Handbook of Sound Reproduction

EDGAR M. VILLCHUR*

A discussion of the basic structure of one of the most important elements of a sound system, with an analysis of the effect of constructional features on its performance.

Chapter 10. Loudspeakers. (Part 1)

LOUDSPEAKERS are electro-acoustic devices for converting the electrical output of audio amplifiers into mechanical and then acoustical energy. Modern loudspeakers are almost exclusively of the dynamic (moving-coil) type. The dynamic loudspeaker allows the electrical signal to pass through a coil which is free to move along its longitudinal axis, and which is suspended in a transverse, fixed magnetic field. Since the coil is made of non-magnetic material the static field exerts no force on it except when current flows. An electrical signal changing in the same complex way as the original sound pressure will set up imitative vibrations, and the moving "voice" coil is given a bite of the air by an attached cone or diaphragm. The efficiency of the conversion from mechanical to acoustical energy is increased by means of some type of acoustical coupler between the speaker and room, such as a horn or baffle.

It may be seen that the first step of the above conversion, from electrical to mechanical energy, is exactly analogous to the action of an electric motor, where current is passed through an armature free to rotate in a fixed magnetic field.

Figure 9-1 illustrates a typical direct-radiator loudspeaker, so called because of the fact that the cone, unlike the diaphragm of a horn-type speaker, makes immediate contact with the air into which it radiates sound.

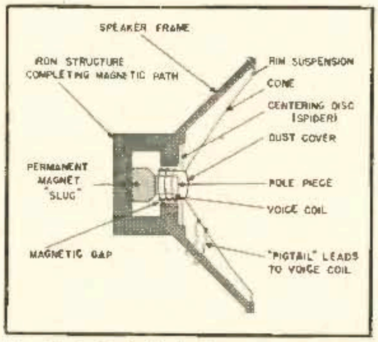


Fig. 10-1. Typical single-cone, single-voice-coil, direct-radiator speaker.

The Mechanical System of the Speaker

If the cone and voice coil were massless and perfectly rigid, and there were perfect freedom of motion for the voice coil, an analysis of cone vibrations would only need to be concerned with the electrical and magnetic characteristics of the speaker "motor". Unfortunately for speaker fidelity, however, the mass, elasticity, and friction of the mechanical system of moving parts have a strong influence on motion of the cone. When the voice coil is forced into vibration the inertia of the moving mass and the springiness of the spider and rim suspension create forces of their own. The speaker mechanical system is a resonant source of sound in addition to an imitative one, and when stimulated it tends to oscillate at its own natural frequency independently of the controlling signal, especially when the stimulus is at a frequency at or near resonance. Behavior at other frequencies follows the laws of resonant systems unwillingly forced into unnatural vibration.

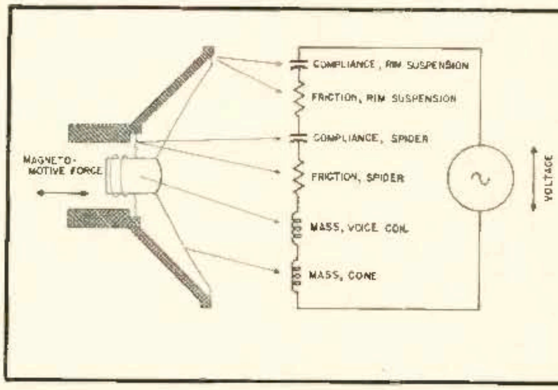


Fig. 10-2. Mechanical system of a dynamic loudspeaker (ignoring air load) and electrical analogy.

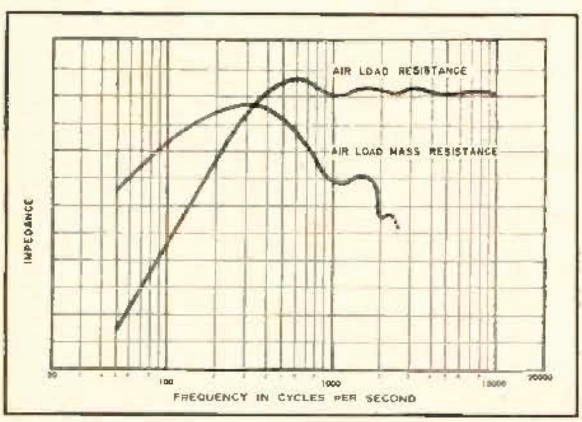


Fig. 10-3. Air-load impedance per unit area of cone in infinite baffle. After Olson.

