OXFORD TECHNICAL HANDBOOKS

FIRST PRINCIPLES OF RADIO

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FIRST PRINCIPLES OF RADIO

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PREFACE

In the preparation of First Principles of Radio the aim of the author has been to present the basic subject matter of the science in a manner that is compact, up-to-date, and well within the grasp of the student of average ability. Attention is called particularly to the following outstanding features and devices which will, it is hoped, help the book achieve the end desired.

Scope and Content: In the main, this book closely follows the official outline prepared by the United States Office of Education for use in the so-called pre-induction training courses. Though the sequence of topics differs slightly from that in the publication just mentioned, nevertheless no important items have been omitted from this present volume. Indeed, a number that do not appear in the government manual are included here.

Since any treatment of radio must take for granted some knowledge of the principles of electricity, ample discussion of that topic has been presented. Following the discussion of electricity and its behavior under various circumstances, the student is made acquainted with the general principles of electronics. That done, he is introduced, successively, to the essential parts of the radio receiving set and their respective functions. Electromagnetic waves, their production, and their relation to radio- and audio-frequency amplification, are next taken up in detail. The book concludes with a discussion of radio broadcasting, a brief explanation of television, and a suggestive chapter on the possible use of radio in other fields.

Illustrations and Diagrams: Extensive use of visual aids in the form of illustrations and diagrams lightens the student's labors and hastens his progress. Clear, well-made, and carefully labeled line drawings acquaint him with instruments and other devices commonly used by the radioman. The more abstract principles of the science are made clear by means of graphs and similar drawings, clearly thought out and well executed.

An outstanding feature of this text is the abundance of wiring diagrams. Beginning with an explanation of electrical symbols and their use, especially their use in radio work, the student is gradually familiarized with all the more common of these. Thus, at every stage of study, he is equipped to understand whatever he may read elsewhere about the topic under consideration. Besides, he trains himself by using these symbols throughout his daily work. Although a knowledge of mathematics is essential to the proper understanding of radio, nevertheless this book takes for granted only the student's ability to make numerical substitutions in formulas.

Exercise Material: A large selection of exercise material is placed at the conclusion of every chapter. Well-planned questions help the student to assure himself that he understands what he has read. From time to time he is called upon to prepare simple sketches that make clear how a device functions, or a wiring diagram that illustrates a certain hookup. In instances he is asked to perform some simple experiment; in others, to make an independent observation of a particular electrical phenomenon.

Clear, Concise, and Complete: Despite the character of the subject matter treated, this book presents the material with extreme clarity. Both language and method of treatment are adapted to the needs of beginners. Omission of irrelevant topics and inconsequential detail, and strict attention to the concise presentation of indispensable fundamentals, combine to make this handbook both thorough and complete. For this reason it is well suited to the needs of those who want to be securely grounded in the science.

The author is grateful to the many persons and organizations that provided him with material of various kinds.

T. J. W. O'Neil

New York,
March, 1944.

CONTENTS

FIRST PRINCIPLES OF RADIO

CHAPTER 1

PRINCIPLES OF ELECTRICITY

The Electron Theory.—Modern notions concerning electricity are based upon the Electron Theory. This theory assumes that all matter is electrical. It asserts that the infinitesimal particles that make up all substances are positive and negative charges. The negative charge is known as the *electron*. A body that shows no charge possesses sufficient electrons to offset the effect of the positive charges. A body that is negatively charged has an *excess* of electrons, while a body that is positively charged has a *deficiency* of electrons. This theory has been amply verified by experiment. In fact, the mass of the electron has been precisely determined as 9.1×10^{-28} grams, or 3.3×10^{-29} ounces. Although it is impossible for us to appreciate such a small mass, it is plain that the loss or gain of even a large number of these electrons by a body would not at all affect its weight. At the present time, many other types of infinitesimally charged particles are believed to exist. A description of these, however, is unnecessary for our discussion.

The Nature of an Electric Current.—When electrical charges are in motion, the amount of the charge that flows per unit of time past a given point is called the *electric current*. In the case of solids, the only charges that move are the electrons. The flow of electrons is called the *electronic current*. Before the Electron Theory was formulated, it was thought that the current flowed in a direction opposite to that of the movement of the electrons. Today this fictitious current is called the *traditional current*, or simply, the *current*. Although it is realized that the actual flow of electricity does not take place in the direction of this latter current, nevertheless this is almost universally accepted as the direction of the current. Special care should be taken to note that electrons actually flow in a direction *opposite* to that of the current.

What Is a *Conductor?*—The flow of electricity can best be visualized by comparing it to the flow of water. We know that water usually flows through pipes. Similarly, electricity flows through wires. The wires are known as *conductors*. Just as pipes offer resistance to the flow of water, so conductors also offer resistance to the flow of electricity. In the case of conductors, this resistance is called the *electrical resistance.*

The Meaning of *Resistance.*—It is apparent that the larger the cross-sectional area of a pipe, the less its resistance will be; the longer the pipe, the greater will be the resistance. This applies in the same fashion to the resistance of electrical conductors. The resistance of a wire varies directly as its length, and inversely as its cross-sectional area. The resistance of a wire also depends upon the characteristics of the material out of which it is made. This latter factor is known as the *specific resistance.* The following formula expresses the resistance of a wire at constant temperature:

$$R = \frac{KL}{A},$$

where R = the resistance, usually measured in ohms; L = the length in feet; A = the area in circular mils (a *circular mil* is the area of a wire one-thousandth of an inch in diameter), and K = the specific resistance in ohms per mil foot (a *mil foot* is a wire 1 foot long and 1 mil in diameter). Substances that have a small value for K are called good conductors; examples of these are silver, copper, and aluminum. On the contrary, those substances that have a very high value for K are called nonconductors, or *insulators;* examples are glass, paper, paraffin, and wood. The table below gives the specific resistance of a number of common substances.

TABLE I

Material	Specific Resistance Ohms per mil foot at 68° F.
Aluminum	17.0
Brass	42.0
Constantan	295.0
Copper	10.4
Silver	10.0 to 11.0
Tungsten	33.2

An inspection of the table shows why copper is commonly used for conductors, and why constantan is used for resistors. A *resistor* is simply a wire that has a very high resistance. All pure metals have a higher resistance at higher temperatures; in the case of carbon and some alloys, however, the resistance decreases with an increase of temperature.

What *Potential Difference* Means.—Again using our analogy of the flow of water through a pipe, it is not sufficient merely to have the pipe and the water, in order to have a current of water flow through the pipe. It is also necessary to have a *difference of pressure* between the ends of the pipe. With the flow of electricity, the situation is likewise similar to that of the flow of water. This difference in electrical pressure is called the *potential difference.*

Electrical Units and Their Measurement.—Plainly, then, three factors are essential to the flow of electricity. The first factor is the quantity of electricity that flows past a given point per unit of time; this is called the *current* and is measured in *amperes.* An *ammeter* is used for measuring the current. The second factor is the *potential difference,* which is measured in *volts.* A *voltmeter* is used for measuring the potential difference. The third factor is the *resistance,* which is measured in *ohms.*

The Sources of Potential Difference.—A device designed for producing potential difference is called an *electric generator.* Its function is to change various other forms of energy into electrical energy. A generator that changes *chemical* energy into electrical energy is commonly known as a *cell.* Any two dissimilar metals placed in a dilute solution of an acid, base, or salt will produce a potential difference. The dry cell is based on this principle, but the solution, known as the *electrolyte,* does not spill because it is held by some absorbent material. The electrodes are made of zinc and of carbon, respectively, and the electrolyte is ammonium chloride. The potential difference produced, often called the *electromotive force* (e.m.f.), is about 1.5 volts. Cells of this type are known as *primary cells* because when most of the available energy has been utilized the cell must be discarded.

The general principle of a secondary cell, or so-called *storage cell,* is the same as that of a primary cell, with this exception: When the cell has given up most of its available energy, then, instead of discarding the cell, electrical energy is sent back into it and this restores the cell to its original condition. This latter process is known as *charging.* The most common type of storage cell is the lead storage cell. It has one electrode of spongy lead and the other of lead peroxide. The electrolyte is dilute sulfuric acid. The lead peroxide is packed into small pockets in a frame-work, or grid, made of an alloy of lead. This is the positive plate. The spongy lead, packed into a similar grid, forms the negative plate. The electrolyte, dilute sulfuric acid, is contained in a glass or rubber jar. The number of amperes delivered by the cell, multiplied by the number of hours required to discharge it completely, is known as the *ampere-hour capacity*. In order to achieve a large ampere-hour capacity, it is necessary to make the area of the plates very large. This is accomplished by using a number of plates, so placed that the positive and negative ones are arranged alternately. Sheets of insulating material placed between them prevent short-circuiting. The e.m.f. of a lead storage cell is approximately 2.05 volts.

The Dynamo-Generator.—Nowadays, however, cells and batteries are rarely employed, except for portable use. The most commonly used generators are those that depend on converting *mechanical* energy into electrical energy. Such a device is called a *dynamo-generator*, or simply a *dynamo* or a *generator*. These are of two general types. The first type is known as a direct-current (*d. c.*) generator because it supplies a steady current; the other type produces an alternating current (*a. c.*). For an understanding of both the direct-current and the alternating-current dynamos, a review of magnetic fields and their relation to electricity is necessary. This is presented below.

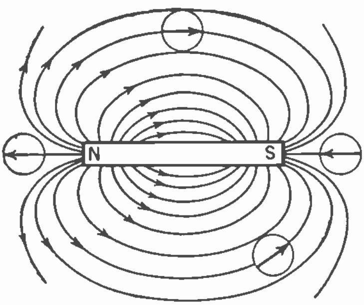


Fig. 1.

Magnets and Their Action.—That end of a magnet which turns toward the north is called the north-seeking pole, or the north pole (N). Similarly, the end that turns toward the south is called the south-seeking pole, or the south pole (S). The action of magnetic poles is very similar to that of electric charges. Two north poles repel each other, but a north pole attracts a south pole, and vice versa. This gives us the law of magnetic poles, which is as follows: *Like poles repel each other, and unlike poles attract each other.* The importance of magnetic poles is their ability to act upon other magnetic poles and upon magnetic substances. The space in the vicinity of a magnetic pole is called a *magnetic field of force.*

Magnetic Fields of Force.—The properties of a magnetic field are represented by lines of force in the same way that electric lines of force are used for visualizing the electric field of force. The direction of a line of force at a given point is the direction of the force that the field would exert upon a north pole placed at this point. In order to determine this fact, a small compass needle is placed in the field at the point to be investigated. The direction in which the compass needle points is the direction of the field as shown by Fig. 1. The fields in the vicinity of like poles and unlike poles are shown by Figs. 2 and 3, respectively.

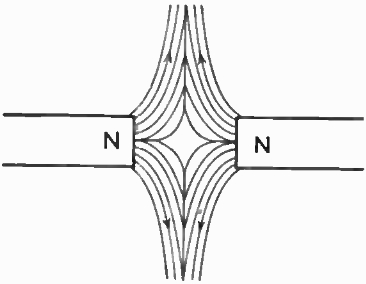


Fig. 2.

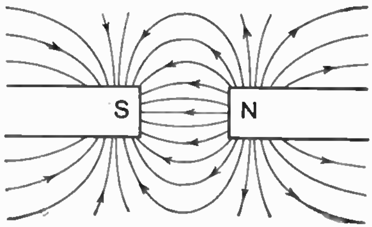


Fig. 3.

The Nature of Electromagnetism.—During the early part of the nineteenth century it was discovered that when a current flows in a wire, a magnetic field is produced in the neighborhood of the wire. Suppose that a vertical wire is run through a horizontal glass plate, and that iron filings are then sprinkled upon the glass. When a strong current is sent through the wire, the filings arrange themselves in concentric circles. The actual direction of the lines of force may be determined by means of a compass needle. Fig. 4 shows the magnetic field about a wire that carries a current. It must be kept in mind, however, that *the magnetic field exists only when the current is flowing.* When the current ceases to flow, the magnetic field disappears. The strength of the field is proportional to the amount of

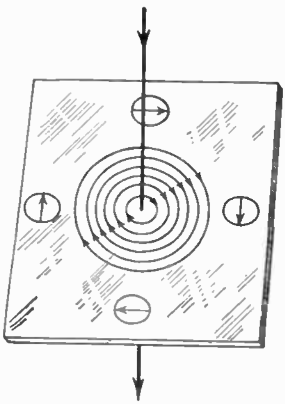


Fig. 4.

the current. A convenient method for determining the direction of the magnetic field is shown by Fig. 5. The right hand grasps the wire so that the thumb points in the direction of the current; the fingers then encircle the wire in the direction of the lines of force. This is known as the *right-hand rule* for determining the direction of the magnetic field caused by an electric current. This rule may also be used for determining the direction of the current when the direction of its magnetic field is known.

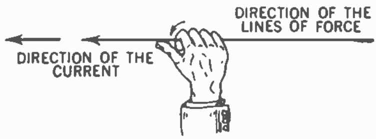


Fig. 5.

The Electromagnet and Its Work.—If a wire is wrapped around an iron bar, and a current is then sent through the wire, the iron bar behaves as though it were a bar magnet having a north pole at one end and a south pole at the other. Such an arrangement is shown by Fig. 6. This form of magnet is known as

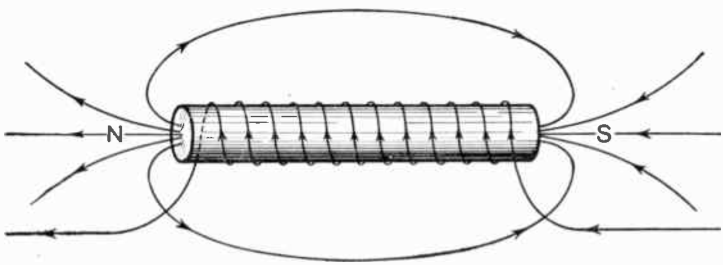


Fig. 6.

an *electromagnet*. The polarity of this type of magnet can also readily be determined by means of another right-hand rule. Grasp the magnet with the right hand, fingers pointing in the direction of the current; the thumb then points toward the north pole.

Electromagnets have many practical applications. In addition to being used for lifting heavy pieces of iron, as is true of large lifting magnets, they are also used for supplying the magnetic field for dynamo-generators and motors, as shown for the bipolar dynamo in Fig. 7. Many automatic devices depend upon the electromagnet for their operation.

The Magnetic Flux.—The strength of the magnetic field, known as the magnetic field intensity, is represented by the symbol H. It is measured in *oersteds*. If we examine the magnetic lines of force in Fig. 8, we notice that they form a closed loop. This is similar to the current in the electric circuit. In the magnetic circuit, the total

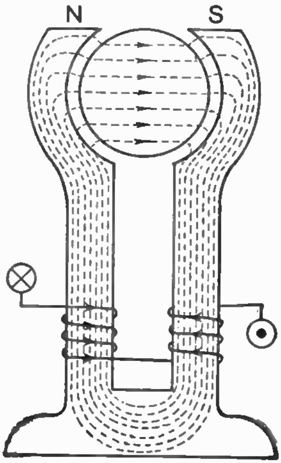


Fig. 7.

