to produce a just audible sound; as yet, however, very few manufacturers supply this information.



Radio operators for commercial or amateur communication systems ordinarily use a pair of headphones like those shown here, in which two units are mounted on the headband and connected together in series. Single headphones with a headband are widely used by experimenters, by hospitals having radio facilities for each patient, and by the hard-of-hearing. A single headphone unit with a handle is used chiefly by those who have only slightly impaired hearing and who therefore need use the sound-amplifying system only at intervals.

Analysis of Vibrating Systems

A complete study of the mechanically vibrating parts used in loudspeakers involves a number of new fundamental ideas which you should understand before proceeding farther with your study of loudspeakers. A mechanical vibrating system has certain properties which compare with those of an electrical vibrating or oscillating system; for instance, you will learn that an inductance (coil) in an electrical oscillating circuit can be compared to *mass* in a mechanical vibrating system, capacitance in an oscillating circuit can be compared to *compliance* in a mechanical system, and resistance in an oscillating circuit can be compared to *friction* or to *mechanical resistance.* A few examples will help you to understand what these new terms mean.

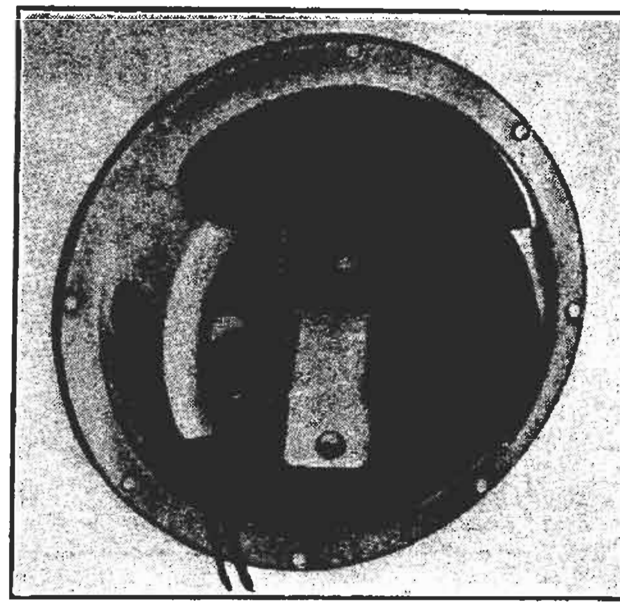
Consider any large, heavy body on wheels; an automobile will do as an example. When pushing the car on a smooth, level road, you know that creases again to a maximum as it goes through point *3*, and then gradually decreases to zero again at point *4*. If we plot this velocity of particle *X* from instant to instant, we secure the dotted line curve in Fig. *4*.

Maximum Displacement. When we deal with the vibrating systems used in loudspeakers, we are particularly interested in the peak or maximum displacement of the mass or of particles on it. In the bi-polar magnetic driving unit, for example, a strong coil current will give a greater displacement than a weak current, and an alternating coil current will cause the diaphragm to move in and out in an alternating manner similar to that shown in Fig. *4B*. If the alternating current is of high frequency, then the diaphragm will likewise vibrate at this same high frequency.

Suppose that the diaphragm is moving the same distance (has the same peak displacement) first for a low frequency and then for a high frequency; clearly it will take less time to go through one complete cycle at the higher frequency. The speed or velocity of the diaphragm is therefore *considerably greater* at the higher frequencies of vibration.

Velocity of a Vibrating Mass. At a given frequency of vibration, any increase in displacement likewise means an increase in the velocity of the mass or particle. Your own experience will prove this to be true, for you know that the farther you pull the weight in Fig. *3C* down from its "at rest" position, the faster will it move upward past its "at rest" position when released. The velocity of a vibrating mass therefore depends upon *the frequency of vibration* and upon *the maximum displacement of the mass* from its normal position.

When the diaphragm of a headphone or loudspeaker is vibrating, it causes particles of air in its vicinity to vibrate in a similar manner. These air particles will vibrate at the same frequency as the diaphragm, and will also have the same velocity as the diaphragm at any instant. The vibration is transmitted from one air particle to another, giving rise to sound waves. It is the frequency at which these air particles vibrate which determines the pitch or tone of the sound, and it is the *velocity* of the *air particles* which determines the power * (loudness or volume) of the sound.



Courtesy Arlavox Mfg. Co.

This magnetic loudspeaker, available with cone diameters ranging from 3 inches to 8 inches, will be found in many small Universal A.C.-D.C. receivers. It uses a balanced armature type of driving unit. Note the U-shaped permanent magnet.

* You know that in an electrical circuit like that in Fig. *3D*, the power absorbed by the resistor is equal to the square of the current multiplied by the ohmic value of the resistor ($P = I^2R$). Likewise, in a mechanical vibrating system, the square of the air velocity multiplied by the mechanical resistance gives the *mechanical power* used by the system; this represents acoustical power.

Facts to Remember about Vibrating Systems. It will be some time before you will be able to appreciate fully the facts just brought out in connection with the vibrating systems used in loudspeakers. For your present study of loudspeakers, it will be sufficient for you to keep in mind the following important facts:

1. **Any physical object has *mass,* which can be considered as *mechanical inductance.***

2. **A physical object can have *compliance* (you can call this springiness if you prefer), and this characteristic can be considered as *mechanical capacitance.***

3. **The motion of any physical object is accompanied by friction, which represents power used or wasted.**

4. **Any physical object which has mass and compliance can be shocked into vibration by a sudden application of force; it will then vibrate at its natural frequency of vibration, which is determined by its *mechanical inductance* (mass) and its *mechanical capacitance* (compliance). Increasing either of these two values lowers the natural frequency of vibration.**

5. **The application of a steady alternating force to a vibrating system will cause a corresponding alternating or vibrating motion of the system at the same frequency. We can consider this mechanical vibrating system as equivalent to an electrical series resonant circuit. When the natural frequency of the system corresponds to the frequency of the applied alternating force, resonance occurs and the system acts as a mechanical resistance. At frequencies above resonance, the vibrating system acts as a mechanical inductance (a mass). At frequencies below the natural resonant frequency, the system acts as a mechanical capacitance.**

6. **Since mass can be considered as an inductance, and compliance as a capacitance, these parts of a mechanical vibrating system have the additional property of mechanical reactance, which takes frequency into account.**

7. **The application of an alternating force to a vibrating system causes the system to vibrate with a velocity dependent upon its mechanical reactance and mechanical resistance.**

Mechanical Resonance in Headphones

Referring again to Fig. *2A,* we recognize that the diaphragm is the mechanical vibrating system in this bi-polar magnetic driving unit. Even though quite small, the diaphragm has mass (weight) and compliance (springiness). When the diaphragm is set into vibration by an alternating current flowing through the coils, it causes air particles in the vicinity to vibrate in a corresponding manner. The resulting sound produced naturally represents radiated energy, and therefore the diaphragm must overcome mechanical resistance in radiating this energy. The diaphragm has a small mass and therefore its mechanical inductance is low; being quite stiff, it has a low compliance and its mechanical capacitance is likewise small. The natural frequency of vibration of the diaphragm is therefore quite high; in fact, diaphragms in high-fidelity headphone units are designed to have a natural frequency of vibration which is considerably above the highest audio frequency being reproduced. This prevents resonant peaks in the response curve of the headphone. Clearly the question of mechanical resonance is of great importance when high fidelity is required from a bi-polar magnetic driving unit such as is used in a headphone.