Speaker Dynamical Analogies

Dynamical analogies relating mechanical, acoustic and electrical phenomena prove helpful in the understanding and design of speakers. Many articles on elec-

* *Contributing Editor*, AUDIO ENGINEERING.

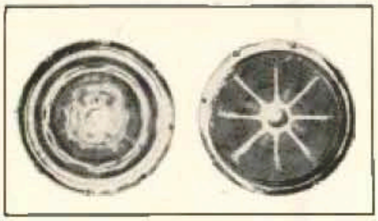


Fig. 9-4. (A), Cone break-up at 450 cps (photograph taken by dusting lycopodium powder on the cone, which is shaken off by the velocity loops and retained by the nodes). (B), Cone break-up at 2700 cps. After Corrington.

tro-acoustic devices have appeared which cannot be read intelligently without a knowledge of electrical analogies.

In order to draw the equivalent electrical circuit of the speaker mechanical system in *Fig.* 9-2 we must recall the basic elements of our analogical system, which are here reviewed:

Electrical	Mechanical
Voltage	Force
Current	Velocity
Inductance	Mass
Capacitance	Compliance (reciprocal of stiffness)
Resistance	Mechanical resistance (friction)

The mechanical system of a loudspeaker may thus be represented by the electrical analogy of *Fig.* 9-2 (assuming that the cone moves as a unit, and ignoring the effect of the air load.) The two inductances appear in series because both cone and voice coil add to the total mass, while if the inductances had been shown in parallel the inductance of each would detract from the total inductance of the combination. The two capacitors must also be shown in series (although the suspension compliances seem to be in parallel mechanically) because the stiffness of each of the elastic suspensions detracts from the total compliance, just as each capacitor reduces the total capacitance of the electrical system. Another way of seeing the necessity for representing the two cone suspensions with a series electrical connection is to think of one of them as frozen. Cone velocity would then become zero, in the same way that opening one of the series capacitors would stop all current flow. ("Frozen" implies infinite *stiffness*, and its reciprocal is zero *compliance*, which corresponds to zero, or open, *capacitance.*)

The inductive and capacitive elements of the electrical system form a series resonant circuit, presenting minimum impedance at resonance, and the exchange of energy between them follows the same laws as the energy exchange in the mechanical system.

We may now examine the behavior of the loudspeaker mechanical system when alternating magnetomotive forces of various frequencies are applied to the voice coil. The analogous electrical circuit will be referred to when it seems advantageous. Such references are only for the sake of clarification; they are not essential to the explanation. For simplicity we will at first ignore the influence of the internal impedance of the amplifier source and the effect of the extra load on the cone imposed by the air.

If the system is subjected to vibration at frequencies below resonance the inertial effect of the moving mass will be relatively small, and the predominant influence on motion will be the stiffness of the elastic suspension, or, to put it another way, the system will be compliance controlled. (In the analogous electrical system the generator will see a net capacitance.) Velocity will decrease with frequency, in the same way that alternating current through a capacitor decreases with frequency.

At resonance only friction must be overcome and the velocity of the cone will be at a maximum. Just as inductive and capacitive reactances balance each other out at resonance of the electrical circuit—leaving only resistance and allowing maximum current flow—the mass and compliance "mechanical reactances" balance out. Thus the opposing inertial and restoring forces are just equal.

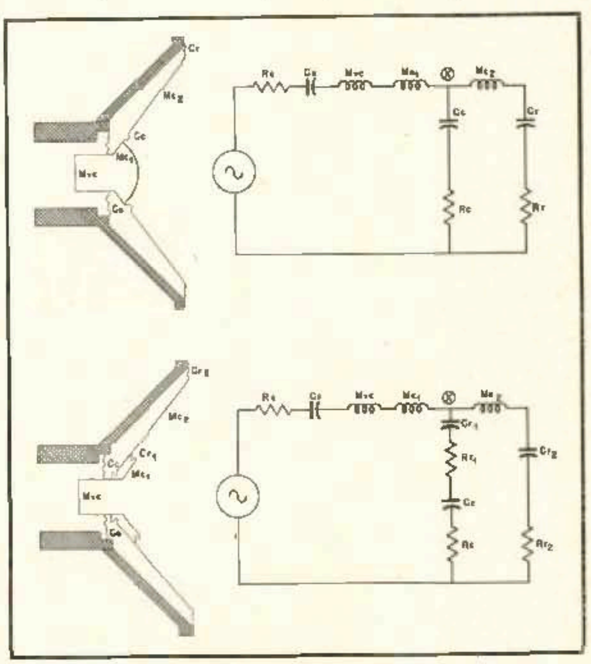
At frequencies above resonance the system becomes mass controlled (the generator sees a net inductance). The effect of inertia increases with the more rapid changes of velocity, while the impedance of the suspensions decreases. (Inductive reactance increases, capacitive reactance decreases with frequency.) Velocity for the same applied force will therefore decrease as the frequency is raised, like current through an inductance, and force and velocity assume a reversed phase relationship.