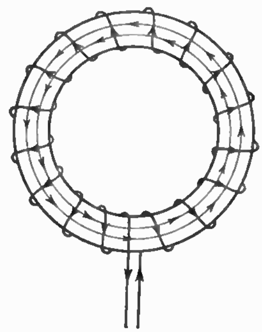


Fig. 8.

number of lines threading the circuit is called the *magnetic flux*. It is represented by the symbol ϕ (pronounced *fy*), and its unit is the *maxwell*.

Magnetomotive Force.—In the case of the electric current, a potential difference, or electromotive force, is required for establishing the current. To produce a magnetic flux, a magnetic pressure is necessary. This is called the *magnetomotive force* and is designated by m.m.f.; it is measured in *gilberts*. The number of gilberts is equal to 0.4π, or 1.26, times the product of the amperes flowing in the coil and the number of turns of wire in the coil. The product of amperes and number of turns is known as the *ampere turns*. Hence m.m.f. $= 1.26 \times$ ampere turns.

The Meaning of *Reluctance*.—In the case of the electric current, as we have seen, there is always a resistance to the flow of electricity, due to the characteristics of the conductor. In the magnetic circuit there is a similar resistance known as the *reluctance*. It is that property of the medium which opposes the establishment of the lines of force. Like electrical resistance, it also depends upon three factors: (1) the length of the medium, (2) its cross-sectional area, and (3) its nature. The reluctance is directly proportional to the length, and inversely proportional to the cross-sectional area. The relationship is expressed by

$$\mathbf{R} = \frac{L}{\mu A},$$

where $\mathbf{R}$ = the reluctance, L = the length, A = the cross-sectional area, and μ = a property of the medium known as its *permeability*.

***Permeability* Explained.**—The magnetizing force, H, is the magnetic pressure necessary for establishing a given number of lines through 1 centimeter of the given circuit. The magnetizing force is measured by the *oersted*, which is 1 gilbert per centimeter. The flux density, B, is defined as the number of lines per square centimeter established in the given substance. The unit of flux density is the *gauss*. The ratio of B to H is equal to μ, the permeability. Hence $\mu = \frac{B}{H}$. As was previously indicated, μ is a measure of the ease with which a given substance can be magnetized. Air and all other nonmagnetic substances have a permeability of 1.0. Soft iron has a value in the order of thousands. This means that for the same magnetizing force, a magnetic flux thousands of times greater can be established in a given circuit if soft iron is used instead of air. For this reason an attempt is always made to use a substance of large permeability in a magnetic circuit, and to avoid air or any other nonmagnetic substance so far as possible. Fig. 9 shows a modern ironclad electromagnet. Note that the greater part of the flux path is in the iron. In designing dynamos, motors, transformers, and other electromagnetic devices, a similar attempt is made to keep the flux in the iron.

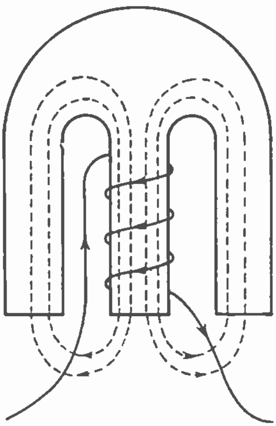


Fig. 9.

Significance of *B-and-H* Curves.—The permeability of a magnetic substance is not the same for all magnetizing forces. A graph of the relationship of B and H for some commonly used substances is given in Fig. 10. This graph is called a *B-and-H curve*. It has already been noted that $\mu = \frac{B}{H}$. Hence μ can be determined for any value of H by obtaining the corresponding value of B from the graph. Careful examination of the graph will show that for each curve there is a point beyond which there will be an appreciable increase in B only for a large increase in H.

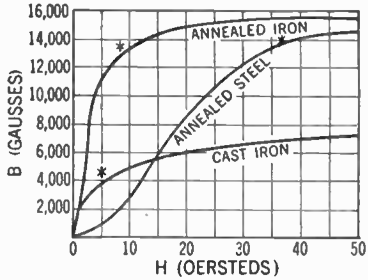


Fig. 10.

This point is called the *saturation point*. It is marked with an * on each curve. In practice, no attempt is made to magnetize the iron beyond this point, since doing this would require a disproportionate amount of energy in order to obtain the result achieved.

The Meaning of *Retentivity*.—Just as magnetic substances vary in the ease with which magnetism can be set up in them, so they also differ as to their capacity to retain the magnetism, once it has been established. This latter property of a magnetic substance is called its *retentivity*. A permanent magnet should have a very large retentivity. Hardened steel has this property. For this reason the magnets used in telephone receivers, ammeters, voltmeters, and galvanometers are made of hardened steel. In some cases, however, a large retentivity may be a decided disadvantage. Examples of this are all kinds of alternating-current machinery (transformers, dynamos, motors, and such) which depend upon magnetic fields that change with the alternations of the current. The property of retentivity is a serious disadvantage in any of these cases. Hence substances having small retentivity are used for the magnetic materials in this type of machinery.

Law of the Magnetic Circuit.—We have already seen that in order to set up a magnetic flux it is necessary to have a magnetomotive force. But, due to the magnetic medium, there is an opposition to the setting-up of this flux. This latter factor is the reluctance. There is a simple relationship between these quantities. It is expressed as ϕ (maxwells) $= \frac{m.m.f.}{R}$ (gilberts), where ϕ is the total magnetic flux, *m.m.f.* is the magnetomotive force, and R is the reluctance.

Magnetic Substances.—Although iron and steel are the most important magnetic substances, both nickel and cobalt also have a fair permeability. The value for these substances is about two hundred times as great as the permeability of nonmagnetic substances, but they have only about 5 per cent of the permeability of iron. In recent years a number of alloys that possess extremely high permeability have been developed. An example of such an alloy is *permalloy*, which, under certain circumstances, has a permeability of about 9,000. The composition of permalloy is approximately 78.5 per cent nickel and 21.4 per cent iron. Many similar alloys that possess unusual magnetic properties are constantly being developed.

Magnetic Shielding.—If a piece of soft iron is placed in a magnetic field, the magnetic lines will tend to crowd through the piece of iron rather than pass through the air because iron has a much greater permeability than air. If such a piece of soft iron is placed in the vicinity of a bar magnet, the lines of force will be similar to those shown in Fig. 11. This principle is utilized in

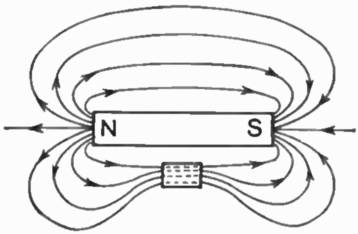


Fig. 11.

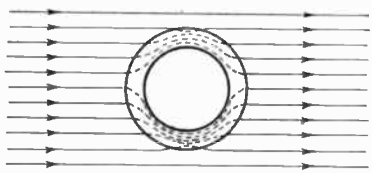


Fig. 12.

protecting regions from magnetic fields. Fig. 12 shows an iron ring placed in a uniform magnetic field. It will be noticed that there are no lines of force in the space within the ring. In order to protect a given region from magnetic fields, it may be surrounded by a substance of large permeability. This is known as *magnetic shielding*.

QUESTIONS

1. What are the two kinds of electricity?

2. Will two positive charges attract or repel each other?

3. What is the nature of the charge on an electron?

4. If the electric current in a wire is flowing east, in which direction are the electrons flowing?

5. Explain the difference between a *conductor* and a *resistor*.

6. Explain why copper is the material generally used for conductors.

7. Why must the resistance of an electric lamp be measured when the filament is hot?

8. Name the units of current, potential difference, and resistance.

9. If you want to measure a potential difference, what instrument must you use?

10. Although the specific resistance of aluminum is almost twice that of copper, many electric transmission lines are made of aluminum. Why?

11. If two strips of copper are placed in a dilute solution of H_2SO_4, and a voltmeter is connected to them, how many volts will the instrument read? **Ans.** 0.

12. Does the dry cell or the storage cell give the greater e.m.f.?

13. What instrument is used for testing the condition of the charge of a storage cell?

14. Draw a diagram that shows the magnetic field in the vicinity of two parallel bar magnets.

15. Explain some device which you have seen that depends upon an electromagnet for its operation.

16. Name a substance that has an extremely large permeability.

17. What is the unit of magnetomotive force?

18. If a compass needle is placed above a wire in which the current is flowing east, in which direction will the needle point?

19. Draw a diagram of a horseshoe electromagnet and on it indicate the poles of the magnet and the direction of the current.

20. Explain the nature of the magnetic field that surrounds a wire that carries an alternating current.

CHAPTER 2

DIRECT-CURRENT CIRCUITS

The Direct-Current (d.c.) Circuit.—In order for electricity to flow steadily in one direction, it is necessary to have a closed circuit. Electricity that flows in this manner is known as direct-current electricity; the circuit is called a direct-current (*d.c.*) circuit. In this chapter we shall study the characteristics of the direct-current circuit and the laws that govern it. We have already learned that three essential factors are associated with the flow of electricity: (1) the current, measured in *amperes;* (2) the potential difference, measured in *volts;* and (3) the resistance, measured in *ohms*. In order to establish a potential difference, we must have some source of e.m.f., such as a primary cell, a storage cell, a dynamo, or some other.

Electrical Symbols and Their Use.—In order to represent a circuit on paper, it would be impractical to draw a sketch of each of the various types of electrical device every time we wished to show it. For this reason, conventional symbols have been adopted for the purpose of representing most of the commonly used electrical devices. With slight exceptions or modifications, these symbols are almost universally used. Those given on page 13 are the ones that we shall use throughout this book. Whenever a new symbol occurs in the text, reference should always be made to this chart.

How Wiring Diagrams Are Used.—By making use of these electrical symbols, it is a relatively simple matter to represent clearly and concisely even very complicated circuits. Whenever possible, a circuit diagram should be drawn. Fig. 14 shows a simple circuit consisting of a battery, a variable resistance or rheostat, a lamp, a switch, and an ammeter.

The Series Arrangement of Cells.—If the positive terminal of one cell is connected to the negative terminal of the next, the cells are said to be arranged *in series*. A group of five dry cells,

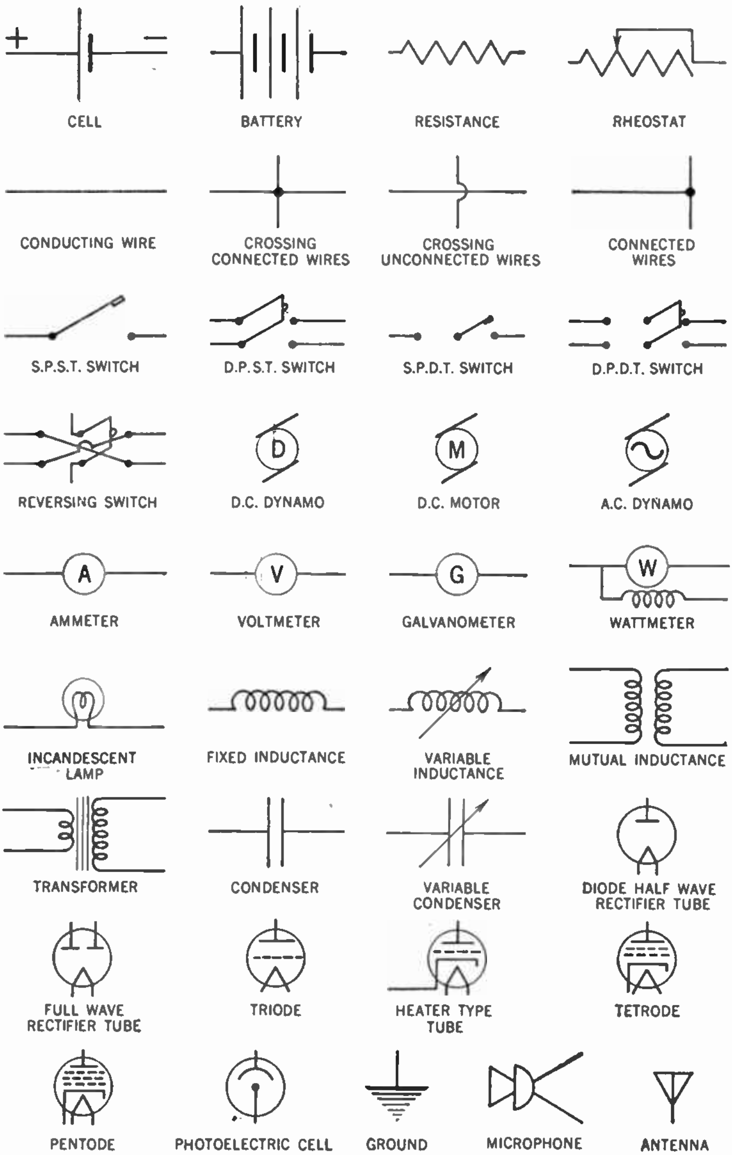


Fig. 13.—Some of the More Commonly Used Electrical Symbols.

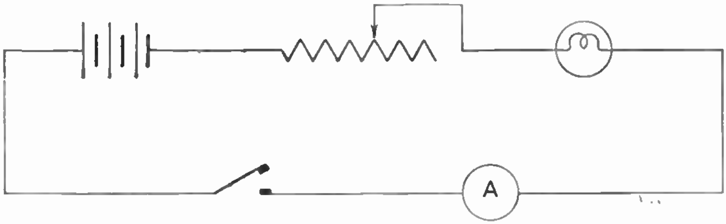


Fig. 14.

connected in series, is shown in Fig. 15, together with the wiring diagram of the connection. The e.m.f. of such a combination is equal to the sum of the e.m.f.'s of the individual cells. If the cells in the illustration were dry cells having an e.m.f. of 1.5 volts each,

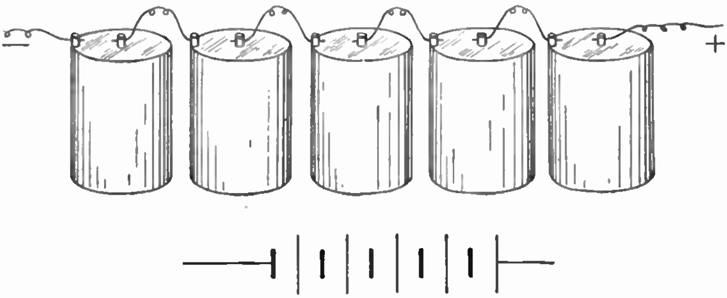


Fig. 15.

the total e.m.f. would be 5 × 1.5 or 7.5 volts. This rule likewise applies to any other source of potential differences when arranged in series. Thus

$$E = e_1 + e_2 + e_3 + e_4 + e_5$$

Arrangement of Resistances in Series.—An arrangement of resistances in series is shown in Fig. 16. When resistances are

Fig. 16.

connected in series, the combined resistance is the sum of the individual resistances. If the resistances just referred to were

3, 5, 6, and 9 ohms, respectively, then the combined resistance would be

$$R = R_1 + R_2 + R_3 + R_4,$$

or,

$$R = 3 + 5 + 6 + 9 = 23 \text{ ohms}.$$

The Parallel Arrangement of Cells.—*In parallel*, cells are so arranged that the positive terminals of all are connected together, and, likewise, the negative terminals. This group of cells is then connected to the rest of the circuit as though it were a single cell. Fig. 17 shows an arrangement of cells in parallel,

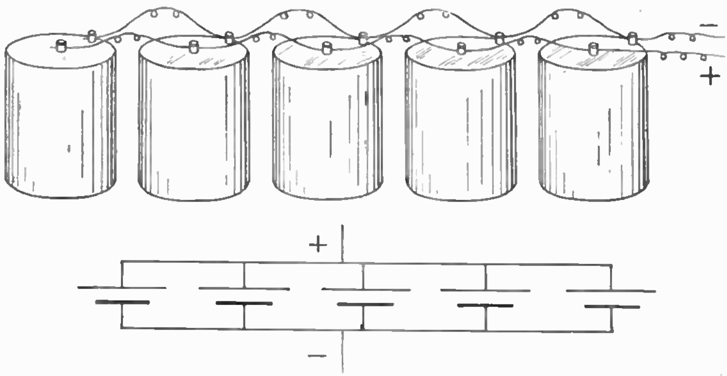


Fig. 17.

together with the wiring diagram. It is good practice to connect in parallel only cells having the same e.m.f. The combined e.m.f. of such an arrangement is the same as that of one cell, regardless of how many cells may be connected in parallel. If the cells in the illustration were dry cells, and if each had an e.m.f. of 1.5 volts, nevertheless the combined e.m.f. of the five cells would still be only 1.5 volts.