Balanced Armature Type of Magnetic Driving Unit

Although the bi-polar magnetic driving unit is remarkably simple in design and can be made to have high sensitivity, it is not entirely suitable for loudspeaker applications where high sound output (high volume) is required. Application of excessive input signal voltage to this type of unit results in distortion, due either to the diaphragm striking the pole tips or to a frequency-doubling effect which occurs when the air gap is increased to permit greater volume. Furthermore, normal movements of the diaphragm cause the air gap to vary, with the result that the permanent magnetic flux also varies and a certain amount of distortion occurs. When the diaphragm is made stiff enough to prevent it from hitting the pole pieces, it then becomes quite thick, and its increased mass lowers the natural frequency of vibration. A stiff, light-weight disc would be desirable, but this cannot be easily obtained in the bi-polar type of construction.

The balanced armature type of magnetic driving unit, illustrated in Fig. *5A*, overcomes most of these disadvantages. A light-weight strip of soft iron, called the armature, is pivoted in the center of a coil through which flows the A.F. signal current. This coil may have only a few turns when large A.F. currents are available, but may be built with several thousand turns for low A.F. currents. The coil does not interfere in any way with the movement of the armature. The ends of the armature move between two U-shaped pole pieces which are clamped to a U-shaped permanent magnet which is generally larger and more powerful than the permanent magnet used in bi-polar units. The permanent magnet in this case makes one set of pole pieces permanently of north polarity and the other of south polarity. One end of the armature is rigidly linked to a diaphragm which may be made of mica, duralumin, or any other light material; if the diaphragm is not sufficiently stiff a spring steel metal strip may be attached to the other end of the armature as indicated, to increase the stiffness (reduce the compliance) of the system.

When no current is flowing through the coil, the armature is not magnetized. All four pole pieces then attract the armature equally, and we have a balanced condition in which the armature stays midway between the pole pieces. It is from this characteristic that the balanced armature magnetic driving unit gets its name. When a current i flows through the coil in the direction shown (arrow indicates electron flow), this current will magnetize the armature and give it the polarity indicated in Fig. *5A*. The N pole of the armature will be attracted to the nearest S permanent pole and will be repelled by the permanent N pole. A similar action occurs at the other end of the armature, which is magnetized with south polarity. The result is that the armature twists on its pivot in a counter-clockwise direction, as indicated by the curved arrow line, pushing the diaphragm upward. When the current through the coil reverses its direction, the armature is twisted in the other direction and the diaphragm is pulled downward.

Figure *5B* shows the two paths taken by the magnetic flux produced by the armature when currents flow through the coil. These paths are entirely through soft iron, which has a low reluctance and therefore permits a large amount of flux to circulate. Notice that movement of the armature in either direction will cause one air gap in one of the paths to decrease and the other air gap in that path to increase, with the result that the total air gap for any one path remains essentially the same regardless of the position of the armature. This is a desirable condition for distortionless operation.

Now let us see what effect the position of the armature has upon the path taken by the permanent magnetic flux. Referring to Fig. *5B*, let us assume that the armature is rotated counter-clockwise, so that air gaps g_1 and g_2 are considerably smaller than the other two. Naturally the flux coming out of the north pole of the permanent magnet will choose to take the path through pole N_1 because g_2 offers less reluctance than g_3. This flux will pass through the entire armature and then through gap g_1 to pole S_2. The result is that poles N_1 and S_2 are strengthened, while poles N_2 and S_1 are weakened. But remember that the motion of the armature depends upon repulsion as well as attraction; an increase in the attraction on any one end of the armature is offset by a decrease in the repulsion on the same end, with the result that the effect of the permanent magnetic flux upon the armature *is essentially independent of the position of the armature.*

A balanced magnetic driving unit can swing through considerably greater distances than a bi-polar magnetic unit without serious distortion. The use of large and powerful permanent magnets made of new magnetic alloys makes possible a large air gap, with resulting increase in output volume. The moving system can be made light enough to prevent mechanical resonance in the range of audio frequencies being handled.

With the balanced armature type of construction there is generally ample

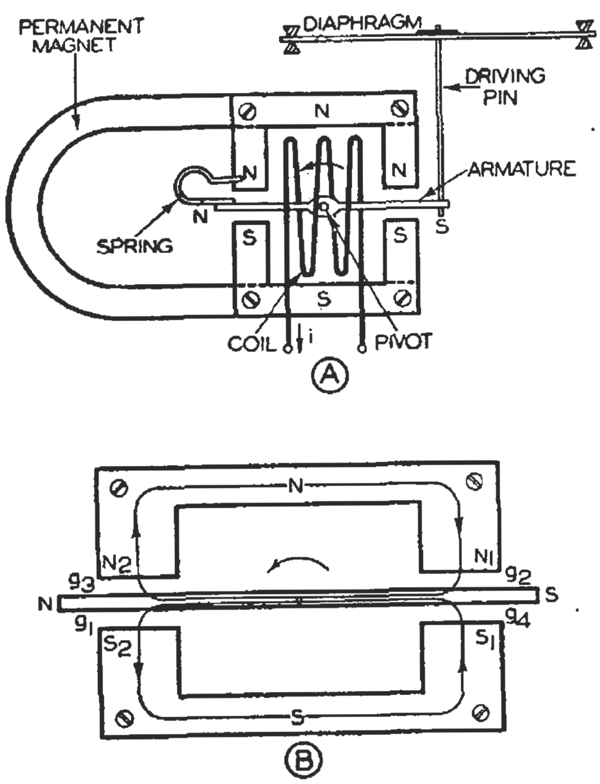


FIG. 5. These diagrams illustrate the construction and principle of operation of a balanced armature type magnetic driving unit.

room for the coil, permitting the use of larger-sized wire with fewer turns in order to reduce the coil inductance. This allows higher-frequency audio currents to flow, increasing the frequency range of the loudspeaker. In general, then, a balanced armature type magnetic driving unit gives higher output and a wider frequency range than a bi-polar magnetic driving unit. With proper design the magnetic type of driving unit can be made to have reasonably uniform frequency response over the middle range of frequencies, from 150 cycles to 3,000 cycles.

Dynamic Driving Units

The amount of audio sound power radiated by a given loudspeaker at a definite frequency depends upon two things: the area of the diaphragm, and the displacement or maximum movement of the diaphragm. These two factors together determine the

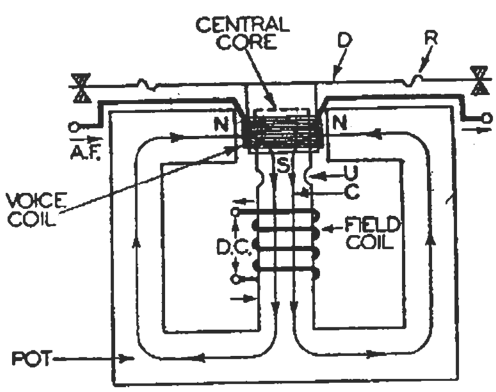


FIG. 6. Simplified diagram illustrating the operating principles of an electrodynamic driving unit.

volume of air moved and thereby determine the amount of sound produced at a particular frequency. (The in-and-out motion of a loudspeaker diaphragm is often referred to as *piston action,* for the diaphragm acts much like the piston in a water or air pump; the larger the piston area and the farther it moves, the more water or air will be moved.) The greater the volume of air which is moved by a given diaphragm, the greater is the load on the diaphragm and the greater is its mechanical resistance.