The behavior described above would seem to dictate very uneven reproduction of the audible spectrum of sound frequencies, with peak output at the resonant frequency of the speaker's mechanical system. But there are certain factors that work in favor of level frequency response, and there are measures which may be taken to help achieve this goal.

Below resonance, the output of the speaker falls off as sharply as we would expect it to unless special mounting devices are used. Above resonance, cone velocity also decreases with increase of frequency, but this effect is offset by the fact that the air load resistance increases with frequency at about the same rate. (*See Fig.* 9-3.) It is the air load resistance which determines how much speaker mechanical energy will be absorbed by the acoustic load, and so the acoustic output of the speaker is kept fairly uniform, in spite of decreasing velocity of motion, up to a frequency at which the air load resistance reaches its maximum and remains constant. This frequency is reached when the diameter of the speaker cone is about two-thirds the wavelength of the signal. For a twelve-inch speaker the critical frequency would be in the neighborhood of 700 cps.

Above this point speaker output should start decreasing in inverse proportion to the frequency, but an additional element mitigates and, in the lower treble octaves, even overcompensates the deficiency. At higher frequencies the cone ceases to move rigidly and "breaks up" into new modes of vibration, (see *Fig.* 9-4), so that the mass of each individually vibrating section is much less than the total mass. New, higher resonances come into play, and standing waves are formed. One of the purposes for which concentric corrugations are often inserted in the cone is to partly control this break-up, by creating high compliance at predetermined points along the line from base to apex. As in the case of other resonant modes of the speaker mechanical system, break-up resonances cause transient response and linearity of output to suffer, and peaks and dips are intro-

Fig. 9-5. (A), Mechanical system of a two-cone, single-voice-coil speaker and electrical analogy. (B), Variation of (A).



duced into the frequency response curve.

Other methods to subdue the speaker's bid for a life of its own are:

1. Damping.

In an electrical resonant circuit the presence of resistance dissipates energy in heat. Instead of energy merely being tossed back and forth between coil and capacitor, a certain amount of power is consumed by the system. The circuit becomes broadly tuned and has its resonant peak reduced, a condition in which it is said to be damped.

In a mechanical resonant system the same results are produced by friction, which takes its toll of energy during each exchange between inertia and restoring force. The violence of resonant oscillation for a given applied force, and the time required for oscillations to die out, are decreased. Speakers are not, of course, purely mechanical systems, and they are damped in three ways: internally, through mechanical friction in the suspension system and cone; acoustically, through the air load resistance; and electrically, through the source impedance of the amplifier, which acts as a shunt load to the electrical generator system of the voice coil and magnetic field.

Too much friction in the speaker suspensions will obviously cause a severe loss in efficiency, since the energy dissipated is entirely wasted. It is especially advantageous, however, to damp the rim suspension of the cone mechanically. This suspension is the termination of the path, beginning at the voice coil, that is followed by the sound when the cone ceases to move as a unit. If the rim is damped (internally or by an external application of viscous material) in such a way that sound waves reaching it encounter a minimum of impedance discontinuity, a good part of the energy that has not been radiated can be dissipated in the mechanical resistance of the suspension, instead of being reflected back along the cone. The formation of standing waves is thus discouraged, while vibration of the cone in smaller masses can still take place. Standing waves are also damped by the use of a soft, spongy cone material.

Energy absorbed by the air load resistance is being used precisely as intended, and improving the air coupling has the dual benefits of effective damping and increased efficiency. Since the resistive component of the acoustic load impedance allows power to be permanently transferred to the medium, the resistance reflected back into the speaker cone is called *radiation resistance*.

Electrical damping by the amplifier, which will be discussed in detail in the chapter on power amplifier stages, is also very effective and does not create efficiency loss.