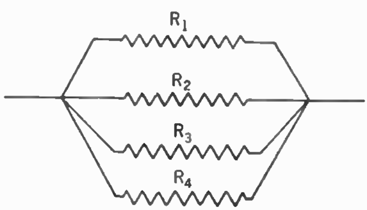


Fig. 18.

The Parallel Arrangement of Resistances.—Just as cells may be connected in parallel, so also resistances may be connected in parallel. Four resistances in parallel are shown in Fig. 18.

The total resistance of such an arrangement is given by the formula

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}.$$

If the values of these resistances are 2, 3, 6, and 12 ohms, respectively, the combined resistance will be

$$\frac{1}{R} = \frac{1}{2} + \frac{1}{3} + \frac{1}{6} + \frac{1}{12} = \frac{13}{12}. \text{ Hence, } R = \frac{12}{13} \text{ ohm.}$$

In finding R, special care should be taken not to forget to invert $\frac{1}{R}$.

In the problem above, $\frac{1}{R} = \frac{13}{12}$, but $R = \frac{12}{13}$ ohm.

Ohm's Law and Its Application.—In a direct-current circuit there is a very simple relationship between the current, the potential difference, and the resistance in the circuit. This relationship is expressed by *Ohm's law*, which states that the current in amperes flowing in a circuit is equal to the potential difference in volts divided by the resistance in ohms. The formula is:

$$I \text{ (amperes)} = \frac{E \text{ (volts)}}{R \text{ (ohms)}}.$$

It is well to keep in mind that this law applies not only to the entire circuit but also to any part of it, provided that the factors taken are associated with the part of the circuit under consideration. It is useful to know that in addition to the form $I = \frac{E}{R}$, Ohm's law may also be written in two other ways. These are: $E = IR$ and $R = \frac{E}{I}$. A few simple problems will help you to understand how Ohm's law is used.

PROBLEM 1

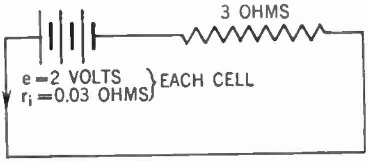


Fig. 19.

Three series-connected cells are arranged in series with a resistance. Each cell has an e.m.f. of 2 volts, an internal resistance of .03 ohm, and the external resistance is 3 ohms. It is desired to find the current. A wiring diagram of this circuit is shown by Fig. 19.

According to Ohm's law, $I = \frac{E}{R}$. Since the cells are in series, $E = 3e = 3 \times 2 = 6$ volts. The internal and external resistances are in series. Hence

$$R = 3r_i + r_e = 3 \times 0.03 + 3 = 3.09 \text{ ohms.}$$

$$I = \frac{6}{3.09} = 1.94 \text{ amperes.}$$

It is important to realize that the current in every part of the circuit is 1.94 amperes, and that it is flowing at the same time in all parts of the circuit. If the potential difference across the 3-ohm resistance were required, then Ohm's law could again be used, but this time only for that part of the circuit that contains the 3-ohm resistance. Whenever the potential difference is to be found, Ohm's law may be written $E = IR$. In this problem, since the current is 1.94 amperes, and the resistance is 3 ohms, then $E = 1.94 \times 3 = 5.82$ volts.

***Terminal Voltage* Explained.**—In the above problem, the current through any cell is 1.94 amperes. The potential difference due to the resistance of the cell is $E = Ir_i = 1.94 \times 0.03 = 0.058$ volts. This potential difference reduces the effective potential difference at the terminals of the cell. This latter potential difference is called the *terminal voltage* in order to distinguish it from the e.m.f. of the cell. Therefore, in order to find the terminal voltage of a cell, the potential difference due to internal resistance must be subtracted from the e.m.f. That is, $TV = EMF - Ir_i$, where TV is the terminal voltage and r_i the internal resistance of the cell. In the above problem, $TV = 2 - 0.058 = 1.942$ volts. The e.m.f. of a cell depends only upon the chemical composition of its electrodes and upon the electrolyte. So long as these remain the same, there is no change in the e.m.f. of the cell. The terminal voltage of a cell depends upon the current being delivered by the cell and upon the cell's internal resistance. The greater the current being delivered by the cell, the smaller will be the terminal voltage. As a cell becomes older, the internal resistance becomes greater, and consequently the terminal voltage becomes smaller. In the case of very small currents, the difference between the e.m.f. and the terminal voltage is not very great. Because of this fact, a voltmeter test does not give a good indication of the condition of the cell under normal working conditions.

The Series Circuit.—When all parts of a circuit are connected in series, it is then known as a *series circuit.* The solution of such a circuit makes use of Ohm's law, the combined e.m.f. of the cells in series, and the combined resistance of the resistances in series. The following problem illustrates such a situation.

PROBLEM 2

Three dry cells are connected in series, together with three resistances in series. If each of the three cells has an e.m.f. of 1.5 volts, and also an internal resistance of 0.2 ohm, and if the three resistances are 1, 3, and 6 ohms, respectively, what is the current? The wiring diagram is shown by Fig. 20.

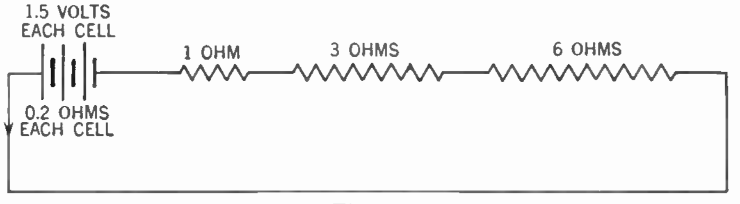


Fig. 20.

The total e.m.f. of the cells is $E = 3e = 3 \times 1.5 = 4.5$ volt. The total resistance is

$$R = 3r_i + r_1 + r_2 + r_3 = 3 \times 0.2 + 1 + 3 + 6 = 10.6 \text{ ohms}.$$

It is important to observe that the internal resistance of the cells is included. In this case, since there are three cells, the resistance is 3×0.2 ohm. The current is

$$I = \frac{E}{R} = \frac{4.5}{10.6} = 0.42 \text{ amperes}.$$

PROBLEM 3

In Problem 2, what is the potential difference across each resistance, and what is the terminal voltage of the cell?

From Ohm's law,

$$E = IR.$$

Hence, for the 1-ohm resistance, $E = 0.42 \times 1 = 0.42$ volt;
for the 3-ohm resistance, $E = 0.42 \times 3 = 1.26$ volts;
for the 6-ohm resistance, $E = 0.42 \times 6 = 2.52$ volts.

The terminal voltage must equal the total potential difference outside the cell, or,

$$TV = 0.42 + 1.26 + 2.52 = 4.20 \text{ volts.}$$

The Parallel Circuit.—In parallel arrangements, the sum of the individual currents in the parallel branches must equal the total current in the circuit. Across all resistances that are in parallel, the potential difference is the same.

PROBLEM 4

Three resistances of 40, 60, and 120 ohms, respectively, are connected in parallel and supplied with 100 volts by a direct-current dynamo. Find the current in each resistance, and the total current supplied by the dynamo.

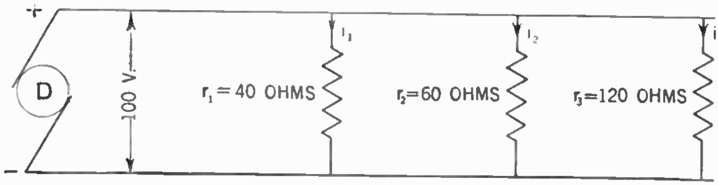


Fig. 21.

$$i_1 = \frac{E}{r_1} = \frac{100}{40} = \frac{10}{4} \text{ ampere;}$$

$$i_2 = \frac{E}{r_2} = \frac{100}{60} = \frac{10}{6} \text{ ampere;}$$

$$i_3 = \frac{E}{r_3} = \frac{100}{120} = \frac{10}{12} \text{ ampere.}$$

The total current is

$$I = i_1 + i_2 + i_3 = \frac{10}{4} + \frac{10}{6} + \frac{10}{12} = \frac{60}{12} = 5 \text{ amperes.}$$

Combination Series-Parallel Circuits.—Combinations of series and parallel connections may be made throughout the circuit. The method used for solving any such problem is to break the circuit down into parts that are either simple series or parallel arrangements, and then to use the method previously employed. Illustrations of general circuit calculations follow.

PROBLEM 5

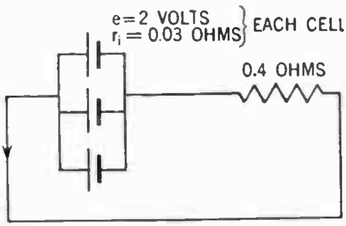


Fig. 22.

Three storage cells, each having an e.m.f. of 2 volts and an internal resistance of 0.03 ohm, are connected in parallel. A resistance of 0.4 ohm is then connected to this arrangement of cells. Find the current in the 0.4-ohm resistance and the potential across it. The total e.m.f. of all the cells is the same as for one cell; or,

$$E = e = 2 \text{ volts}.$$

The internal resistances of the cells are in parallel. Since all have the same value, therefore the total resistance of the cells is

$$\frac{r_i}{3} = \frac{0.03}{3} = 0.01 \text{ ohm}.$$

The total resistance of the circuit is

$$R = 0.01 + 0.4 = 0.41 \text{ ohm}.$$

Hence, according to Ohm's law,

$$I = \frac{E}{R} = \frac{2}{0.41} = 4.9 \text{ amperes}.$$

PROBLEM 6

Three storage cells, each having an e.m.f. of 2 volts and an internal resistance of 0.1 ohm, are connected in series. Three resistances of 2, 3, and 6 ohms, respectively, are connected together in parallel. The combination of resistances is connected in series to the storage cells. Find (*a*) the current delivered by the cells; (*b*) the potential difference across the resistances; and (*c*) the current through each resistance.

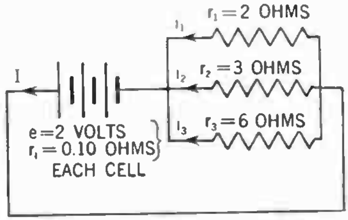


Fig. 23.

To find the combined resistance of the parallel arrangement,

$$\frac{1}{r} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3},$$

or

$$\frac{1}{r} = \frac{1}{2} + \frac{1}{3} + \frac{1}{6} = 1.$$

Hence

$$r = 1 \text{ ohm}.$$

From the formula for resistances in series, the total resistance of the circuit is:

$$R = 3(0.1) + 1 = 1.3 \text{ ohms}.$$

The total e.m.f. for cells in series is:

$$E = e_1 + e_2 + e_3 = 3(2) = 6 \text{ volts}.$$

From Ohm's law

$$I = \frac{E}{R} = \frac{6}{1.3} = 4.6 \text{ amperes}.$$

For the parallel branches, using Ohm's law in the alternative form,

$$e = Ir = 4.6 \times 1 = 4.6 \text{ volts},$$

which is therefore the potential difference across each of the parallel resistances.

Finally, using Ohm's law for each of the parallel resistances,

$$i_1 = \frac{e}{r_1} = \frac{4.6}{2} = 2.3 \text{ amperes};$$

$$i_2 = \frac{e}{r_2} = \frac{4.6}{3} = 1.5 \text{ amperes};$$

$$i_3 = \frac{e}{r_3} = \frac{4.6}{6} = 0.77 \text{ ampere}.$$

Kirchhoff's Laws Explained.—Although Ohm's law is quite general, and consequently applies to all direct-current circuits, nevertheless, in the ordinary form of it that we have been employing, one sometimes has difficulty in applying it to the solution of complicated circuits. On this account it has been found advisable to express Ohm's law in a different way. Kirchhoff did this by means of two simple laws. The first law states that, *at any point in a circuit, there is as much current flowing away from that point as there is flowing to it.* The second law states that *the algebraic sum of the IR-drops in any closed path in a circuit is equal to the algebraic sum of the e.m.f.'s impressed on the circuit in this closed path.* It will be noticed that the Kirchhoff laws seem strangely familiar. This is because we have been unconsciously using them in the simple problems we have thus far encountered.

Kirchhoff's first law may be readily understood. It is apparent that the number of electrons arriving at a given point must equal the number leaving that point, otherwise there would be an accumulation of charges that is not possible at a single point.

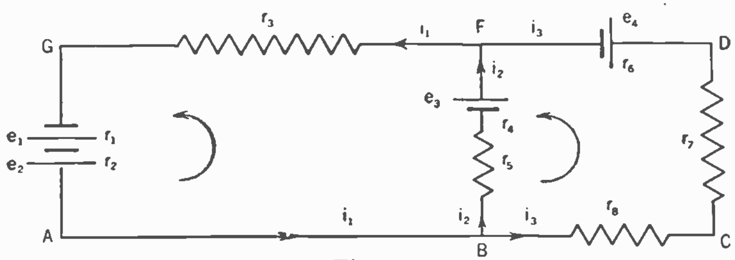


Fig. 24.

Kirchhoff's second law is as simple to understand as is the first, though somewhat more difficult to state clearly. An *IR*-drop is the potential difference between two points, brought about by the current that flows through the resistance between these two points. The *IR*-drop, as its name implies, is equal to the current multiplied by the resistance. The *direction* of the *IR*-drop is given by the direction of the current. If the *IR*-drop is in the same direction as you progress in the closed path, then the sign is taken as positive; if the direction is contrary to this, then the *IR*-drop is negative. In the case of the algebraic sum of the e.m.f.'s, the e.m.f. of a cell or generator that is in the direction of following the path is positive, and one that is contrary to this is negative.

The Application of Kirchhoff's Laws.—The circuit shown in Fig. 24 illustrates a problem that can best be solved by Kirchhoff's laws. The value of the e.m.f. of each cell and its resistance are given in the diagram. We are to find the currents in all parts of the circuit. Using Kirchhoff's first law at junction *B* or *F*,

$$i_1 = i_2 + i_3. \qquad (1)$$

From Kirchhoff's second law, and going around the path *ABFG* in a counterclockwise direction (as indicated by the curved arrow), the equation is

$$i_2r_5 + i_2r_4 + i_1r_3 + i_1r_1 + i_1r_2 = e_3 + e_1 + e_2. \qquad (2)$$

Also from the second law, going around path *BCDF* counterclockwise,

$$i_3r_8 + i_3r_7 + i_3r_6 - i_2r_4 - i_2r_5 = - e_4 - e_3. \qquad (3)$$

Since all the resistances and all the e.m.f.'s are known, the three currents can be found from these three equations. It is important to remember that when an e.m.f. is opposite to the direction of going around the path, it is considered to be negative.