With the maximum displacement of the diaphragm limited by the air gap length in magnetic types of loudspeaker driving units, engineers turned to an entirely new type of electro-mechanical driving system, known as the *dynamic loudspeaker.* A study of the simplified diagram in Fig. *6* will show the operating principles of this dynamic unit, which consists simply of a small coil, carrying signal current, which is attached to a large diaphragm and which is located in a strong magnetic field.

Bear in mind that the diagram in Fig. *6* represents a cross section of a cylindrical unit. The permanent magnetic field is provided by sending direct current through a field coil wound around the center cylindrical soft iron core. An iron shell or *pot* surrounds this core and coil to complete the magnetic path up to the air gap in which is located the voice coil; this coil consists of a few turns of fine wire wound on a bakelite-impregnated paper or mica coil form. It is essential that the air gap be kept as small as possible without having the coil or its form rubbing against the cylindrical pole piece or the central core. To reduce the thickness of this voice coil, a spiral groove is often cut in the form for the wires. Mica is often used for the coil form because it will not warp when subjected to excessive heat due to resistance losses in the voice coil. The leads to the voice coil must, of course, be exceptionally flexible and arranged in such a way that they do not interfere with the movement of either the coil or the diaphragm.

Diaphragm *D,* to which the voice coil is attached, is usually made of stiff duralumin, in order that the coil will return to its normal no-current position when the voice coil current drops to zero. The diaphragm is corrugated around its edges, such as at *R*, in order that the inner portion of the diaphragm can move with the voice coil even though the outer edges are rigidly clamped in position.

Now let us see how this dynamic driving unit operates. First of all, I want to point out that the operation is the same regardless of whether the permanent magnetic flux through the air gap is produced by a coil carrying direct current or by a powerful permanent magnet having essentially the same shape as the soft iron core shown in Fig. *6*. It is the interaction between the permanent magnetic flux and the flux produced by the voice coil current which produces motion; the principle is the same as that applying to electric motors.

To understand just why the voice coil should move when current passes through it, consider only one part of the air gap, as shown in Fig. *7A*. The magnetic lines of force here come out of the ring-shaped *N* pole piece and go through the air gap to the cylindrical center core which is made an *S* pole by the permanent magnet or by the field coil. This is the field which is present in the vicinity of the voice coil at all times.

As you know, any wire which is carrying current will have around it a circular magnetic field like that shown in Fig. *7B*. If the electron flow through this wire is into the paper, the magnetic lines of force will have the direction shown.

When this single current-carrying wire is in the air gap, we have the conditions shown in Fig. *7C*. The two magnetic fields react with each other. Notice that the magnetic lines of force underneath the wire are in the same direction and reinforce each other, while those above the wire are in opposite directions and tend to cancel out. There is a crowding of flux lines below the wire and a less-than-normal number above the wire; the motion of the wire will be such as to redistribute the flux more uniformly, and the wire will therefore move upward as indicated by the long arrow. If the current through the wire reverses, the magnetic field of the wire will be reversed in direction and the wire will be forced downward. With a voice coil in the air gap, this same

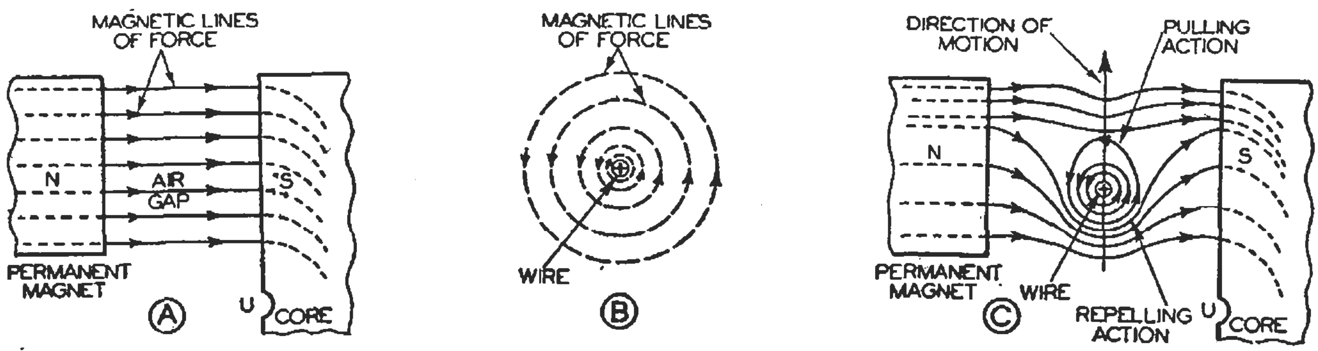


FIG. 7. What makes the voice coil move in a dynamic loudspeaker? These diagrams will tell you. The fixed magnetic field is shown at *A*, while the magnetic field around a voice coil wire is shown at *B*. The inter-action of these two fields, as at *C*, results in motion of the voice coil. The + symbol in the wire indicates that the electron current is flowing into the paper (away from you) through the wire.

action takes place at all points in the air gap and on all turns of the voice coil, with the result that the entire voice coil is either moved upward or downward depending upon the direction of current flow.

The strength or magnitude of the force acting upon the voice coil depends upon three things: *1, the strength of the fixed magnetic field* existing in the air gap; *2, the length of the wire used for the voice coil; 3, the voice coil current.* Increasing any one or all of these three factors increases the force acting upon the voice coil.

If the force acting on the voice coil is to be proportional to the voice coil current at all times, the magnetic flux must be of uniform strength throughout the air gap. You will generally find a groove cut into the central core at *U* to prevent the flux from thinning out at the lower edge of the air gap; furthermore, the length of the voice coil will generally be less than the height of the air gap.

The weight of the diaphragm and voice coil assembly should be low, and the diaphragm should have sufficient stiffness so that mechanical resonance will occur above the audible frequency range.

Since the voice coil in a dynamic unit has only a few turns of wire (from 1 to 50 turns), its reactance is quite low even for the highest audio frequencies; the high-frequency response of a dynamic loudspeaker is therefore not limited by the voice coil inductance, but rather by the mass of the moving system. Diaphragm movements of one-half inch are not uncommon in dynamic loudspeaker units which are capable of handling large amounts of audio power.

Condenser Driving Units

Although condenser loudspeakers are relatively little used today, they have certain special advantages which make it advisable for you to be familiar with their construction and operating principles. They depend for their operation upon the attraction of a positive charge for a negative charge, and might therefore be called electrostatic units.

In a condenser driving unit a heavy, stationary plate is charged with one polarity and a light, movable plate, mounted a short distance away, is charged with opposite polarity. The separation between plates is uniform and is made as short as possible without causing the charges to equalize by jumping across the air gap. As you know, these two plates constitute a condenser; increasing the areas of the plates and reducing the distance between them increases the capacity of the condenser and thereby increases the charge which can be stored on the plates. For a given electrical charge on the plates, reducing the air gap between them increases the force of attraction between the plates.