2. Design for Low Resonant Frequency.

The lower the resonant frequency of a speaker the more extended its low-frequency response, and the less annoying the resonant peak will be. In some cases it is possible to keep speaker resonance below the main band of frequencies being reproduced. Typical values for commercial speakers twelve inches and larger are from forty to eighty-five cps. Low-frequency resonance calls for higher compliance relative to the mass, or high mass relative to the compliance, but other design considerations must be taken into account before values of mass and compliance can be decided upon. For a given mass the compliance must exert enough relatively linear restoring force so that the voice coil is not carried out of the area of uniform magnetic field, or does not allow the voice coil to "bottom" against the flange of the pole piece. Another factor that must be considered is the influence of a large mass in impeding reproduction of the higher frequencies, or of the transients of lower frequency tones. The air load again comes to our assistance in this matter. At low frequencies the air load has a proportionately high "reactive" component, which is to say it adds mass to the speaker system and lowers the resonant frequency. Although we normally expect a mass reactance to increase with frequency, the air load is peculiar. Above a certain frequency (see *Fig.* 9-3) the reactance *decreases* with frequency, so that compared to the mass reactance of the cone and voice coil it is greatly reduced at higher frequencies. It is a case of having our cake and eating it too.

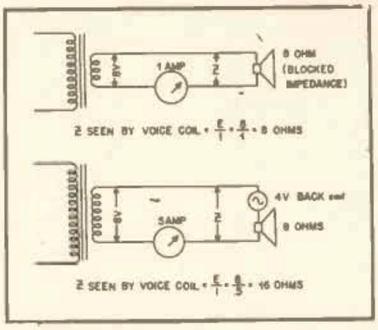


Fig. 9-7. How back e.m.f. increases the effective electrical voice-coil impedance seen by the amplifier (source impedance neglected).

3. Distribution of Mass of the Moving System.

The principle of inserting cone corrugations for controlling break-up may be followed through in a special design which uses definite segregated vibration systems in the cone and/or voice coil. In *Fig.* 9-5, (A) illustrates a speaker of this design, in current commercial use, which has an aluminum dome-shaped diaphragm for high-frequency sound propagation and dispersion. At low frequencies the entire suspended mechanism vibrates as a unit, but at high frequencies the small cone and diaphragm are able to vibrate by themselves because of their compliance with the cone proper.

The reader will find that tracing the equivalent electrical circuit of this speaker system increases appreciation of the way it works. In (A) of *Fig.* 9-5, the magnetomotive force must always overcome the friction of the spider R_s, the stiffness of the spider, determined by C_s, the mass intertia of the voice coil M_{vc}, and the inertia of the first section of cone and aluminum done M_{c_1}. At this point, marked X on the diagram, there is a choice of path. At low frequencies C_c will have a high impedance (will remain mechanically stiff) and M_{c_2} a low impedance, so that current will flow through M_{c_2} rather than C_c. The current through M_{c_2} will be the same as that through M_{c_1}, which represents the fact that the two sections will have the same velocity and will move as one.

As the frequency is raised the impedances of the two paths approach each other in value. At some particular point they will be equal, and half of the current will be by-passed through C_c, which means that half of the energy supplied will be used up in vibrating M_c independently from M_{c_2}. The compliance of C_c relative to other components of the system is adjusted so that the impedances of the two parallel paths become equal at the desired frequency, called the crossover frequency. The system of mass and compliance which determines the frequency of equal path impedance is sometimes referred to as a mechanical crossover network.

At much higher frequencies C_c assumes a very low value of impedance. Current is short circuited through it, leaving little or no energy for M_{c_2},

(*Continued on page 66*)

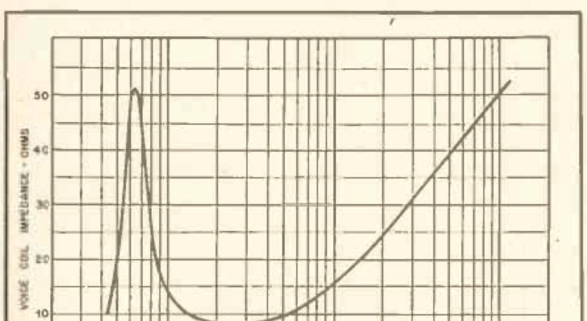


Fig. 9-6. Electrical voice-coil impedance of typical 8-ohm speaker. After F. Langford Smith.

HANDBOOK [*from page 34*]

which is decoupled and remains at rest during purely treble stimulation.