The Meaning of *Power*.—If the current in amperes is multiplied by the potential difference in volts, then the product is the *power*, expressed in watts. The relationship is

$$P \text{ (watts)} = I \text{ (amperes)} \times E \text{ (volts)}.$$

The following problem illustrates the method used for calculating power.

PROBLEM 7

What is the power consumption of an electric heater that takes 1.5 amperes on a 110-volt circuit?

$$P = I \times E = 1.5 \times 110 = 165 \text{ watts}.$$

Since Ohm's law states that $I = \frac{E}{R}$, we can also find the power by using the formula

$$P \text{ (watts)} = \frac{E^2 \text{ (volts)}^2}{R \text{ (ohms)}}.$$

An example of this is given in the problem that follows.

PROBLEM 8

An electric lamp has a resistance of 220 ohms when the filament is hot. What power is consumed by the lamp on a 110-volt circuit?

$$P = \frac{E^2}{R} = \frac{110 \times 110}{220} = 55 \text{ watts.}$$

By Ohm's law we also know that $E = IR$.

Hence P (watts) $= I^2$ (amperes)^2 R (ohms).

PROBLEM 9

If a long conductor has a resistance of 25 ohms, and carries a current of 2 amperes, what is the power consumption?

$$P = I^2R = 4 \times 25 = 100 \text{ watts.}$$

If the power consumption is known, the energy can be found by multiplying the power and the time. Since the power is in watts, and the time is in seconds, the energy will be in *watt-seconds*.

$$W \text{ (watt-seconds)} = P \text{ (watts)} \times t \text{ (seconds).}$$

PROBLEM 10

What is the energy consumed in 4 hours by an electric lamp rated at 25 watts?

$$W = Pt = 25 \times 4 \times 3{,}600 = 360{,}000 \text{ watt-seconds.}$$

Units of Electrical Power and Energy.—It is apparent from the last section that in many cases the units for power and energy there discussed would be unsuitable where a large consumption of energy takes place. For this reason large amounts of power are measured in *kilowatts*. The kilowatt (*kw*) is equal to 1,000 watts. Hence

$$\text{Power (kw)} = \frac{I \text{ (amperes)} \times E \text{ (volts)}}{1{,}000}$$

PROBLEM 11

An electric generator supplies 50 amperes at 220 volts. What is its power?

$$P\ (\text{kw}) = \frac{50 \times 220}{1{,}000} = 11\ \text{kw}.$$

Although electrical power is usually measured in watts or kilowatts, it is sometimes necessary to express it in a unit known as the *horse power;* 1 horse power is equivalent to 746 watts.

$$\text{Power}\ (HP) = \frac{\text{Power}\ (kw)}{0.746}.$$

Electric energy may also be expressed in a larger unit, the kilowatt-hour (*kw. hr.*). The energy in kilowatt-hours is equal to the power in kilowatts multiplied by the number of hours.

$$\text{Energy (kw. hr.)} = \text{Power (kw.)} \times \text{time (hours)}.$$

PROBLEM 12

An electric motor that has a rating of 600 watts is used for 20 hours. How much energy does it take?

$$\text{Energy (kw. hr.)} = \frac{600}{1{,}000} \times 20 = 12\ \text{kw. hr.}$$

Significance of the Joule Effect.—Whenever a current flows through a resistance, heat is produced. This heat can be utilized in many ways. Everyone is familiar with this principle as made use of in the electric toaster, the electric flatiron, the electric heater, and similar devices. This principle is of particular value in the radio tube. This conversion of electricity into heat is called the *Joule effect.*

Joule's Law and Its Application.—The amount of heat produced by the Joule effect is given by Joule's law. In order to understand this law, it is necessary to know the definition of the commonly used unit of heat called the *calorie.* The calorie is the amount of heat necessary to raise the temperature of 1 gram of water 1 degree centigrade. Joule's law is then given by the following formula:

$$H = 0.24\ I^2Rt,$$

where H is the heat produced in calories, R is the resistance in ohms, and t is the time in seconds. It is obvious that I^2Rt is the electrical energy in watt-seconds. Hence the equation may also be written

$$H = 0.24 \frac{E^2}{R} t,$$

where E is in volts. If R is not known, the equation used will be

$$H = 0.24\ EIt.$$

The following problems illustrate the proper choice of the above formulas for calculating the heat produced when a current flows through a resistance.

PROBLEM 13

An electric heater that has a resistance of 50 ohms requires 4 amperes for operation. How many calories does the heater produce in an hour?

$$H = 0.24\, I^2Rt = 0.24 \times 4 \times 4 \times 50 \times 60 \times 60 = 691{,}200 \text{ calories.}$$

PROBLEM 14

What resistance must an electric stove have in order to produce 500 calories per minute when used on a 100-volt circuit?

$$H = 0.24 \frac{E^2}{R} t,$$

$$500 = 0.24 \times \frac{100 \times 100 \times 60}{R}. \text{ Hence } R = 288 \text{ ohms.}$$

PROBLEM 15

How much current must be sent through a filament that is operated on 3 volts, in order to produce 5 calories per second?

$$H = 0.24\ EIt,$$
$$5 = 0.24 \times 3 \times I \times 1,$$
$$I = 6.9 \text{ amperes.}$$

The Thermocouple Explained.—If two different metals, such as copper and iron, are joined together in a circuit, as in Fig. 25, and if one junction, A, is hot, and the other junction, B, is cold, an e.m.f. is produced. The two junctions are called thermojunctions, and the entire arrangement is called a *thermocouple*. The effect was discovered by Seebeck and is consequently known as the *Seebeck effect*. The direction of the e.m.f. is shown by the diagram. The amount of current that flows is small, to be sure, but a sensitive ammeter will show the value of the current and its direction. The principal use of thermocouples in radio is in radio-frequency measuring instruments. This will be discussed under alternating-current measurements. (See page 74.)

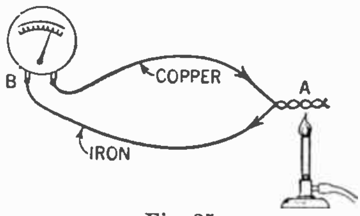


Fig. 25.

Direct-Current Measuring Instruments.—Although direct current can be measured by means of electrochemical principles, most measuring instruments today depend upon electromagnetic effects. These instruments are usually classified into two types. The first is known as the *moving-magnet* type; the second as the *moving-coil* type. In the first, a current flowing in a fixed coil sets up a magnetic field that causes the rotation of a magnet that is either suspended by a fiber or mounted on a pivot. In the second type, the magnet is fixed and a coil is mounted so as to be free to rotate. The current is sent through the coil, and its magnetic field reacts with the poles of the magnet in such manner that the coil is caused to rotate.

The D'Arsonval Galvanometer.—The D'Arsonval galvanometer is an instrument of the moving-coil type. Fig. 26 shows the construction of such a device. The fixed magnet is a permanent steel one, whose poles (N and S) are shown in the figure. The coil is wound on an aluminum spool that is mounted on jeweled bearings and held by a fine spring in such position that when no current is flowing the axis of the coil is at an angle to the field between the poles of the magnet. When a current flows, a magnetic field is set up. The coil tends to set its axis along the field of the

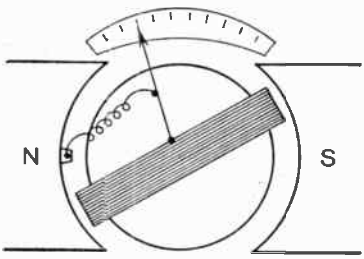


Fig. 26.

permanent magnet, but is opposed by the light spring. The amount of deflection is therefore proportional to the current flowing; it is indicated by the pointer attached to the coil. A suitable scale is placed beneath the pointer so as to show the amount of deflection. An instrument of this type indicates very small current. However, it cannot withstand very large currents. A slight modification can be made which will enable the instrument to measure large currents.

The Construction of an Ammeter.—Essentially, the ordinary *ammeter* is a galvanometer having a low resistance in parallel with the coil. This low resistance is called a *shunt*. Fig. 27 shows an ammeter that has a shunt. The purpose of the shunt is to carry most of the current so that only a small portion of it passes through the coil of the galvanometer. Many different shunts may be used so as to give a variety of ranges of the current to be measured.

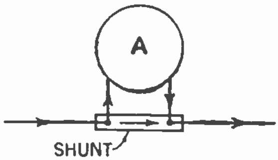


Fig. 27.

Calculation of Shunts for the Ammeter.—The calculation of the proper value of the shunt for any given range of an instrument can be made by using Ohm's law. Fig. 28 represents the resistance of the galvanometer, r_g, and the resistance of the shunt, r_s. The current to be measured divides into two parts: I_g, the current through the galvanometer, and I_s, the current through the shunt. Therefore

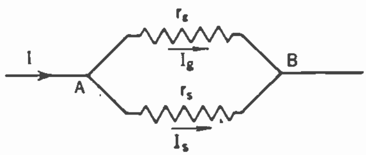


Fig. 28.

$$I = I_g + I_s$$

Also the potential, E, between A and B, is the same for the galvanometer and for the shunt. From Ohm's law

$$E = I_g r_g = I_s r_s,$$

which is the same as

$$\frac{I_s}{I_g} = \frac{r_g}{r_s}, \quad \text{or} \quad r_s = \frac{I_g r_g}{I_s}.$$

This enables us to find the resistance of the shunt. The following problems give examples of how to determine the resistance of the shunt for an ammeter.

PROBLEM 16

A D'Arsonval galvanometer has a coil that has a resistance of 10 ohms, and that deflects 1 division of its scale when a current of 0.01 ampere flows through it. If the instrument is to be used as an ammeter having 1 ampere per scale division, what resistance should the shunt have?

If the galvanometer takes 0.01 ampere, then .99 amperes must flow through the shunt in order to take care of the 1 ampere flowing in the circuit. Hence

$$r_s = \frac{I_g r_g}{I_s} = \frac{0.01 \times 10}{0.99} = 0.101 \text{ ohms.}$$

PROBLEM 17

A full-scale deflection for an ammeter having a resistance of 0.05 ohm is 20 amperes. What should be the resistance of the shunt in order to cause a full-scale deflection with 100 amperes? Since the ammeter can take 20 amperes, the shunt would have to carry 80 amperes. The resistance of the shunt would be:

$$r_s = \frac{I_g r_g}{I_s} = \frac{20 \times 0.05}{80} = 0.0125 \text{ ohms.}$$

The Voltmeter and Its Use.—When an ammeter is used, it is always connected in series with the circuit; therefore it must have a very small resistance, otherwise it will add appreciable resistance to the circuit and so give a false reading of the current. In most cases the combined resistance of the ammeter and its shunt satisfies this low resistance condition. On the contrary, a voltmeter must be connected in parallel to the two points of the circuit between which the potential difference is to be determined. In this case the resistance of the voltmeter must be large, otherwise most of the current will flow through the meter instead of through the circuit. This is taken care of by placing a high resistance in series with a D'Arsonval galvanometer, as shown by Fig. 29. This resistance is called a *multiplier*. By using various resistances, the range of the voltmeter can readily be changed at will.

Fig. 29.

Calculation of Multiplier Resistance for a Voltmeter.—The series resistance, or multiplier, for a given voltmeter can be calculated by using Ohm's law.

PROBLEM 18

A galvanometer having a resistance of 500 ohms has a full-scale deflection when 5 volts are connected to its terminals. What must the multiplier resistance be so as to require 100 volts to produce a full-scale deflection? Since the voltmeter can take care

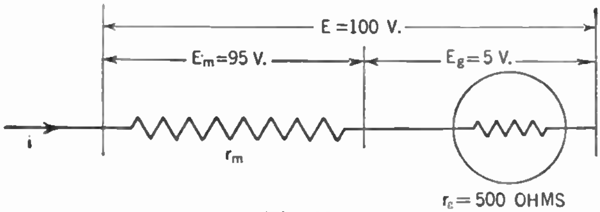


Fig. 30.

of only 5 volts, the remaining 95 volts must be handled by the multiplier. Since the multiplier is in series with the voltmeter, the current is the same in both. According to Ohm's law, the potential difference varies directly as the resistance in a series circuit because the current is the same in all parts of the circuit.

Therefore
$$\frac{r_m}{r_g} = \frac{E_m}{E_g},$$
$$\frac{r_m}{500} = \frac{95}{5},$$
$$r_m = 9{,}500 \text{ ohms}.$$

Ammeter-Voltmeter Method of Measuring Resistance.—A simple though not very accurate method of measuring resistance is to allow a current to pass through the given resistance, then to measure the current with an ammeter and the potential difference across it with a voltmeter, as shown by Fig. 31. The resistance is then found by dividing the potential difference in volts by the current in amperes.

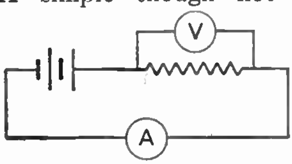


Fig. 31.

The Wheatstone Bridge and Its Use.—Since the ammeter-voltmeter method is not a very precise one for determining resistance, it is necessary to employ some other method if fairly exact results are required. The Wheatstone Bridge gives very precise values for unknown resistances. The principle of this method can be determined from the diagram of the Wheatstone Bridge circuit given in Fig. 32.

If the galvanometer does not deflect when switch S_1 is closed, and then switch S_2, the bridge is said to be *balanced*. This is the only condition of the bridge that we shall consider. When the current, i, reaches point A, it divides into current i_1, going from A to B, and current i_2, going from A to D. Since no current flows from B to D, i_1 must continue from B to C and i_2 from D to C. Because there is no current from B to D, B and D must be at the same potential. From these facts it follows that the potential difference between A and B must equal the potential difference from A to D. In a similar manner, the potential difference from B to C is the same as that from D to C. We can state this as follows:

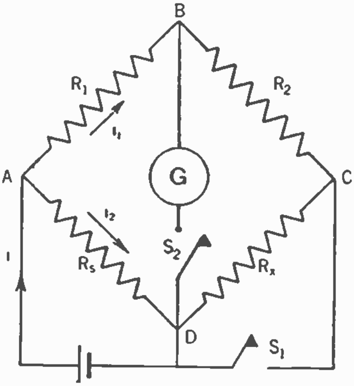


Fig. 32.

$$E_{AD} = E_{AB} \quad \text{and} \quad E_{DC} = E_{BC}.$$

From Ohm's law

$$i_2R_s = i_1R_1 \quad \text{and} \quad i_2R_x = i_1R_2.$$

Dividing the second equation by the first, we have

$$\frac{R_x}{R_s} = \frac{R_2}{R_1},$$

or

$$R_x = \frac{R_2}{R_1} \times R_s,$$

where R_x is the resistance to be measured, and R_s is a standard resistance.