Application of a high-voltage A.F. signal to the plates is not enough to give the desired operation, for the plates will always be of opposite polarity and will therefore always attract each other (except when the voltage is zero, which occurs twice during each cycle). As a result, we have a frequency-doubling effect just as would occur in a bi-polar magnetic unit if there were no permanent magnet. The remedy is quite simple and comparable to that used in the headphone unit; a D.C. or polarizing voltage is applied to the plates, so that there is a constant attraction between the plates. The A.F. voltage acts in series with this fixed or polarizing voltage, increasing or reducing the attraction. In this way the displacement of the light, movable plate corresponds to the wave form of the A.F. signal.

In practical condenser loudspeakers the movable plate usually consists of metal foil which is cemented over a sheet of thin, stretched rubber which is supported at its edges. A D.C. polarizing voltage of about 500 volts is applied to the plates. The essential features of this construction are shown in Fig. 8.

Although condenser loudspeakers are simple in construction and comparatively inexpensive, their power output is limited because of the extremely limited displacement of the moving plate (the maximum obtainable displacement is always much less than the thickness of the stretched rubber sheet). When increased output is desired, it is necessary to use several condenser loudspeaker units arranged side by side and connected in parallel; each unit ordinarily is about one foot square. Another drawback is the fact that the rubber used as an insulating material has a limited life, becoming hard or deteriorating with time. The low-frequency response of a condenser unit is rather poor, and some provision for correcting this must ordinarily be made in the audio amplifier. The high-frequency response is quite good, however, for the reactance of the loudspeaker unit decreases with frequency and the mass of the moving system is not great enough to prevent high-frequency movement. High-frequency response is further improved by punching holes in the stationary plate to permit free movement of air through this plate. Sounds travel out from a condenser loudspeaker at right angles to its moving plate, and the units therefore have desirable directional characteristics.

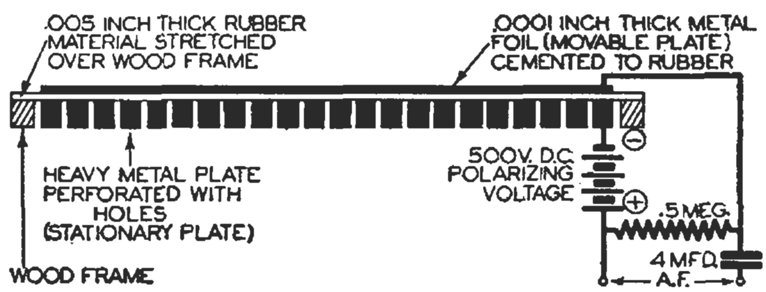


FIG. 8. Cross-section view of a typical condenser loudspeaker, showing essential constructional features. The plates were usually made about 8" x 12" in size.

Crystal Driving Units

The basic action of a crystal loudspeaker is as follows: The application of a voltage of given polarity to the faces of specially-cut crystal slabs causes a change in shape which is used to drive a diaphragm or cone. Rochelle salt crystals, which can be grown artificially from chemical solutions in quite large sizes and in a relatively short time, are most often used in crystal loudspeakers. A typical Rochelle salt crystal slab might be cut to a size of about 2.5 inches square and ⅛ inch thick, as shown in Fig. *9A*. The slab must be cut from the crystal in a definite manner in order to secure a maximum change in shape when voltage is applied. When this crystal element is rigidly fastened at three of its corners, *A*, *B* and *C*, the application of an electric charge to its faces by means of tinfoil sheets cemented on each side will cause length *A-D* to increase or decrease, depending upon the manner in which the slab was originally cut from the complete crystal and the polarity of the applied charge. This change in length is of course quite small, but engineers have discovered how to utilize it to greatest advantage.

In the practical crystal loudspeaker, two slabs are cemented together. One increases in length when a voltage with a given polarity is applied, while the other decreases in length; the result is that the combined slab bends at its free corner through a distance far greater than the original change in length of either crystal. The principle is much like that of the bi-metallic strip so widely used in some thermometers (two different metals are welded together in the form of a thin rectangular strip; one expands more than the other when temperature increases, with the result that the strip bends or curls with changes in temperature).

When two crystal elements are cemented together, giving a two-crystal unit, we have what is known as a *bi-morph cell*. The construction of the usual bi-morph cell is as shown in Fig. *9B*, where tinfoil sheets are cemented to each face of each crystal before the crystals are cemented together; in this way each crystal can be so charged that one will expand while the other contracts.

The construction of a typical crystal driving unit is shown in Fig. *9C*. Three corners of the bi-morph crystal cell are rigidly supported between rubber pads, while a metal cap and a driving link or lever are cemented to the fourth corner. The entire cell is

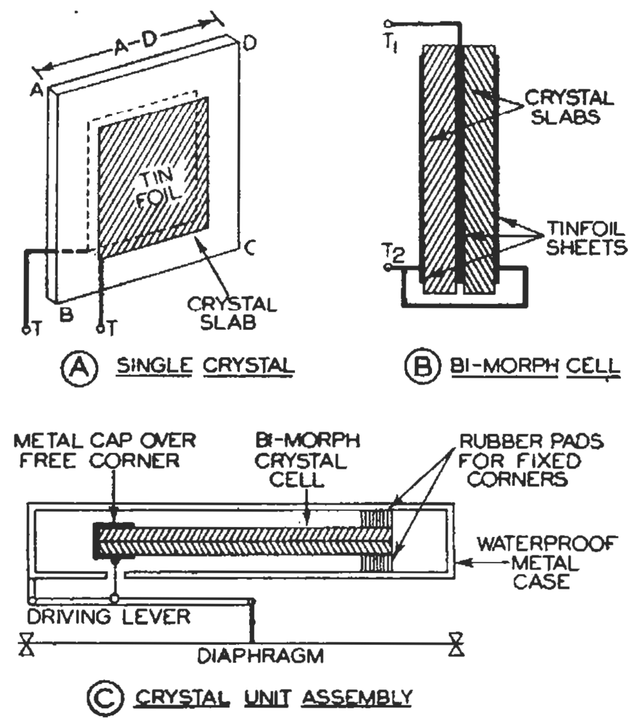


FIG. 9. How does a crystal loudspeaker work? These three diagrams give you the complete story.

mounted in a water-proof housing, for Rochelle salt crystals dissolve in water and deteriorate in the presence of moisture. They are also affected by high temperatures and must not be used in locations hotter than 125° F. The motion of the free edge of the crystal unit is transferred to the diaphragm by the mechanical link or lever system.

Crystal driving units are essentially condensers; in fact, a 2.5 inch square bi-morph crystal cell has a capacity of about .03 mfd. This means that its reactance will decrease at the higher frequencies, and it will therefore have a very good high-frequency response. Although crystal driving units can be designed to reproduce the entire audio frequency range, they are primarily used for the reproduction of the higher audio frequencies.

Loudspeakers Can Also Serve as Microphones

Before considering further details of sound-reproducing units, it is worth noting that any device for converting A.F. signals to sound can also be operated in reverse, so that sounds produced in the vicinity of the diaphragm or moving system will develop an electrical signal of corresponding wave form; in other words, a loudspeaker will also operate as a microphone. The better the fidelity of the loudspeaker as a sound reproducer, the better will be its performance as a microphone. One basic difference must be kept in mind; sound reproducers are designed to furnish large sound output powers, with the diaphragm or moving element pushing a large volume of air, while microphones are usually designed to respond to movements of small volumes of air or to weak sound inputs. In modern intercommunicating systems, small dynamic loudspeakers are widely used as microphones.