Analysis of the circuit of (B) in *Fig.* 9-5, one of the possible variations of the two-cone, single-voice-coil design, is very similar, and is left to the reader as an exercise in using dynamical analogies.

Distribution of mass at different frequencies may also be achieved by the use of separate speakers. The frequency spectrum is divided into two or three parts and a speaker with appropriate mechanical characteristics is assigned to cover each band. These speakers may be mounted on the same axis, which gives the assembly the title of coaxial speaker.

The Magnetic System of the Speaker

After the suspended mechanical system of the speaker has been made suitable, to a greater or lesser degree, for forced vibration over a given band of frequencies, an electro-magnetic system for converting the electrical signal into mechanical force is required. The fixed magnetic field in which the voice coil is placed should be as intense as possible. The greater the magnetic flux of this field the more efficient the conversion, and the more effective will be electrical damping. It is also necessary that the field be uniform over the area through which the voice coil will move, so that a constant relationship can exist between the instantaneous amplitude of the signal and the magnetomotive force applied to the voice coil.

The usual magnetic structure is of the type appearing in *Fig.* 9-1, where only the slug is made of magnetic material. The field path between the north and south pole of the slug is directed by the U-shaped iron structure and the pole piece of mild steel. The low reluctance of this magnetic circuit, compared to that of air, confines almost all the lines of force to the metallic path, and the voice-coil gap then receives the full concentration of lines when they must cross the gap to complete the circuit. Other types of magnet structure are used, but aside from questions of cost the final merit of the structure is judged by the magnetic flux produced in the gap, and its uniformity over the path of voice-coil excursion. The strength of the magnetic field at the gap is determined by the material and weight of the slug, the degree to which the field in confined to the metallic circuit and gap by the magnet structure, the size of the gap, and the saturation limit of the steel.

Some years ago really powerful magnets could be produced only by field coils wound on soft iron cores. With modern magnetic compounds made of iron, aluminum, cobalt, nickel, and a small amount of copper (Alnico V) the permanent magnet type of slug is able to produce fields of high intensity. Earlier types of $Alnico_4$ designated by lower numbers, produce weaker fields. A typical inexpensive "console" speaker of 12-inch diameter uses a 6.8 oz. Alnico V slug. Quality 12-or 15-inch speakers may use Alnico V magnets of several pounds.

The gap is made as small as can be afforded without danger of rubbing. The voice coil must therefore not warp easily, and the spider must have maximum radial rigidity to keep the coil in the narrow path prepared for it.

The Electrical System of the Speaker

Some years ago high-impedance speaker voice coils, connected directly into the output a. c. plate circuit, were used. High-impedance voice coils have one great advantage, in that the need for a matching output transformer—the most costly and critical part of an audio amplifier—is eliminated. The use of this type of voice coil was abandoned, however, for the greater convenience of low-impedance coils, which used fewer turns and heavier wire. Recently the high-impedance design has been revived, and new output circuits make possible lower requirements for voice-coil impedances.

The typical modern voice coil has a rated impedance of from 2 to 16 ohms. The common 5-inch table radio speaker has an impedance of 3 to 4 ohms, and large speakers are rated at 8 ohms or higher. The d. c. resistance of the wire is usually about three-fourths of these figures.

The value of the rated or nominal impedance represents the actual electrical impedance of the loudspeaker at about 400 cps and at that frequency only. The effective electrical impedance presented to the amplifier at other frequencies varies considerably. It is strongly influenced by what is called the *motional impedance* of the speaker, and the electrical inductance of the voice coil presents an increased impedance to signals of higher frequency. (See *Fig.* 9-6.)

If the voice coil were clamped so that it could not move the speaker would have an impedance, at a particular frequency, referred to as the *blocked impedance*. When the voice coil is allowed to move in the magnetic field it becomes the armature of an electric generator, and a back electromotive force is produced, opposing the input signal voltage. Effectively, then, it is more difficult for the source to send current through the voice coil, since back e.m.f. must be overcome in addition to the voice coil impedance, and the source "sees" an increased impedance between the speaker terminals. The increase of impedance may also be described in terms of Ohm's law; for the same signal voltage applied to the speaker, less current will flow. This is illustrated in *Fig.* 9-7.

The increase is the value of the motional impedance. Since in a given speaker it is determined by voice-coil velocity, it is affected by all the components of the mechanical impedance, and of the acoustic impedance reflected into the speaker mechanical system, that influence this velocity. It is a maximum at speaker resonance, where voice-coil velocity is greatest.