A simple form of Wheatstone Bridge is shown in Fig. 33. A uniform wire is stretched out on top of a rule. The resistance to be measured is connected at *E* and *F*, and a standard resistance is connected at *G* and *H*. A galvanometer is connected from *D* to a sliding contact at *B*. A cell having a tap switch is connected between *A* and *C*. The remainder of the connections are thick brass

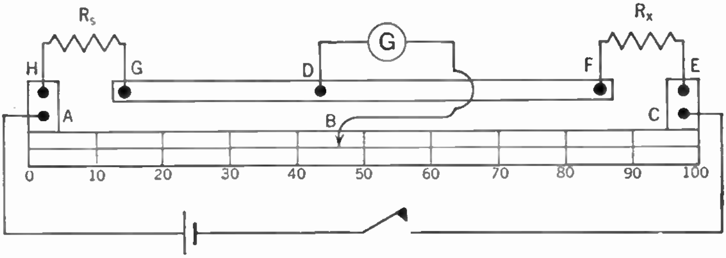


Fig. 33.

bars. After the tap key is closed, the contact, *B*, is moved along the wire until no current flows in the galvanometer. This is the balanced condition. Comparison of Fig. 32 with Fig. 33 will show that the circuits are the same; the resistance of the wire from *A* to *B* is R_1, and the resistance from *B* to *C* is R_2.

From the equation of the Wheatstone Bridge we have

$$R_x = \frac{R_2}{R_1} R_s,$$

but we know from our discussion of resistance that

$$R_1 = \frac{kl_1}{A}, \quad \text{and} \quad R_2 = \frac{kl_2}{A}.$$

Since the wire is uniform, both *k* and *A* are the same for both sections of the wire. Hence

$$\frac{R_1}{R_2} = \frac{l_1}{l_2},$$

or the bridge equation becomes

$$R_x = \frac{l_2}{l_1} R_s.$$

It is only necessary to determine the length of the wire from A to B, and from B to C. This can readily be obtained from the reading on the rule.

For commercial work the same principle is employed, though carefully made coils take the place of the wire. Such a device is known as a *decade* Wheatstone Bridge. In this bridge the ratios of R_2 to R_1 are usually in steps of 10.

The Ohmmeter and Its Use.—It is often necessary to have a simple rapid method of measuring resistance. There are a number of instruments that give directly the value of an unknown resistance. Since the measurement is given in ohms, these instruments are called *ohmmeters*. The more precise ohmmeters are some modification of the Wheatstone Bridge. Where precision is not required, an ohmmeter using the principle of Fig. 34 is used. The unknown resistance is connected between P and Q. The ammeter is calibrated to read *ohms* instead of amperes. When PQ is short-circuited, the ammeter pointer has the largest deflection, but the scale at this point is marked 0. As the resistance between P and Q becomes larger, the deflection of the pointer becomes smaller, though it indicates a larger resistance. Since the cell will gradually become weaker, an adjustment of the instrument must be made by checking the deflection for 0 resistance. The instrument must read 0 when PQ is short-circuited.

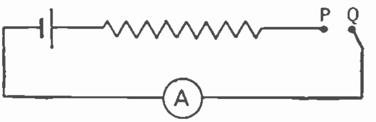


Fig. 34.

The Potentiometer and the Voltage Divider.—It has already been pointed out that the terminal voltage of a cell delivering current is less than the e.m.f. of the cell. The drop in potential is caused by the necessity for overcoming the internal resistance of the cell. Since this potential drop is equal to Ir_i, it is apparent that the drop will be greater for larger currents; in consequence, the terminal voltage of a cell delivering a large current will be considerably less than the e.m.f. In measuring the e.m.f. of a cell with the voltmeter, we are really measuring its terminal voltage; but if the voltmeter has a high resistance, the IR-drop is small and the terminal voltage is approximately equal to the e.m.f. Where precision is necessary in measuring the e.m.f., or where the internal resistance is extremely high, the voltmeter is unsatisfactory for measuring the e.m.f. For these cases a *potentiometer* is used. The circuit diagram is shown by Fig. 35.

A battery is connected to a rheostat, switch, and uniform wire AB. When a current flows from A to B, the potential difference

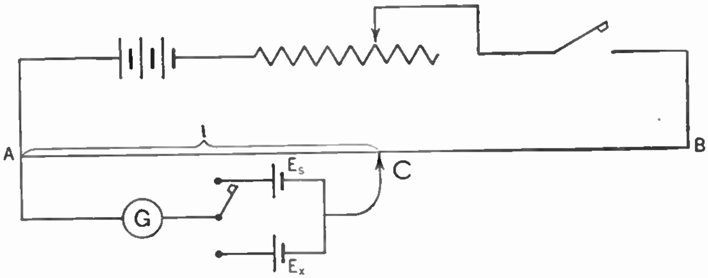


Fig. 35.

between A and any point on the wire is proportional to the length of that section of wire. This circuit is called the *working circuit.* Between A and C, and in parallel with the working circuit, a cell and a galvanometer in series are connected. By moving the sliding contact, C, along the wire, the galvanometer can be made to read 0. The potentiometer is then balanced. Since no current flows from the cell, the e.m.f. of the cell just balances the potential drop in the working circuit from A to C. By means of the double-pole switch, the balance is first obtained for a known cell whose e.m.f. is E_s, and then for another cell whose e.m.f. is E_x. Since the potential drops are proportional to the lengths of the two sections of wire, the e.m.f. of the tested cell is

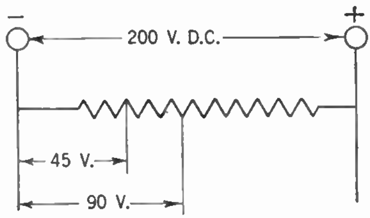


Fig. 36.

$$E_x = \frac{l_x}{l_s} E_s.$$

This principle may also be utilized for obtaining lower voltages from higher ones. Fig. 36 shows a method for obtaining such lower voltages from a 200-volt direct-current source of supply. An arrangement of this sort is called a *voltage divider.*

QUESTIONS

1. What is the combined e.m.f. of three storage cells connected in series? **Ans.** 6 volts.

2. What is the combined e.m.f. of three storage cells connected in parallel? **Ans.** 2 volts.

3. How many dry cells would it take to have an e.m.f. of 90 volts? **Ans.** 60 cells.

4. Draw a diagram showing how to connect three 2-ohm resistances in order to get a total resistance of 3 ohms.

5. Three cells, each having an e.m.f. of 1.5 volts, and an internal resistance of 0.2 ohm, are arranged in series with a 3-ohm resistance. (*a*) What is the current in the circuit? (*b*) What is the terminal voltage of each cell? (*c*) Find the potential difference across the 3-ohm resistance. **Ans.** (*a*) 1.25 amperes; (*b*) 1.25 volts; (*c*) 3.75 volts.

6. Find the combined resistance of 2, 8, and 12 ohms connected in parallel. **Ans.** 1.41 ohms.

7. Three cells, each having an e.m.f. of 2 volts, and an internal resistance of 0.09 ohm, are connected in parallel. If a resistance of 0.5 ohm is connected with the cells in the above arrangement, (*a*) what current flows through this resistance? (*b*) How much current is delivered by each cell? **Ans.** (*a*) 3.77 amperes; (*b*) 1.26 amperes.

8. What instrument would you use for measuring resistance precisely?

9. Explain a simple method of measuring resistance.

10. If a circuit is too complicated to use Ohm's law, how would you proceed to solve the circuit?

11. Explain a simple method of getting a potential of 6 volts to operate the filament of a vacuum tube if only a 110-volt direct current were available.

12. Explain how a single galvanometer can be made to serve both as an ammeter and as a voltmeter.

CHAPTER 3

THE ALTERNATING CURRENT

The Significance of Electromagnetic Induction.—At this point it is well to recall that there is a very close relationship between the phenomena of electricity and those of magnetism. Wherever an electric current flows, a magnetic field is somehow associated with it. As the current increases or decreases, the magnetic field correspondingly increases and decreases. This, however, is only one of a number of important connecting links between electricity and magnetism. The most important link is

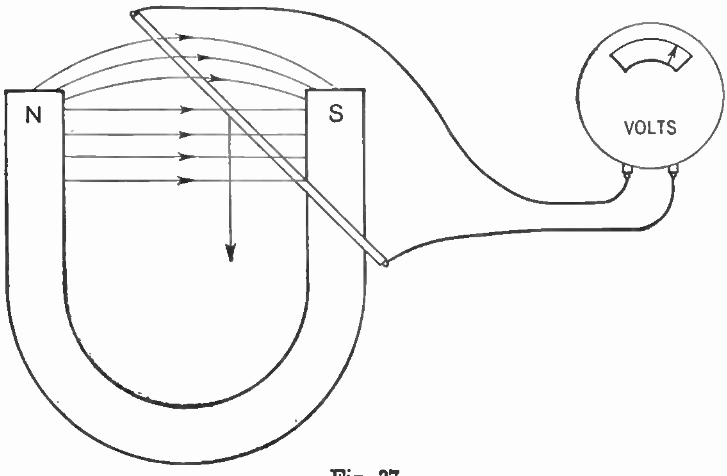


Fig. 37.

the one that enables us to change mechanical energy into electrical energy through the medium of magnetism. This idea can best be understood by examining a few easily performed experiments.

If a copper wire connected to a galvanometer, as shown by Fig. 37, is rapidly moved downward between the poles of an ordinary U-magnet, the galvanometer pointer will be deflected in one direction.

In other words, the mechanical work done by moving the wire through the magnetic field has been transformed into electrical energy. The extreme simplicity of this idea can hardly be overemphasized. All we did was to move a wire near to a magnet and an e.m.f. was thereupon produced. Production of electricity in this manner is known as *electromagnetic induction.* Though there are many other examples of electromagnetic induction that are just as readily understood as is this, nevertheless we shall postpone consideration of them until later.

The Direction of the Induced e.m.f.—Before we consider in detail the construction of an alternating-current dynamo, it will be advisable to investigate the nature of the induced e.m.f. If the wire in Fig. 37 had been moved upward instead of downward, the galvanometer would have deflected in the opposite direction, thus showing that the e.m.f. induced was in a direction opposite to that when the e.m.f. was induced at the time the wire was moved downward. A convenient method for determining the direction of the induced e.m.f. in a wire that is moved through a magnetic field is shown by Fig. 38. The thumb, forefinger, and middle finger of the right hand are extended at right angles to each other. If the thumb is pointed in the direction of motion of the conductor, and the forefinger is pointed in the direction of the magnetic lines of force, then the middle finger points in the direction of the induced e.m.f. This is sometimes known as the right-hand–three-finger rule.

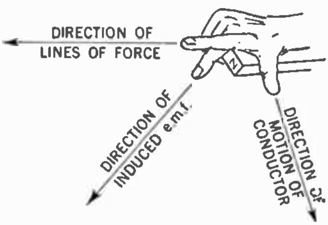


Fig. 38.

The Magnitude of the Induced e.m.f.—Now that we have determined the direction of the induced e.m.f., we must, of course, find its magnitude. According to Fig 37, if the wire were moved slowly instead of rapidly, the deflection of the galvanometer would be much less. This indicates that the strength of the induced e.m.f. depends upon the rate at which the lines of force are cut. This can be further verified by substituting a weaker magnet. When that is done, we find that for the same speed of the wire there is a much smaller induced e.m.f. Again moving the wire between the poles of the stronger magnet, but this time *parallel* to the lines of force instead of perpendicular to them, we observe that the induced e.m.f. is smaller when the wire is moved parallel to the lines. In fact, if the wire could be moved exactly parallel to the lines, there would be no induced e.m.f. at all. From these demonstrations we conclude that the e.m.f. is at a maximum when the wire moves perpendicularly to the lines of force, and that the amount of the induced e.m.f. is proportional to the rate of the cutting lines of force. Figure 39 shows a wire moving through a magnetic field of strength H. The velocity of the wire is v, and its direction of motion makes an angle θ with the field. The induced e.m.f. is then given by the formula:

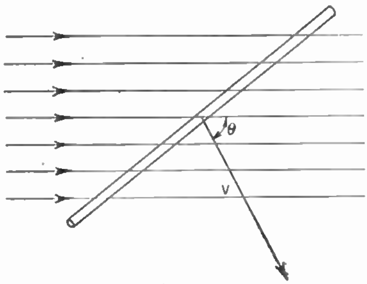


Fig. 39.

$$E = \frac{l\, v\, H \sin\theta}{10^8},$$

where E is the induced e.m.f. in volts, l is the length of the wire in centimeters, v is the speed of the wire in centimeters per second, H is the magnetic field intensity in oersteds, and θ is the angle that the direction of motion of the wire makes with the lines of force.

It is evident that when the wire is moving perpendicularly to the field, θ is 90°, and that $\sin\theta$ is equal to 1. This condition, under which E has its greatest value, is known as the *maximum value*. It will be observed that we must divide by 10^8, which means that 100 million lines of force must be cut per second in order to produce 1 volt.

E.M.F. Induced in a Loop That Rotates in a Uniform Magnetic Field.—A rectangular loop of wire is rotated between the poles of a strong magnet having wide pole pieces, as shown by Fig. 40. If the loop is rotated about an axis in the direction indicated by the curved arrow, it is apparent that CD and AB are always parallel to the lines of force, so that these parts of the loop will produce no induced e.m.f. On the contrary, AD and BC are always perpendicular to the lines of force, and are therefore active in producing an induced e.m.f. It will be necessary to investigate the relationship of the direction of motion of *AD* and *BC* with respect to the lines of force. In order to do this, it will be convenient to represent wires *AD* and *BC* by two small circles

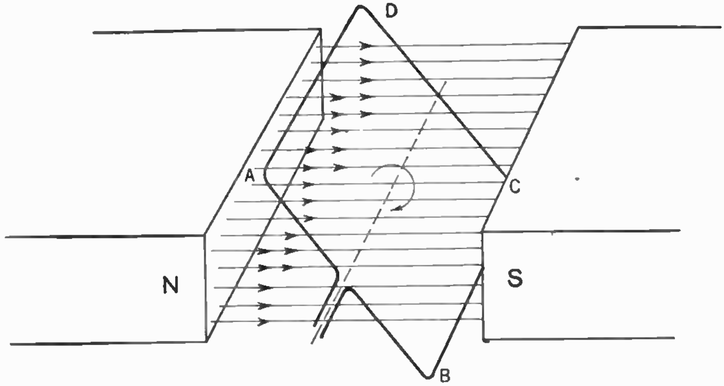


Fig. 40.

that picture their cross sections, since the wires are perpendicular to the paper. In Fig. 41 the loop is shown in a vertical position, and we observe that both *AD* and *BC* are moving parallel to the lines of force, and that the angle θ, which we used in the formula, is 0. Hence the induced e.m.f. is 0 for this position of the loop.

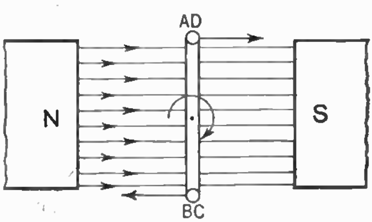


Fig. 41.

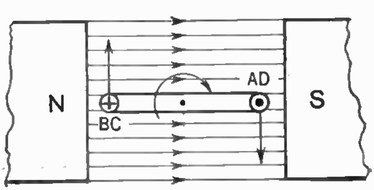


Fig. 42.