Action of a Horn as a Loudspeaker Coupling Unit

We have now considered the various methods ordinarily used for setting the diaphragm of a loudspeaker into vibration. Naturally we want this vibration of the diaphragm to produce a large sound output. Since the horn is a common air coupling system used for this purpose, it will be taken up next.

As you already know, the acoustical characteristics of a vibrating diaphragm in a driving unit may be represented by an electrical circuit like that shown in Fig. *10*. The mass of the diaphragm is represented by L_m (mechanical inductance), the compliance or springiness of the diaphragm is represented by C_m (mechanical capacitance), and the mechanical resistance of the diaphragm is represented by R_m. The mechanical force applied to the diaphragm by

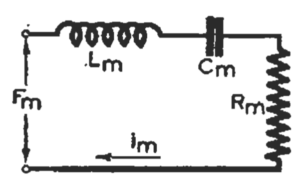


FIG. 10. Equivalent mechanical circuit of a vibrating diaphragm in a loudspeaker.

the driving unit is represented by F_m; for simplicity we can assume that it is an alternating force having a simple sine wave characteristic. We can then vary the frequency of this source and determine the effects of these variations on the performance of our loudspeaker.

The simple series circuit in Fig. *10* will serve as our guide for analyzing the action of a vibrating diaphragm. The applied force F_m causes the diaphragm to vibrate, and at any frequency the velocity of vibration will be governed by the mechanical reactances of L_m and C_m and by the mechanical resistance of R_m. When the two mechanical reactances are exactly equal, their effects cancel and we have mechanical resonance, with only R_m in the circuit to limit mechanical current flow. This mechanical current (i_m) represents the velocity of the diaphragm, and consequently also represents the velocity of air particles in the vicinity of the diaphragm. It is this air velocity which contributes toward the desired sound output. At input frequencies below the resonant frequency of the diaphragm, the mechanical reactance of C_m will be greater than that of L_m, and the diaphragm will act as a mechanical capacitance in series with a mechanical resistance. At above-resonance frequencies, the diaphragm will act as a mechanical inductance in series with a mechanical resistance but neither the mass (inductance) nor the compliance (capacity) involves loss of power; they merely offer opposition to changes in diaphragm position. It is the mechanical power absorbed by R_m which determines the loudspeaker sound output.

From Fig. *10* it is obvious that increasing the value of R_m increases the amount of mechanical power absorbed and therefore increases the sound output of a loudspeaker. Likewise increasing the driving force F_m will cause greater mechanical current flow, increasing the diaphragm displacement and velocity and thereby increasing the air velocity and the sound output power.

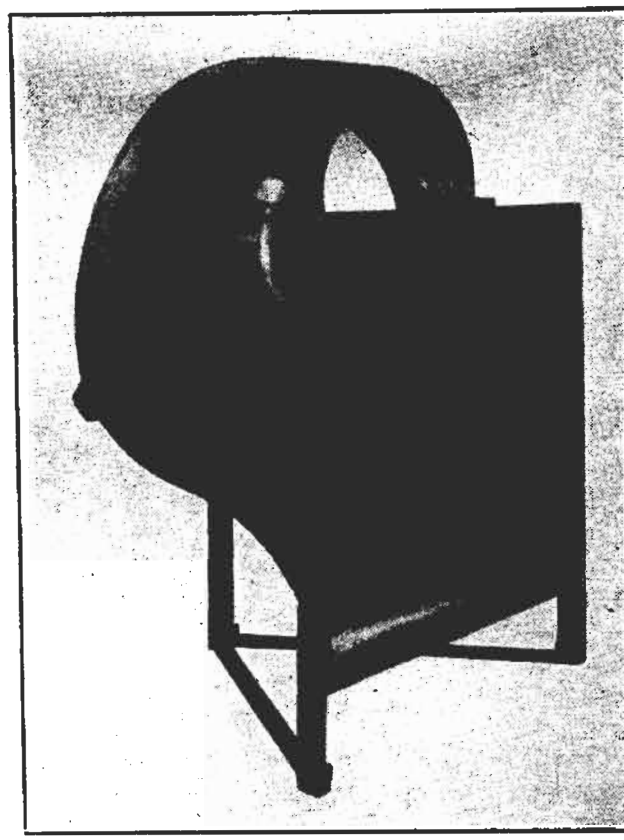
In the case of crystal or condenser driving units, the mechanical force F_m can be increased directly by increasing the A.F. voltage applied to the driving unit, while in other types of driving units an increase in the applied A.F. voltage will cause greater A.F. current to flow and this will increase the mechanical force F_m. Increased mechanical force F_m obviously will cause greater diaphragm displacement and greater air velocity, with more power being absorbed by R_m.

If a driving unit of a loudspeaker were placed in a vacuum, R_m would merely represent losses due to friction in the diaphragm itself; there would be no useful sound output since no air would be moved. The only limitations to the velocity of motion of the diaphragm would be this very low value of R_m and the difference between the mechanical reactances of L_m and C_m; at resonance these mechanical reactances would balance out, and we could expect extremely large velocities and displacements of the diaphragm. Considering these facts from a practical standpoint, we can easily see that with a loudspeaker operating outside the gondola of a balloon high in the stratosphere (where atmospheric conditions approach a vacuum), the displacement of the diaphragm might be large enough to ruin the driving unit.

When the diaphragm is allowed to act upon air, a load is applied or coupled to the diaphragm and this is equivalent to increasing the value of R_m. This is a desirable condition, for it allows us to secure a greater amount of useful work from the loudspeaker.

Measuring Loudspeaker Efficiency. When loudspeaker engineers desire to check the efficiency of a particular loudspeaker as a sound reproducer, they measure the electrical resistance of the loudspeaker input terminals under the following two conditions: *1*, with the driving unit blocked, so that the diaphragm and the other moving elements cannot move; this gives the resistance due to electrical losses in the driving unit only, and is known as the *blocked resistance* of the loudspeaker; *2*, with the moving elements free to move.* These resistance measurements are repeated for a number of frequencies over the entire audio range. The difference between the two measured resistance values at each audio frequency then represents the additional resistance due to the production of sound; this is called *motional resistance.* The ratio of the motional resistance to the total resistance when the diaphragm is free determines the loudspeaker efficiency; multiplying this ratio value by 100 gives the percentage efficiency. If, for example, these tests show that a loudspeaker has an efficiency of 10% at 1,000 cycles, the engineer knows that he will only get 2 watts of acoustical power out of the loudspeaker when he feeds 20 watts of electrical power into the loudspeaker.

Loading the Diaphragm. Loudspeaker engineers quickly learned that small diaphragms operating in free air without horns or other air coupling systems gave little sound output regardless of their velocity or displacement; measurements of loudspeaker efficiency verified this by indicating a very low motional resistance. The reason for this is easy to see; air directly in front of the diaphragm is alternately compressed and thinned out, and the same effect occurs at the back of the diaphragm. Whenever there is compression in front, there is thinning out or rarefaction at the back. Since compressed air tries to spread out or relay its effects to adjacent air particles in the easiest way possible, it merely moves around the diaphragm to the rear to equalize the thin air there, and only a very small volume of air is thus actually set into vibration by the diaphragm.