The variation in amplifier load indicated in *Fig.* 9-6 has a serious effect on performance at different frequencies. Amplifier design which incorporates a very low source impedance, and a mounting which affords good acoustic loading for the cone, will counteract this effect to a large degree.

Part II will appear next month.

A MONTHLY SUMMARY of product developments and price changes of radio electronic-television parts and equipment, supplied by United Catalog Publishers, Inc., 110 Lafayette Street, New York City, publishers of Radio's Master.

These REPORTS will keep you up-to-date in this ever-changing industry. They will also help you to buy and specify to best advantage. A complete description of most products will be found in the Official Buying Guide, Radio's Master—available through local radio parts wholesalers.

Recording Equipment, Speakers, Amplifiers, Needles, Tape, Etc.

ELECTRO-VOICE—Increased price on Model 6-HD diffraction horn to $15.00 net.

FAIRCHILD RECORDING EQUIP.—Added Model 650-C preamplifier at $47.50 . . . Model 651-B power supply at $51.00 net, and Model 652-C preamplifier at $47.50 net. Decreased price on Model 620-CL power amplifier to $190.00 net.

GARRARD SALES—Discontinued multispeed transcription turntable Model 201/B5.

GENERAL ELECTRIC—Added Model UPX-009, pickup and transcription arm at $9.33 net . . . Model RPX-051 triple-play variable-reluctance cartridge at $5.28 net, and Model RPX-042 variable-reluctance cartridge at $4.35 net. Discontinued Model RPX-046 broadcast type variable reluctance cartridge.

LOWELL MANUFACTURING CO.—Added "The Richmond" series of wall-type speaker baffles. Decreased price on Model B-24 hi-fidelity decorative grille to $10.50 net.

MAGNECORD—Discontinued Model PT7-A recorder mechanism for portable, rack or cabinet models . . . Model PT7-AX, same as Model PT7-A less case . . . Model PT7-CC, console combination.

PRECISION ELECTRONICS—Decreased price on Model 100-BA basic amplifier to $41.25 net, and Model 215-BA high-fidelity triode amplifier to $99.50 net. (West coast prices slightly higher).

REEVES SOUNDCRAFT—Added Soundcraft 45-r.p.m. recording disc at $.66 net.

MARK SIMPSON MFG.—Increased prices on No. 52 series of tape recorders.

Test Equipment

RADIO CITY PRODUCTS—Added Model 345 super vacuum-tube voltmeter at $47.50 net, and Model 8873 TV servishop unit at $139.95 net. Discontinued Model 664 V.T. voltmeter . . . Model 449A pocket multitester, and Models 447BK and 447BPK multitester kits.

R.C.A.—Increased price on Model WO-88A, 5-in. oscilloscope to $169.50 net.

Tubes—Receiving, Television, Special Purpose, etc.

GENERAL ELECTRIC—Added germanium diodes 4JA1A1 at $1.95 net . . . 4JA1A2 at $3.85 net . . . 4JA1A3 at $4.80 net . . . 4JA2A4 at $5.30 net . . . 1N81 at $4.35 list and G7G at $2.00 list. Discontinued G-10 series of transistors (G-10, G-10A, G-10B and G-10C).

RAYTHEON—Added special purpose tubes CK5670 at $7.00 net . . . CK5750 at $3.25 net . . . CK6212 at $7.50 net . . . CK6247 at $14.65 net. Also added germanium junction transistors CK721 at $12.50 net, and CK722 at $7.60 net.

SYLVANIA—Added TV picture tube 21ZP4A at $40.00 net . . . special purpose tube 6BF7W at $4.45 net. Also added radio receiving tubes: 6T4 at $3.55 list . . . 6BQ7A at $3.20 list . . . 6BK5 at $2.45 list . . . 12B4 at $2.00 list. Discontinued sub-miniature tubes 6BF7 and 6BG7 and receiving tube 6BQ7. Increased price on germanium crystal diodes 1N60 to $.75 net and 1N105 to $.75 net.

IF YOU ARE MOVING

Please notify our Circulation Department at least 5 weeks in advance. The Post Office does not forward magazines sent to wrong destinations unless you pay additional postage, and we can NOT duplicate copies sent to you once. To save yourself, us, and the Post Office a headache, won't you please cooperate? When notifying us, please give your old address and your new address.

Circulation Department
RADIO MAGAZINES, INC.
Mineola, N. Y.
P. O. Box 629