In Fig. 42 the same loop is shown after it has turned through 90°, and wire *AD* is moving down perpendicularly to the field. Making use of the three-finger rule, we find the e.m.f. directed out of the paper for *AD*, which we shall indicate by ⊙. In the case of *BC*, the e.m.f is directed into the paper, and is indicated by ⊕.

In Fig. 43 the coil is again vertical after having rotated 180°, and *BC* and *AD* are moving parallel to the field, so that the induced e.m.f. is again 0. After passing this point, however, *AD* commences to move upward through the field, and *BC* to move downward. This causes a reversal in the direction of the induced e.m.f. When the coil reaches the position shown in Fig. 44, the

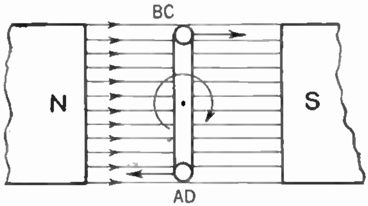


Fig. 43.

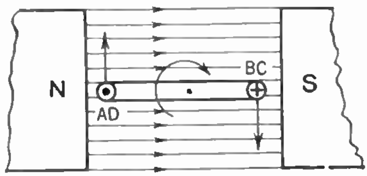


Fig. 44.

direction of motion of *AD* and *BC* is 90° to the lines of force. Thus the e.m.f. is again at a maximum. Comparing Fig. 44 with Fig. 42, however, will show that this maximum e.m.f. is in the *opposite direction* from that in Fig. 42. Another rotation of 90° will bring the loop back to the position it occupied in Fig. 41. Further rotation will simply cause the e.m.f. to repeat the values it had in the first revolution of the coil.

The Sine-Wave Alternating Current.—In order fully to understand the variation of the e.m.f. in the rotating loop, Fig. 45 shows a graph of the value of the e.m.f. and the angle through which the loop has turned, starting from the vertical position. If we trace the change in value of the e.m.f., we see that the

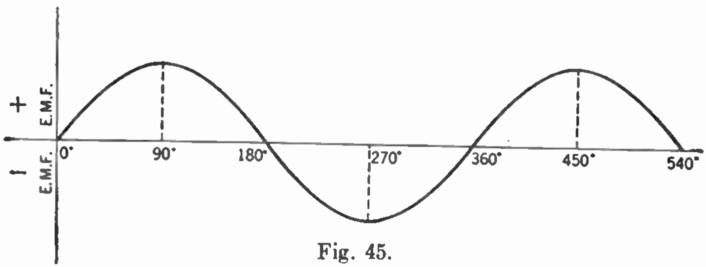


Fig. 45.

e.m.f. starts at 0°, increases to a maximum at 90°, then reduces to 0 at 180°, at which point it reverses its direction. It then increases to a maximum in the opposite direction at 270°, where it then reduces to 0 at 360°. Thereafter it repeats the variation over and over again. This type of e.m.f. is known as a *sine-wave alternating e.m.f.* because its values vary according to the mathematical sine function, as indicated by the graph. A complete variation from 0° to 360° is known as a *cycle*. The number of these cycles per second is called the *frequency* of the alternating current. In ordinary house currents, the frequency is usually 60 cycles per second. The frequencies met with in radio circuits are commonly very much greater.

The Alternating-Current Dynamo.—The rotating loop just explained works upon essentially the principle that is used in an alternating-current dynamo. There, instead of having one loop of wire, we have many turns of wire wound on a core of soft iron that rotates upon an axis placed between the poles of a magnet. This coil, together with the iron core, is known as the *armature*. The same variation of e.m.f. will be produced in the armature as in a single loop, but the individual values will be much greater, due to the fact that a greater length of wire is cutting the field. In order to have a strong magnetic field, an electromagnet is employed. The current is brought from the armature to the outside circuit by means of collecting rings and brushes, as shown by Fig. 46.

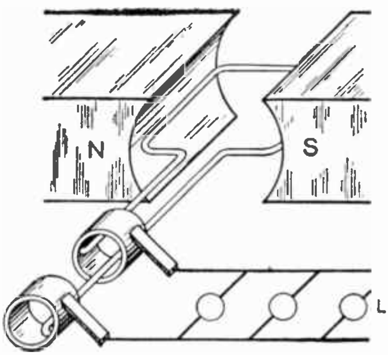


Fig. 46.

Vector Diagram of an Alternating e.m.f.—In order to study the effect of alternating currents, it has been found advisable to represent an alternating e.m.f. by means of a rotating vector. The vector is E_m, the maximum value of the e.m.f. In Fig. 47, the vector E_m is represented as rotating in a counter-clockwise direction. The vector e, as shown in the figure, represents the instantaneous value at a given time. From the diagram it is evident that $e = E_m \sin \theta$, which is in agreement with our general expres-

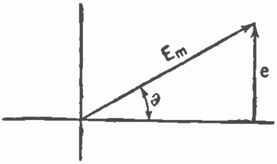


Fig. 47.

sion for the value of the instantaneous e.m.f. This relationship is represented graphically in Fig. 48. Hence there are three ways of representing an alternating e.m.f. and for determining the instantaneous value: the first is the vector diagram of Fig. 47; the second is the graphical representation of Fig. 48; and the third is the equation $e = E_m \sin \theta$.

Instantaneous Values of the e.m.f. and the Current.—The value of the e.m.f. at any instant is called the *instantaneous e.m.f.* It is expressed by the equation $e = E_m \sin \theta$. The largest value of e, called the *maximum e.m.f.*, is designated by E_m. The current, when it flows, follows a similar relationship. The instantaneous value of the current is the value of the current at a given instant. The maximum value of the current is represented by I_m. The value of the instantaneous current is given by $i = I_m \sin \theta$. The graph of i is also a sine wave, and the value of i may be found by vector representation, as in the case of the e.m.f. It is important to realize that there is always an induced e.m.f. when the armature of the dynamo is rotating, but even so there is not necessarily an induced current.

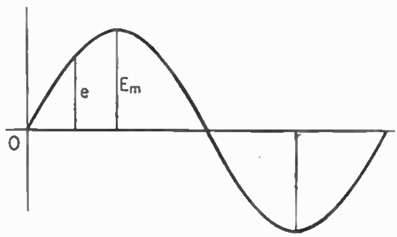


Fig. 48.

Average and Effective Values of the e.m.f. and the Current.—Thus far we have mentioned the instantaneous and maximum values of the e.m.f. and the current. It is necessary to use a single value to represent quantities like these. Since the instantaneous value is constantly changing, it cannot be used for this purpose. Although the maximum value is a single value, it is not suitable for use as being representative of the various values. We naturally think of an average value. Mathematically, the average of the instantaneous values taken over a cycle is 0.637 times the maximum value. In the case of the e.m.f., this would be $E = 0.637E_m$, and for the current, $I = 0.637I_m$. This value is also unsuitable for our purpose, and in consequence is rarely used in practice. The reason for this last statement is that the most important effect of a current is the heat it produces. From Joule's law we know that the heating effect is proportional to the square of the current. Hence the value most commonly used in alternating currents is the square root of the average of the squares of the instantaneous values. This value is called the *root mean square value* (r.m.s.), or *effective value*. By means of mathematics it is found that the effective value of the e.m.f. is $0.707E_m$. The same conditions exist in the case of the current. The average value is $0.637I_m$, and the effective value is $0.707I_m$. As in the case of the e.m.f., the latter value is almost exclusively used when referring to the current. Alternating-current meters give the effective value.

The Significance of Mutual Induction.—Previously we mentioned that there are many examples of electromagnetic induction. Let us consider some further illustrations of this phenomenon. Fig. 49 represents a coil, *AB*, connected to a battery and a switch. Coil *AB* is inside a second coil, *CD*, which is connected to a galvanometer. When the switch is closed, a current flows in *AB*, but momentarily a current also flows in *CD*, even though there is

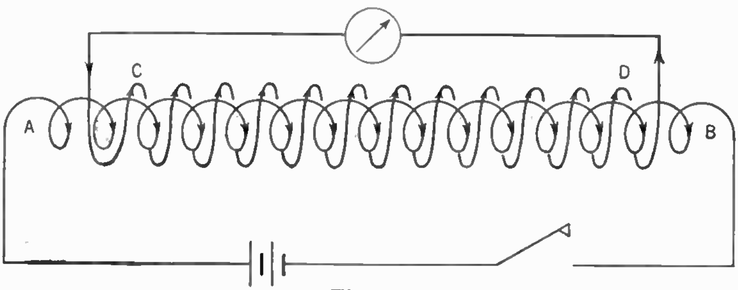


Fig. 49.

no electrical connection between the two coils. In this case of electromagnetic induction, an e.m.f. is induced in coil *CD*, due to the change of magnetic flux of the coil *AB*. It is important to realize that an e.m.f. is induced in *CD* only when there is a change in the current in *AB*. If there is a steady current in *AB*, there is no induction in *CD*. When the switch is opened, however, there is again a deflection of the galvanometer, but this time it is in the opposite direction.

An Explanation of *Lenz's Law*.—As was noted above, the induced e.m.f. differs in direction according to the manner in which the induction takes place. The direction of the induced e.m.f. is determined by an important principle that was first stated by

Lenz and is consequently known as *Lenz's law*. This law is quite general. It states that *the induced e.m.f. in electromagnetic induction is always in such direction as to set up a current whose magnetic field will oppose the forces producing the induced e.m.f.* In the coils described in the previous section, the induced current was opposite to the current in the first coil when the switch was closed; thus the magnetic field of the induced current opposed the building up of the magnetic field that is due to the current in coil *AB*. On the contrary, when the switch was opened, the current in *CD* was in the same direction as that in *AB* because the magnetic field of the induced current opposed the reducing of the magnetic field of the current in *AB*. Thus we see that the magnetic field of an induced current always opposes the rate of change of the lines of force that produce the induced e.m.f.

The Induction Coil and Its Use.—For obtaining high voltages from a low-voltage battery, an induction coil such as is shown in Fig. 50 is often used. This type of coil is known as a

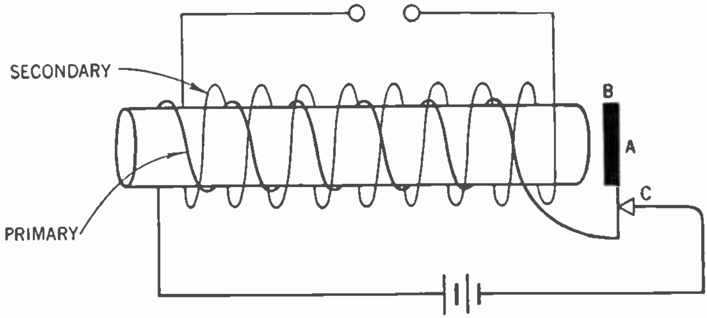


Fig. 50.

Ruhmkorff coil. A coil of a few turns of heavy wire is wound on an iron core. This coil is known as the *primary* coil. The primary coil is connected to a battery through an interrupter, *A*. The interrupter consists of a piece of iron, *B*, attached to a springy piece of brass. When the current flows through the primary circuit, the core becomes a magnet and thus attracts the iron, so that a break in the circuit occurs at the contact point, *C*, and thus the current ceases to flow in the primary circuit. Now that no current is flowing in the primary circuit, the iron is no longer attracted, and contact is again made at *C*. In this manner the current is continuously stopped and started in the primary coil. This results in a large induced e.m.f. in the secondary coil, which consists of many turns of fine wire wound on the same iron core. The interrupter makes and breaks the current in the primary several hundred times per second, and thus the secondary coil is a continuous source of high voltage. The e.m.f. of the secondary coil is not steady. Hence, when such a coil is used for radio purposes, a filter circuit must be used in conjunction with it.

How the Transformer Is Employed.—In the case of direct current it was necessary to vary the current in the primary coil so as to produce an induced e.m.f. in the secondary coil. This is not the case with alternating current, however, because the current is constantly changing on account of its very nature. This principle is made use of in the transformer shown in Fig. 51. Both the primary coil and the secondary coil are wound on the same iron core. Since the current is constantly changing according to the sine relationship, the fluctuating magnetic field induces an e.m.f. in the secondary coil. This induced e.m.f. varies in a manner similar to that of the current in the primary coil, and thus we have a sine-wave e.m.f. at the terminals of the secondary coil. In the diagram, the secondary coil is shown to have more turns than has the primary coil. Such a transformer is known as a *step-up* transformer because the secondary voltage is greater than the primary voltage. If the secondary coil has fewer turns than has the primary coil, it will be a *step-down* transformer. The value of the secondary voltage can be found from the proportion

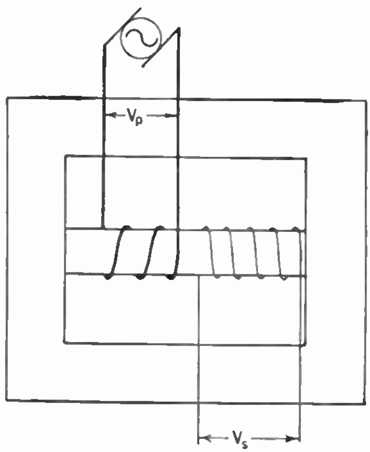


Fig. 51.

$$\frac{E_s}{E_p} = \frac{N_s}{N_p},$$

where N stands for the number of turns on the coil.

An Explanation of Self-Induction.—Both the induction coil and the transformer are examples of mutual induction. We might describe mutual induction as the electromagnetic induction that takes place in neighboring circuits when the current is varied in a given circuit. It is reasonable to expect that induction will also take place in the same circuit. This can be shown by the following experiment. In Fig. 52 there is a current flowing to the right through a coil of many turns wound on an iron core. In parallel with the cell is a neon lamp. This lamp will glow if a sufficiently high potential difference is put across it. There are two semicircular metal disks in the bulb. If the potential is greater at the right terminal of the lamp, the upper disk glows. If the potential at the left is greater, the lower disk glows. When the current is flowing steadily, the potential difference across the coil is not sufficient to make the lamp glow. If the switch is suddenly opened, the lower disk glows brightly, which indicates a large induced e.m.f. in the original direction of the current. This effect is called *self-induction* because the variation of the current in a circuit produces an induced e.m.f. in the same circuit. It will be observed that the direction of this self-induced e.m.f. is in accordance with Lenz's law. The induced e.m.f. tends to keep the current flowing in circuit even after the switch is opened. When the switch is suddenly closed, the upper disk will glow, thus indicating a large induced e.m.f. opposite to the direction of the current. This is also in agreement with Lenz's law because it opposes the production of further induced e.m.f.

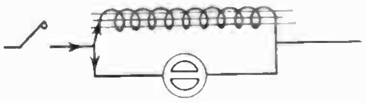


Fig. 52.

***Inductance* and What It Is.**—The self-inductive effect of a coil, by means of which it tends to prevent any change in the current flowing through it, is called its *self-inductance*. The character of self-inductance is *a property of the circuit*, not of the e.m.f. or the current. It depends entirely upon the shape and size of the circuit, and upon the magnetic permeability of the surrounding medium. The unit of inductance is the *henry* (h). A circuit has 1 henry of self-inductance when a change of 1 ampere will cause 10^8 cuttings of magnetic lines by the circuit. The self-inductance of a long coil is $L = \frac{1.26\, N^2 A \mu}{10^8\, l}$, where N is the number of turns, A is the area of the core in square centimeters, μ is the permeability, l is the length in centimeters, and L denotes the self-inductance in henries. Except for very large coils that have iron cores, the henry is too large a unit for practical work. In the case of ordinary coils that have an air core, the *millihenry* (mh) is used; this is 1 one-thousandth of a henry.