Curled exponential horn with circular cross-section near throat; the 5/8" diameter throat fits into a standard driving unit. Note the square cross-section at the mouth and the rectangular cross-section in the middle region. The shape of cross-section is unimportant as long as the cross-sectional area of the horn increases in an exponential manner from throat to mouth.

One way of overcoming this trouble is to use a large diaphragm or cone which will set a large volume of air into motion. Another way is to prevent the air in front of a small diaphragm from reacting on the air in back of the diaphragm. Either of these procedures increases the load on the diaphragm, thereby increasing the

* In order to secure a true A.C. resistance measurement at the chosen frequency, the reactance of the voice coil is tuned out by means of a condenser in both cases.

motional resistance, producing more acoustical output and increasing the loudspeaker efficiency.

The mounting of a megaphone or conical-shaped horn like that shown in Fig. *11A* around the diaphragm of a driving unit was an early attempt to load the diaphragm by preventing air from escaping behind it, and also was intended to direct the moving air toward the listener. Results were not satisfactory, however, for the use of a conical-shaped horn did not take into account the fact that air in motion travels in definite natural paths. We have a small amount of air vibrating at high velocity near the diaphragm; what we really want is a horn which will cause a greater amount of air a farther distance out to vibrate at a somewhat lower velocity, this process continuing until at the opening of the horn a very large volume of air will be vibrating at a low velocity. There must be no dead spots in the horn (regions unaffected by the vibration of the diaphragm); there must be no cancellation of effects along the length of the horn, no turbulence of air and no wasted energy. If all this is realized, the entire amount of air in the horn will be properly coupled to the driving unit, increasing the motional resistance and giving the desired increase in efficiency. Securing this desirable condition is known as matching the impedance of the air with the impedance of the driving unit; it serves to load the unit effectively and give a maximum of useful sound power output.

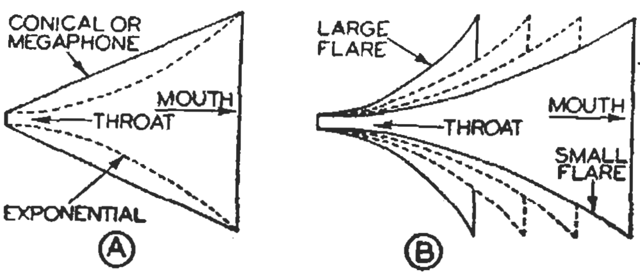


FIG. 11. Comparison of shapes of a conical horn with various types of exponential horns used with loudspeaker driving units.

Exponential Horns. No doubt you are already familiar with loudspeaker horns. At the small end or *throat* of a horn the cross-sectional area is small, while at the large end or *mouth* the cross-sectional area is large and is a maximum. It makes little difference whether the cross-sectional shape of a horn is square, rectangular or circular; it is the manner in which the cross-sectional area increases from the throat to the mouth which determines the effectiveness of the coupling between the driving unit and the air in space. When this area increases according to what mathematicians call an *exponential* formula, giving a graceful curve like that shown by the dotted lines in Fig. *11A*, the coupling will be most effective.

For a given throat area and a given mouth area, there can be any number of exponential horn shapes, but each would have different length and a different flare, as indicated in Fig. *11B*. The *flare* of a horn refers to *the amount of spreading outward in a given horn length*: the shortest horn shown in Fig. *11B* thus has the greatest flare. The amount of flare has a definite and important effect upon the frequency range of a horn loudspeaker, for it determines the efficiency of coupling at various frequencies in the audio range.

The formula used by loudspeaker design engineers in computing the shapes of various forms of exponential horns involves considerable mathematical knowledge, and will not be taken up here since it is seldom if ever needed by the practical man. There are certain facts to be derived from this formula which are of practical interest, however. The smaller the horns having smaller flares. Remember—a horn which is to provide effective coupling between the air and a loudspeaker driving unit at low frequencies should have a small flare.

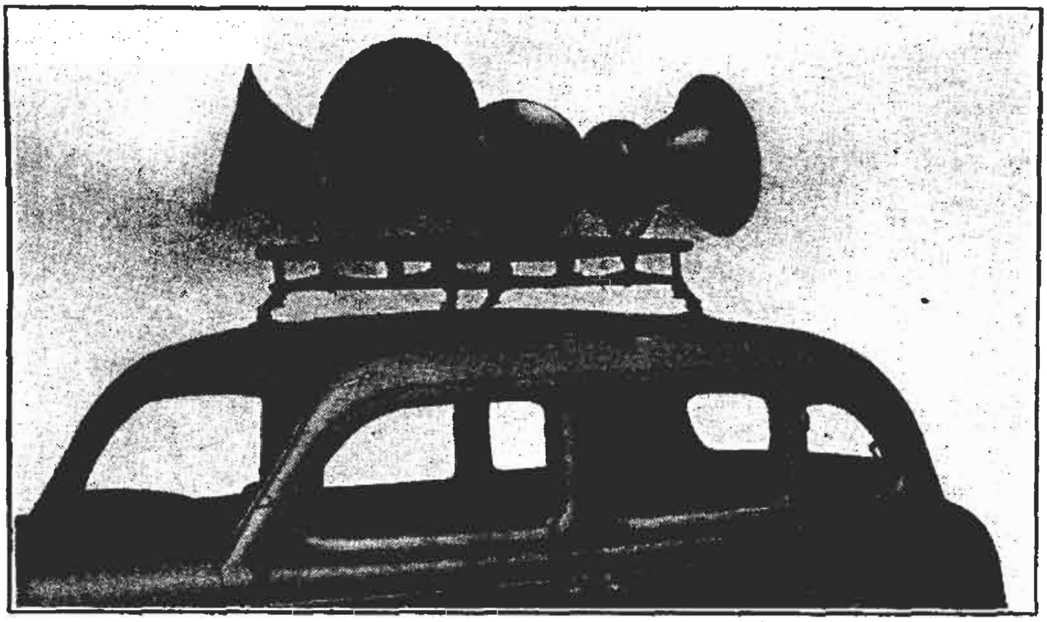
Mouth Area. Although the area of the mouth of a horn does not have an

Courtesy Utah Radio Products Co.

Assembly line in the Utah loudspeaker factory. Finished electrodynamic loudspeakers are placed on the conveyor belt which moves down the center of the long table.

the flare (amount of spreading out) of the horn, the lower will be the frequency which can effectively be coupled to the driving unit and the longer will be the horn for a definite throat and mouth area. That horn in Fig. *11B* having the largest flare consequently cannot be expected to reproduce low frequencies as well as appreciable effect upon the cut-off frequency of the horn (the lowest audio frequency which it will radiate effectively), the mouth area does affect the uniformity of the loudspeaker response curve. A small mouth results in a sudden change in the velocity of air particles as they leave the horn, causing some of the sound waves to be reflected back into the horn. This gives rise to peaks and dips in the loading of the driving unit, causing a ragged sound output. In general, for a horn with a circular cross-section, the diameter of the mouth should be equal to at least one-fourth the wavelength of the lowest frequency which is to be reproduced (the wavelength of sound is equal to its velocity of travel, 1,089 feet per second, divided by its frequency in cycles; at 50 cycles, then, the wavelength would be 1,089 ÷ 50, or about 22 feet). Thus a horn which is to handle frequencies down to 50 cycles should have a mouth diameter equal to at least 22 ÷ 4, or 5.5 feet. The length of this horn would be quite long, for the small flare required to secure efficient coupling at this low audio frequency would make necessary the long length in order to secure the required mouth area.