When variation of current in one circuit causes the magnetic flux to cut another circuit, then the two circuits are said to have a *mutual inductance*. The definition of mutual inductance is very similar to that for self-inductance. When a change of 1 ampere in one circuit causes 10^8 cuttings of magnetic lines in the other circuit, then the mutual inductance of the two circuits is 1 henry. Another way of expressing this fact is that the mutual inductance is 1 henry when a change of 1 ampere per second in one circuit induces 1 volt in the other. The formula for mutual inductance is $M = \dfrac{1.26\, N_1\, N_2\, A\mu}{10^8\, l}$, where M is the mutual inductance in henries, N_1 is the number of turns in one coil, N_2 is the number of turns in the other coil, A is the area of the air core in square centimeters, and l is the length of the core in centimeters.

The Use of Coupled Circuits.—In radio work, circuits that have mutual inductance are said to be *coupled*. When all the magnetic flux in one circuit cuts all the turns in the second circuit, the circuits are said to have a unity coefficient of coupling. The self-inductances of the two coils are, respectively,

$$L_1 = \frac{1.26\, N_1{}^2 A\mu}{10^8\, l} \quad \text{and} \quad L_2 = \frac{1.26\, N_2{}^2 A\mu}{10^8\, l}.$$

If the coefficient of coupling is unity, it is evident from the formula for mutual inductance, that is, $M = \dfrac{1.26\, N_1\, N_2\, A\mu}{10^8\, l}$, that $\sqrt{L_1 \times L_2} = M$. If M is less than $\sqrt{L_1 L_2}$, then the coefficient of coupling is less than 1. Power transformers have large coefficients of coupling, on the order of 0.98. In radio transformers the coefficient is usually less than 0.5. This latter type coupling is known as a *loose coupling*.

The Arrangement of Inductances.—When inductances are arranged in series (Fig. 53) in such manner that there is no mutual inductance, the total inductance is the sum of the individual inductances, or,

$$L = L_1 + L_2 + L_3.$$

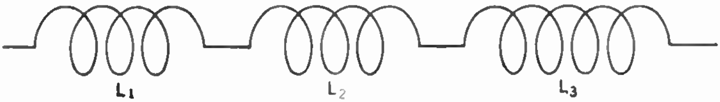


Fig. 53.

If the inductances are connected in parallel, as shown by Fig. 54, but have no mutual inductance, the total inductance can be

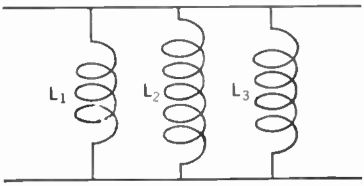


Fig. 54.

found from the formula

$$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}.$$

When there is a mutual inductance between the two coils, the manner in which they are located makes a great difference.

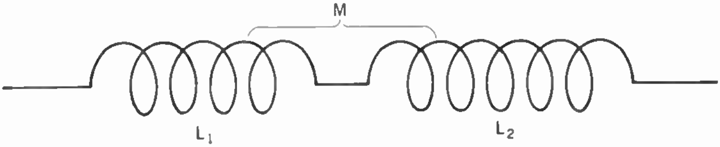


Fig. 55.

Fig. 55, for example, shows two coils arranged in series that aid each other. In this case the total inductance is

$$L = L_1 + L_2 + 2M.$$

Fig. 56 shows two coil series that oppose each other. In this instance the total inductance is $L = L_1 + L_2 - 2M$.

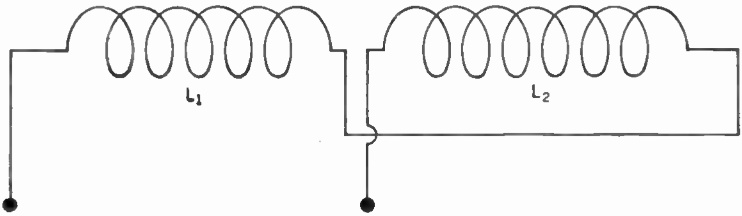


Fig. 56.

Effect of Inductance on Phase Relationship of e.m.f. and Current.—If an alternating current contains only pure resistance, then the graph of the e.m.f. and the current is as shown in Fig 57. The maximum value of the e.m.f. occurs at the same time as the

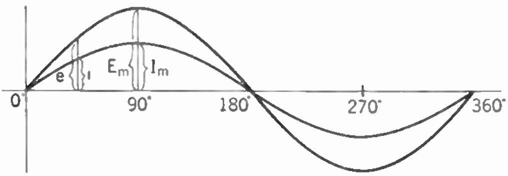


Fig. 57.

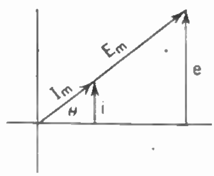


Fig. 58.

maximum value of the current, and this is also true of all the corresponding instantaneous values of the e.m.f. and the current. Under these circumstances, the e.m.f. and the current are said to be *in phase*. A vector diagram of this condition is shown by

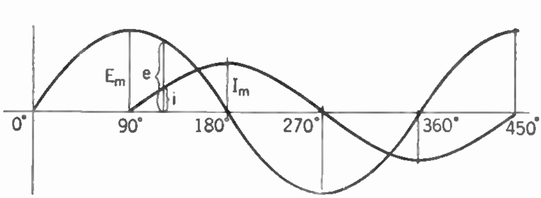


Fig. 59.

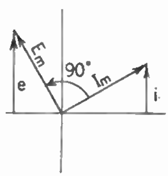


Fig. 60.

Fig. 58. When there is only a pure inductance in the circuit, the current lags behind the e.m.f. by 90°. The graph in Fig. 59 shows the relationship of the e.m.f. to the current in a circuit having

pure inductance. The graph shows that the maximum value of the current does not occur until some time after the e.m.f. has reached its maximum value. The vector diagram of this condition is shown by Fig. 60. The number of degrees of lag is known as the *phase difference.* In this case the phase difference between the e.m.f. and the current is 90°.

Condensers: Their Construction and Use.—We have already noted the importance that inductances play in an alternating-current circuit. An equally important factor is the effect of condensers. A *condenser* consists of two conductors separated by an insulator. A common type of this device is the parallel-plate condenser. It consists of two parallel metallic plates having an insulator between them. The insulating material between the plates is called the *dielectric.* Fig. 61 shows the action of a condenser. By means of its e.m.f., the battery causes the electrons from one plate to go around to the other plate. Even after the battery has been disconnected, the electrons remain on one of the plates; the other plate remains positive, due to its loss of electrons. The electrons are held on the negative plate by the attracting force of the positive charge on the positive plate. Under these conditions the charges are known as *bound charges.* A change is also produced in the dielectric. The action of the charged plates is such as to cause the electrons in the atoms of the dielectric to be displaced. Since the electrons are in most cases strongly held in the atoms of the dielectric, they are not released from the atom, but instead they simply produce a distortion of the atom.

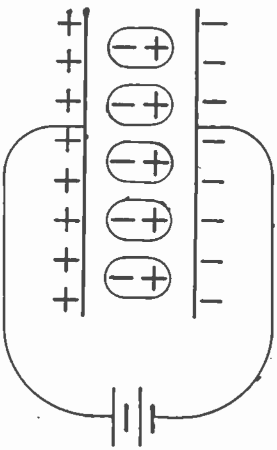


Fig. 61.

The Meaning of *Capacitance.*—The amount of charge that a condenser can hold is determined by its physical construction and by the potential difference impressed across the plates. The *capacitance* of a condenser is the ratio of the charge on the condenser to the potential difference across the plates. The unit of capacitance is the *farad* (f.). The capacitance is expressed by

$$C = \frac{Q}{E},$$

where C is the capacitance in farads, Q is the charge on the condenser in coulombs, and E is the potential difference in volts. Although the standard unit for capacitance is the farad, in practice this value is entirely too large for convenient use. Because of this, most condensers are rated in *microfarads*. The microfarad is 10^{-6} farads, or 1 one-millionth of a farad. In some cases it is even necessary to rate condensers in micro-micro-farads. This latter unit is 10^{-12} farads, or one-millionth of one-millionth of a farad.

Capacitance of a Parallel-Plate Condenser.—The capacitance of a parallel-plate condenser depends upon a number of factors. The larger the area of the plates of the condenser, the greater will be its capacitance. Fig. 62 is a diagram of a parallel-plate condenser. The area of each plate is A, measured in square centimeters. The nearer together the plates are, the greater is the capacitance. The distance between the plates is indicated by t. The dielectric between the plates also determines the capacitance. This property of the dielectric is called the *dielectric constant*. The expression for the capacitance of the parallel-plate condenser is given by

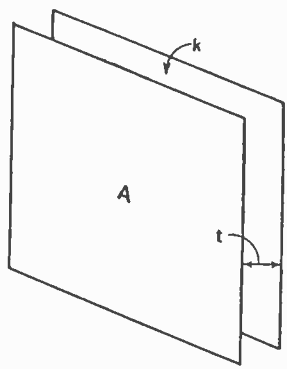


Fig. 62.

$$C = \frac{8.84\,kA}{10^8\,t},$$

where C is the capacitance in microfarads and k is the dielectric constant.

The Dielectric Constant.—The dielectric constant, k, of a substance is a measure of its effectiveness when used in a condenser. It is usually defined as the ratio of the capacitance of a given condenser with the substance between its plates, to the capacitance of the same condenser with air between the plates. The dielectric constant of air must therefore be 1. The dielectric constant of various substances commonly used in the construction of condensers is given in Table II.

TABLE II

Substance	Dielectric Constant	Substance	Dielectric Constant
Air	1.00	*Oil*	2.0 to 2.2
Glass	4.0 to 10.00	*Paper*	1.6 to 3.2
Mica	5.6 to 7.00	*Rubber*	2.0 to 3.6

Breakdown Strength of the Dielectric of a Condenser.—It was stated that the amount of charge that can be stored on a condenser is proportional to the applied potential difference. On this basis it might seem that there is no limit to the amount of charge that can be established on a condenser, so long as we can increase the voltage across the plates. However, one important factor must not be overlooked. It has already been mentioned that the potential difference on the plates causes a displacement of the electrons in the atoms of the dielectric. As the voltage increases, these electrons are further displaced. Eventually (depending upon the particular substance) the electrons break free of the atoms, and pass through the dielectric to the plate of the condenser. In the case of a solid dielectric, the passage of these electrons punctures the dielectric and leaves a permanent hole through it. This passage of electrons may take the form of a spark and so burn a hole in such insulators as are made of paper or of mica. The voltage at which an insulator of a given thickness will break down is called the *breakdown voltage*. Table III gives the breakdown voltage for various substances commonly used as a dielectric in condensers.

TABLE III

Material	Breakdown Voltage (volts/0.001 inch)
Air	50
Glass	200 to 400
Mica	2,500 to 8,500
Parafined Paper	700 to 1,000

The Construction of Fixed and Variable Condensers.—Condensers constructed so that their capacitance cannot be changed, or varied, are called *fixed condensers*. One of the most common methods of constructing such a condenser is by placing very thin sheets of mica between thin sheets of metal foil. Fig. 63 shows the arrangement of foil and mica in such a condenser. This arrangement is ideal because mica has a large dielectric constant and an extremely high breakdown voltage, as can be determined from Tables II and III. For this reason the mica can be made into very thin sheets that tend to give a large capacitance and so make the condenser extremely compact. In addition, mica has the property of breaking into thin sheets. The condenser is usually sealed in a Bakelite case that protects it from moisture. Condensers of the type just described are widely used for radio work. A cheaper form of condenser, commonly called a *paper condenser*, is made by taking two long thin strips of metal foil and placing linen paper of the same dimensions between them. A similar strip of paper is placed on top of the combination and the entire pack

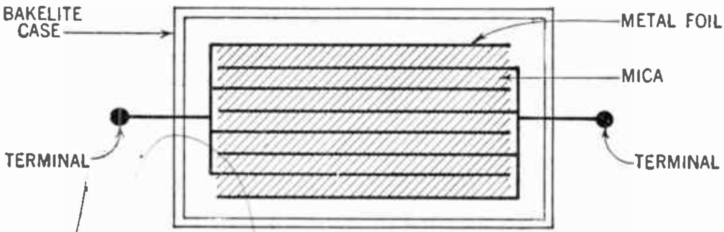


Fig. 63.

of strips is then rolled up much as is a bolt of cloth. Following this, the whole is impregnated with molten wax. After the wax has cooled and hardened, the condenser is sealed in a metal box.

In certain cases, as we shall discover later, it is necessary to have a condenser whose capacitance can be changed. Such a condenser is called a *variable condenser*. We have already learned that three factors determine the capacitance of a condenser. They are (1) the area of one plate, (2) the distance between the plates, and (3) the dielectric constant of the insulator between the plates. Any of these can be varied to change the capacitance of a condenser. It has been found more convenient, however, to vary the effective area of the plates than to vary either of the other factors. Variable condensers usually have air as a dielectric. A type of condenser widely used in radio work is shown in

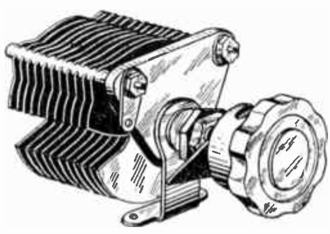


Fig. 64.

Fig. 64. It can be seen that the condenser consists of two sets of parallel metallic plates. One set is fixed; the other is mounted on a shaft. Merely by turning the shaft, the common area of the plates can be varied. When the movable plates are exactly opposite the fixed plates, the condenser then has its maximum capacitance. If the movable plates are turned so that no part of them is opposite the fixed plates, then the capacitance is at a minimum.

The Electrolytic Condenser.—A very popular type of condenser for certain kinds of radio work differs considerably from those previously described. This type is known as an *electrolytic condenser*. When certain metals are put into special electrolytes, a current flows from the electrolyte to the metal, but not in the reverse direction. If the electrode is made of aluminum, an aluminum hydroxide layer is formed over the aluminum, and over this there is a thin gas film of oxygen produced by the electrolytic action. This combination of hydroxide layer and gas film makes up the dielectric. The conductors are the solid aluminum and the electrolyte. Since the films are of microscopic thickness, the capacitance of a condenser having such a small thickness of dielectric is extremely large. For this reason an electrolytic condenser having the same capacitance as a paper or a mica condenser occupies much less space. In addition, the cost of construction is much less. Another feature of this condenser is that it is *self-healing* after a breakdown due to a too high applied voltage.

The Arrangement of Condensers.—Condensers may be arranged in many different ways, but all these arrangements have as a basis two simple methods of connecting the condensers. Fig. 65 shows an arrangement of four condensers in parallel. It will be noticed that this is equivalent to increasing the area of the plates. Hence the total capacitance of the condensers in this arrangement is equal to the sum of the individual capacitances, or,

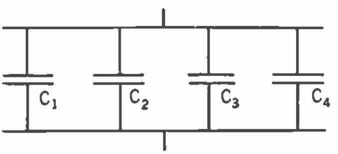


Fig. 65.

$$C = C_1 + C_2 + C_3 + C_4.$$

PROBLEM 19

We connect in parallel 2- , 4- , 5- , and 7-microfarad condensers. What is the total capacitance?

$$C = C_1 + C_2 + C_3 + C_4 = 2 + 4 + 5 + 7 = 18 \text{ microfarads.}$$

Fig. 66 illustrates a series arrangement of condensers. The total capacitance is given by the formula

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4}.$$

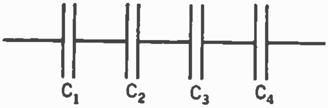


Fig. 66.