Throat Area. The throat area of a horn is controlled essentially by the size of the diaphragm. It is common practice to design driving units for use with a circular throat having a diameter of 5/8 inch, in order that standard horns and driving units can be used interchangeably. With a considerably larger throat area, a short horn with a small flare would provide a fairly low-frequency cut-off, but experience has shown that such a horn would not give efficient coupling at higher frequencies. With a small diaphragm and the conventional small throat, good high-frequency output is possible but the movement or displacement of the diaphragm must be increased in order to secure good bass output. Yes, there are plenty of tough problems confronting the loudspeaker designer.



Courtesy Vac-O-Grip Co.

Four dynamic cone loudspeakers with single-piece spun aluminum exponential horns are here mounted on an ingenious carrying frame which can be used on any passenger car without damaging the roof. Rubber vacuum cups beneath each support prevent the assembly from sliding off while the car is in motion.

Construction of Horn. Any material is satisfactory for horn construction as long as it is dead as far as sound is concerned; in other words, the material must not vibrate under the influence of sound waves. Aluminum is an excellent material, but when used for the longer horns, it should be reinforced with ribs on the outside to prevent the large surfaces from vibrating in unison with the diaphragm. Plywood is widely used for horns of rectangular cross sections. Some horns are made of papier mache (molded paper fiber), while others are made of layers of cloth impregnated with a special glue or binder and formed to the desired shape. Horns which must withstand outdoor weather conditions generally are of sturdy metal construction; when plywood or some other non-metallic material is used, it should be treated to withstand moisture.

As a rule, a straight horn like that shown in Fig. *12A* will give better results than a curled horn like that in Fig. *12B*. It is common practice to build up a large horn in sections, different constructional procedures being followed for each type and size of horn and each type of material. That section which screws onto the driving unit is generally spun or cast from aluminum, and has the same form of exponential curve as the remaining sections of that particular horn.

Where space prevents the use of a long, straight horn having the desired characteristics (a horn length of 18 feet is by no means unusual where frequencies down to 50 cycles must be reproduced), the horn may be curled in the manner shown in Fig. *12B*. The sharpest bend in the horn must not cancel any of the high-frequency sounds. If the difference in length between sound paths *3-4* and *1-2* in Fig. *12B*, around a sharp bend, is less than one-half the wavelength of the highest frequency to be reproduced, the cancellation of sound will not be serious. Cancellation occurs whenever two sound waves become 180° out of phase, and this can occur when one wave travels one-half wavelength more than the other. Curled horns can generally be designed to meet any reasonable space requirements while still observing the flare, mouth area and curvature specifications required for a desired performance.

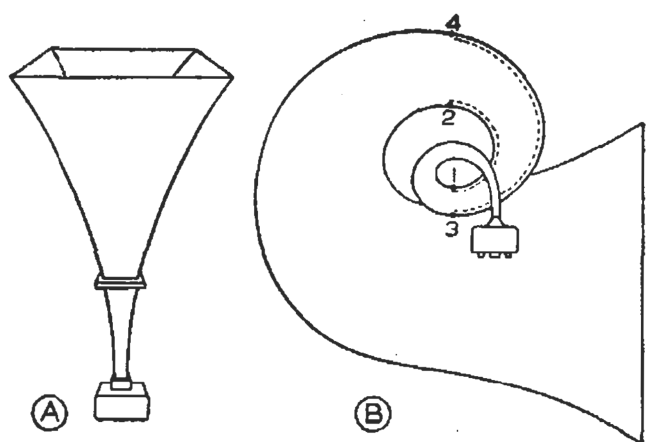


FIG. 12. Straight and curled exponential horns having standard ⅞" throats.

Horn Ratings. If a horn is able to resist heavy sound pressures without self-vibration, it can handle unlimited sound output power. Good horns are therefore rated according to frequency range and *not* according to power-handling ability. Either high- or low-power driving units may be attached to any particular horn. Oftentimes several driving units are used on a single horn by redesigning the throat end of the horn or by inserting the proper type of connecting unit. In general, a long horn with a small flare and a large mouth will have a wide frequency range and will have high efficiency.

Design of Dynamic Driving Units for Horn Loudspeakers

In the high-power dynamic driving units used with horn loudspeakers, the

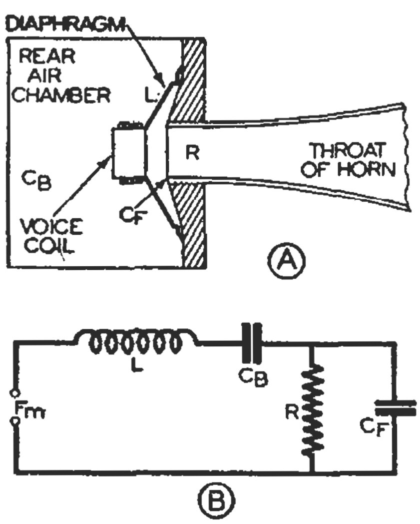
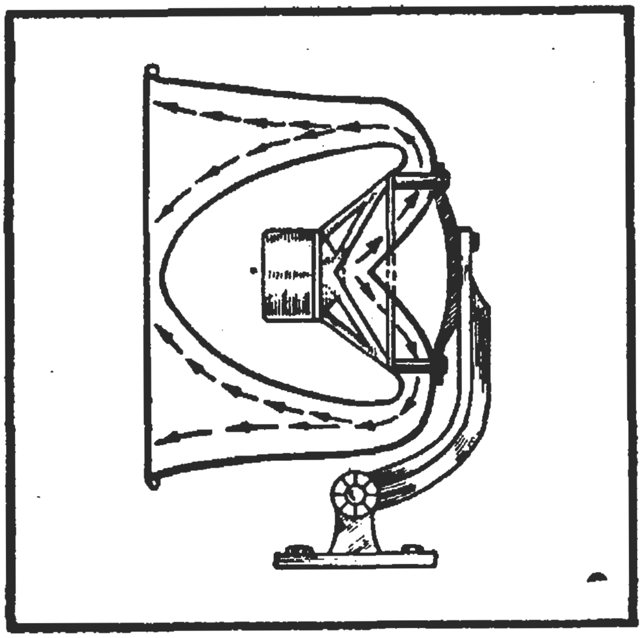


FIG. 13. Method of mounting horn with 5/8" throat on driving unit having a diaphragm considerably greater in diameter than 5/8", and equivalent mechanical circuit for such a combination.

diaphragm is generally made considerably larger than the 5/8 inch throat diameter of the norn, in order to move a larger volume of air and secure a higher initial air velocity. The arrangement of a dynamic driving unit might be as shown in Fig. *13A*. The diaphragm is made in the shape of a cone, to prevent buckling when a



Marine-type mounting of dynamic cone loudspeaker. This weather-proof unit, made by Atlas Sound Corp., gives excellent distribution of sound and at the same time is capable of withstanding the extremely severe weather conditions encountered on board ships, on sound trucks and even on fire trucks. Tests have shown that a stream of water can be played directly into the mouth of the loudspeaker without affecting loudspeaker operation. The horn is made from heavy-gauge aluminum and steel spinnings. Arrow lines show paths of sound waves.

strong force is applied at its center by the voice coil.

The mounting of the diaphragm is such that it has a certain amount of natural springiness, which returns it to a normal position when no current flows through the voice coil, or the cone and the chamber in back of it are made air-tight so that the air space in back of the diaphragm will act as a cushion or spring which returns the diaphragm to its normal position. The diaphragm therefore has mechanical capacitance. Furthermore, since the diaphragm and voice coil together have a certain amount of mass, they also have mechanical inductance. The experience of loudspeaker engineers has shown that these act in series, as shown in Fig. *13B*. The load which is placed upon the cone-shaped diaphragm by the exponential horn can be represented as a mechanical resistance acting in series with the mechanical inductance and mechanical capacitance. We must not overlook the air chamber between the cone and the surface directly in front of it which supports the throat end of the horn. This air space can be considered an extra mechanical capacitance C_F acting in parallel with the mechanical resistance.

We know how an electrical circuit resembling that in Fig. *13B* will behave under various conditions, since it is a common radio circuit, and consequently we can predict the behavior of our loudspeaker by studying this circuit.

Assuming that the value of C_F is small, as it ordinarily is, we can see that the mass of the cone (L) and the compliance of the rear chamber (C_B) form a series resonant circuit. Resonance will occur at some particular frequency, and at resonance the input force F_m will depend upon the length of the wire in the voice coil, upon the voice coil current and upon the flux density in the air gap surrounding the voice coil. Furthermore, at resonance the input force will be acting solely upon mechanical resistance R, and practically all of the input force will serve to produce useful sounds (assuming a perfect exponential horn). The loudspeaker designer can select the values of L and C_B so that mechanical resonance occurs at a low audio frequency, thus providing reinforcement of bass notes, or at some intermediate frequency. This is one way of securing a desired frequency response for a loudspeaker.

Courtesy Racon Electric Co., Inc.

Battery of trumpet horn loudspeakers set up in front of the Hotel Astor at Times Square, New York City for a special event. This arrangement for radiating sound equally well in all directions requires a number of horns, with separate driving units for each.

At high frequencies the mechanical reactance of C_F becomes important Referring to our equivalent mechanical circuit in Fig. *13B*, C_F by-passes high-frequency signals around the load, and consequently in the loudspeaker this air chamber ahead of the cone definitely suppresses the high audio frequencies. The volume of air in this chamber determines to a considerable extent its mechanical capacity, and therefore the effects of this chamber can be reduced by making it as small as possible while still allowing ample room for cone movement. The shape of this air chamber alongside the throat is important for another reason; if the shape is such that air in the chamber can take several paths, of varying length, to the throat of the horn, it is possible that some of the high-frequency sounds will reach the throat out of phase and will cancel. In high-power horns the air pressure in this chamber may be tremendous; air cannot be compressed uniformly under these conditions, and distorted wave forms are the result. All these factors must be taken into account when designing the driving unit for a horn loudspeaker.

A number of typical mounts for the throat and diaphragm of a dynamic horn loudspeaker are shown in Fig. *14*. In each case the air chamber ahead of the diaphragm or cone is designed to give desired performance while reducing undesirable effects. When a wide range of sound frequencies is to be reproduced, it is generally best to use two loudspeakers; one loudspeaker for frequencies from 50 cycles to 6,000 cycles, called a *"woofer,"* and another loudspeaker for frequencies from 6,000 cycles to 15,000 cycles, called a *"tweeter."*

The science of horn loudspeaker design has now advanced to the point where efficiencies of up to 50% can be expected, with reasonably flat response. This means that the best horn loudspeakers will deliver 5 watts of sound power for each 10 watts of electrical input to the voice coil.

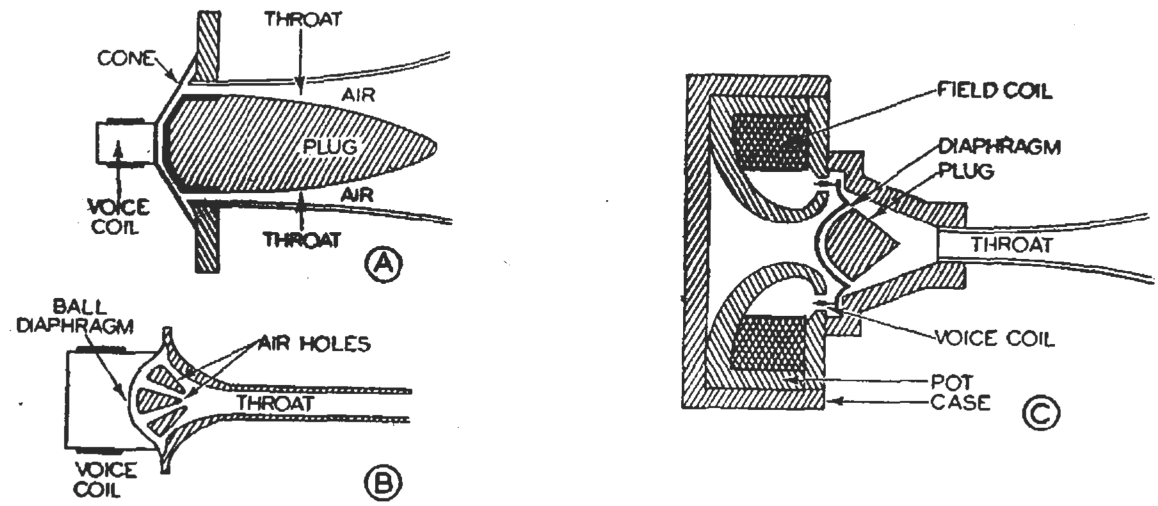


FIG. 14. Constructional features of three typical dynamic driving units are shown here. *A:* Unit employing a ring-shaped air chamber between the cone and the throat (secured by mounting a plug in the throat). The chamber is carefully shaped to reduce cancellation of sound waves at the higher frequencies. *B:* Unit using multiple outlet paths from diaphragm to throat (secured by forming air holes in a plug) to release the back pressure. *C:* Complete dynamic driving unit energizing a modification of the ring-shaped air chamber shown at *A*.

TEST QUESTIONS

Be sure to number your Answer Sheet 26FR-1.

Place your Student Number on every Answer Sheet.

Never hold up one set of lesson answers until you have **another ready to send in.** Send each lesson in by itself before you start on the next lesson. In this way we will be able to work together much more closely, you'll get more out of your Course, and you will receive the best possible lesson service.

1. Name the three sections of a complete loudspeaker. The driving unit, the cone, & the air coupling system.
2. Into what four general groups can loudspeakers be divided? Magnetic, dynamic, condenser, & crystal.
3. How is the undesirable frequency-doubling effect eliminated in a bi-polar headphone unit? A strong permanent magnet is used and the signal currents add to or subtract from the magnetic pull.
4. What does mass in a mechanical vibrating system correspond to in an electrical oscillating circuit? Inductance of a coil.
5. What determines the natural frequency of vibration of any physical object? The mechanical inductance and the mechanical capacitance
6. What three things determine the force acting upon the voice coil of a dynamic loudspeaker? P 16
7. What is the basic action of a crystal loudspeaker? P 17
8. What is meant by the flare of a horn? The amount of spreading outward in a given horn length.
9. If a horn is to provide effective coupling between the air and a loudspeaker driving unit at low frequencies, should a large or a small flare be used? Small
10. Are horns rated according to power-handling ability? No.