PROBLEM 20

If the condensers in Fig. 66 were 3- , 4- , 6- , and 12-microfarads, respectively, what would be the total capacitance?

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4}$$

$$= \frac{1}{3} + \frac{1}{4} + \frac{1}{6} + \frac{1}{12}$$

$$= \frac{4 + 3 + 2 + 1}{12} = \frac{10}{12}$$

Hence $C = 1.2$ microfarads.

Action of a Condenser in an Alternating-Current Circuit.—If a condenser is connected in series with an electric lamp, as shown by Fig. 67, and if it is supplied with an alternating e.m.f. from an alternating-current dynamo, the lamp, L, will light, though the circuit, as we ordinarily think of it, is not a closed one because the dielectric of the condenser is not a conductor. An examination of this situation will give us an idea of a condenser in an alternating-current circuit. An alternating-current dynamo gives an e.m.f. that is constantly changing. While the

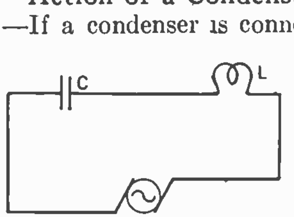


Fig. 67.

e.m.f. is increasing, condenser C becomes charged; but when the e.m.f. begins to decrease, the condenser thereupon discharges, thus giving its charge back to the circuit. If the frequency of the alternating current is 60 cycles per second, the condenser is charged 120 times per second.

Effect of Capacitance on the Phase Relationship of e.m.f. and Current.—In the case of a pure inductance in an alternating-

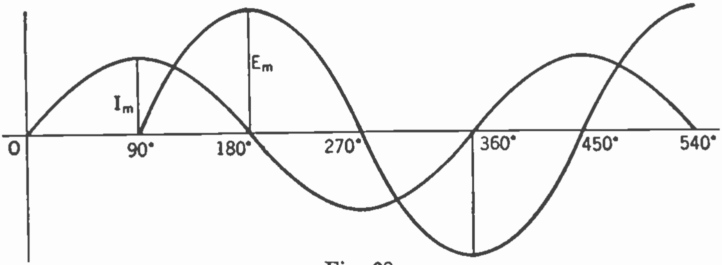


Fig. 68.

current circuit, we found that the current lags behind the e.m.f. by 90°. Just the opposite is true of a current in a circuit that contains only capacitance. In the latter case, the current leads the e.m.f. by 90°. Fig. 68 shows the graph of the current and the e.m.f. in an alternating-current circuit containing pure capacitance. Fig. 69 is a vector diagram of this situation. E_m and I_m are, respectively, the maximum e.m.f. and the current. The instantaneous current and the e.m.f. are i and e, respectively.

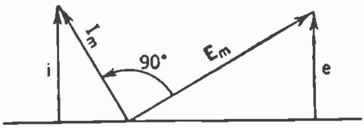


Fig. 69.

QUESTIONS

1. Draw a diagram that shows the magnetic field that surrounds a wire carrying a current.

2. Explain a simple method of producing an e.m.f. by means of electromagnetic induction.

3. Draw two magnetic poles, and show a loop of wire rotating between them in a counter-clockwise direction. Use the three-finger rule for determining the direction of the induced e.m.f.

4. Make a graph of the induced e.m.f. of a coil rotated in a uniform magnetic field, starting from the place where the wire is moving perpendicularly to the lines of force.

5. If the frequency of an alternating current were 10,000 cycles per second, how many times per second would the current change?

Ans. 20,000 times per second.

6. If an alternating-current dynamo had four poles, how many cycles would be produced for each revolution of the armature?

Ans. Two cycles for each revolution.

7. Why is the average value of the alternating current not ordinarily used?

8. What value of the e.m.f. does an alternating-current voltmeter give?

9. Explain the effect upon neighboring circuits of rapidly changing the current in one circuit.

10. What law helps us to determine the direction of the induced e.m.f.?

11. Give an illustration of self-induction.

12. Name the unit of mutual inductance.

13. What is the function of a transformer?

14. Three condensers of equal capacitance are first connected together in series, then in parallel. How much greater is the capacitance of the parallel arrangement than that of the series arrangement?

Ans. The capacitance of the parallel arrangement is nine times as great as the capacitance of the series arrangement.

15. Under what condition does the current lag behind the e.m.f.? Under what condition does it lead the e.m.f.?

CHAPTER 4

ALTERNATING-CURRENT CIRCUITS

Ohm's Law and the Alternating Current.—In the case of direct-current circuits, it has been shown that the relationship of current, potential difference, and resistance is given by Ohm's law. It may be asked whether or not Ohm's law also applies to alternating-current circuits. The answer is definitely yes, *so long as we concern ourselves with circuits containing resistance only.* The law applies equally well to corresponding instantaneous values and to effective values. If there is any inductance or capacitance in the circuit, however, the effect of these upon the current cannot be accounted for by Ohm's law. The special treatment of circuits containing inductance and capacitance will now be considered.

The Nature of Reactance.—In circuits that contain either inductances or capacitances, or both, there is a further opposition to the flow of current, in addition to the resistance of the circuit. This factor of an alternating-current circuit is known as the *reactance*. Previously we have seen that an induced e.m.f. always opposes change in the current. Since alternating current is constantly changing, it follows that there must always be an e.m.f. that opposes this change. This is one of the causes of reactance. This form of reactance is called *inductive reactance*. Furthermore, when there is capacitance in the circuit, this also tends to oppose the change of potential difference. The effect of capacitance in an alternating-current circuit is known as *capacitive reactance*.

Inductive Reactance.—As has just been explained, the opposition of self-inductance to the flow of current is known as inductive reactance. This is measured in ohms, just as is resistance. In the case of a so-called "pure resistance," we found that

$$I = \frac{E}{R}.$$

A similar relationship exists wherever there is a pure reactance. It is thus expressed:

$$I = \frac{E}{X_L},$$

In the above formula, X_L is the inductive reactance. These equations hold good for the maximum values, effective values, or instantaneous values, provided only that the corresponding values of each quantity are used in each case. It must also be recalled that when there is inductance in the circuit, but no capacitance, the current lags 90° behind the potential difference. The value of the inductive reactance is then

$$X_L = 2\pi fL,$$

where X_L is the inductive reactance in ohms, f is the frequency in cycles per second, and L is the inductance in henries.

The Capacitive Reactance.—The opposition that capacitance offers to the flow of current is known as *capacitive reactance.* This is measured in ohms, the unit that is used for both resistance and inductive reactance. The value of the capacitive reactance is

$$X_C = \frac{1}{2\pi fC}$$

where X_C is the capacitive reactance in ohms, f is the frequency in cycles per second, and C is the capacitance in farads. In an alternating-current circuit having only capacitance, the current may be found by means of the formula

$$I = \frac{E}{X_C}$$

It will be recalled that capacitance in a circuit causes the current to lead the potential difference. Upon the phase relations of current and potential difference, therefore, the capacitive reactance has an effect that is precisely the opposite of that of inductive reactance. This can most readily be understood by considering a circuit that contains both inductive and capacitive reactances.

Total Reactance of Combined Inductive and Capacitive Circuit.—Fig. 70 shows a circuit that contains pure inductance and pure capacitance. The inductive reactance is $X_L = 2\pi fL$, and the capacitive reactance is $X_C = \frac{1}{2\pi fC}$. It was previously stated that the inductive reactance causes the current to lag, and that the capacitive reactance causes the current to lead. Since these two reactances produce opposite effects, they naturally tend to nullify each other. In the circuit shown in Fig. 70, the combined reactance is

$$X = X_L - X_C = 2\pi fL - \frac{1}{2\pi fC},$$

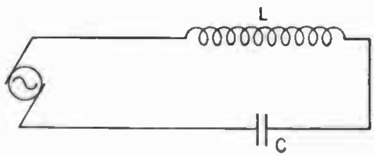


Fig. 70.

where X is the reactance in ohms, f is the frequency in cycles per second, L is the inductance in henries, and C is the capacitance in farads. If the value of the reactance is positive, it indicates that the inductive reactance predominates. On the contrary, if the value of the reactance is negative, the capacitive reactance is greater.

The Significance of Impedance.—The factors that oppose the flow of current are *resistance* and *reactance*. In a circuit that contains only resistance, the current is in phase with the e.m.f. In a circuit that contains only reactance, the current either leads or lags the e.m.f. by 90°. Consequently, the effect of reactance upon the current is at an angle of 90° to the effect of resistance. It is plain that the two effects cannot be combined by means of ordinary addition. The combination of these two factors can be accomplished graphically, however, by the use of a diagram. Fig. 71 shows the method of adding a resistance and a reactance in series. The resistance is represented as a horizontal line drawn to scale. In the illustration, the resistance of 5 ohms is represented by a line 5

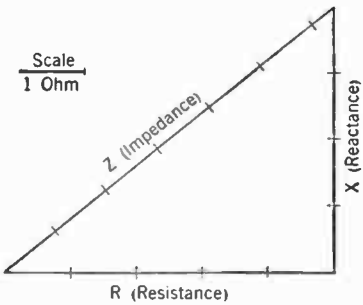


Fig. 71.

units long. At the end of the resistance, and at right angles to it, a line drawn to the same scale represents the reactance. In the diagram the reactance is 4 units, or 4 ohms. The sum of the resistance and the reactance is a diagonal line that connects the ends of the two lines. This combined effect of resistance and reactance, known as *impedance*, is represented by Z. By using the scale, we find that the impedance is 6.4 units, or ohms. Since the reactance is always at right angles to the resistance, the value of the impedance may be found by using the relationship of the sides of a right triangle in place of the graphical method. We know that

$$Z^2 = R^2 + X^2.$$

Hence

$$Z = \sqrt{R^2 + X^2} = \sqrt{5^2 + 4^2} = \sqrt{25 + 16} = \sqrt{41} = 6.4 \text{ ohms}.$$

General Law of the Alternating-Current Circuit.—In the alternating-current circuit there are three principal factors to be considered. They are (1) the effective e.m.f., (2) the effective current, and (3) the impedance. A simple relationship that exists between these quantities is expressed as follows:

$$I = \frac{E}{Z}.$$

In this formula, I is the effective current in amperes, E is the effective e.m.f., and Z is the impedance in ohms. Though the relationship between the quantities is quite simple, nevertheless the separate quantities themselves are far from simple. For this reason it will not be possible, in this limited discussion, to give a complete treatment of alternating-current circuits. In fact, much more space would be needed for discussing this problem completely, due to the complexity and almost infinite variety of such circuits. A few selected situations will be considered, however, so as to explain the procedure as used in solving alternating-current circuits, and also for presenting some types of circuits that are extensively employed in radio.

Circuit with Resistance and Inductance in Series.—Let us first consider a circuit that has a resistance and an inductance in series, as shown by Fig. 72. In a series circuit, the current (whether it be alternating or direct) must be the same throughout the circuit. In the case of the direct current, the total e.m.f. of a series circuit is equal to the sum of the separate e.m.f.'s. The same condition exists in alternating currents, though we must keep in mind that where there are reactances they are at 90° to the resistances, and their corresponding potential drops are also at 90° to the potential drops in the resistances. Plainly, we cannot add these potential drops by means of ordinary arithmetic. For this reason the graphic, or vector, method is used. The potential drop across the resistance, equal to IR, is represented by an arrow drawn horizontally from point O in Fig. 73. The potential drop across the inductance, IX_L, is represented by an arrow drawn vertically upward from O. As we have already seen, $X_L = 2\pi fL$. The potential differences are added by constructing a rectangle and drawing the diagonal from point O. Since $E = \frac{I}{Z}$, then the resultant is $E = IZ$, where Z is the impedance. Resistance alone, however, does not produce a phase change in the current; as a consequence, the direction of IR is also the direction of the current. The angle θ is, then, the phase angle between the total e.m.f. and the current. In this case it may be seen that the current lags behind the e.m.f., and this we know to be a characteristic of an inductive circuit. From the property of the right triangle we have

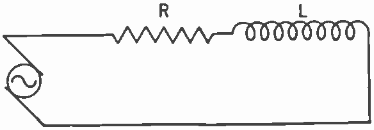


Fig. 72.

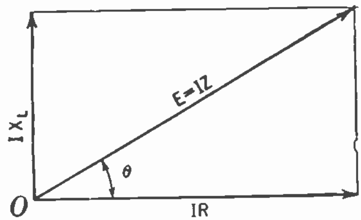


Fig. 73.

$$E^2 = (IR)^2 + (IX_L)^2,$$

or $$E = \sqrt{(IR)^2 + (I2\pi fL)^2} = \sqrt{I^2 (R^2 + 4\pi^2f^2L^2)}.$$

Hence $$E = I\sqrt{R^2 + 4\pi^2f^2L^2} = IZ.$$

The phase angle can also be found, since

$$\tan\theta = \frac{IX_L}{IR} = \frac{X_L}{R} = \frac{2\pi fL}{R}.$$

In this particular case, θ is the lag of the current behind the voltage.

A Circuit Having Resistance and Capacitance in Series.—We shall now consider the case in which we have a resistance and a condenser in series, as shown by Fig. 74. In this circuit there are two potential drops: one is due to the resistance, R, and the other is due to the capacitive reactance of the con-

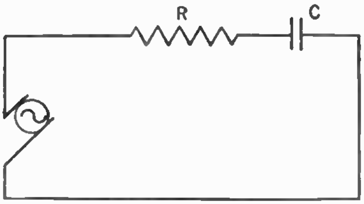


Fig. 74.

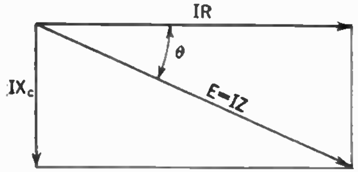


Fig. 75.

denser, C. The method of finding the total potential drop is similar to that used when there was inductive reactance. In Fig. 75 the IR-drop is drawn as in Fig. 73, but the drop due to the capacitive reactance is drawn *downward* instead of upward, as in the case of inductive reactance. The total e.m.f. is again equal to IZ. Since the current leads the e.m.f., the phase angle is equal to θ. The total e.m.f. is again given by the mathematical relationship of the sides of a right triangle. It is

$$E = \sqrt{(IR)^2 + (IX_C)^2} = \sqrt{(IR)^2 + \left(I\frac{1}{2\pi fC}\right)^2},$$

or

$$E = I\sqrt{R^2 + \frac{1}{4\pi^2 f^2 C^2}}.$$

The phase angle is given by

$$\tan\theta = \frac{X_C}{R} = \frac{1}{2\pi fCR},$$

and the current leads the voltage by $\theta°$.

A Circuit Having Resistance, Inductive Reactance, and Capacitive Reactance in Series.—A series circuit having all three factors, that is, resistance, inductive reactance, and capacitive reactance, is solved by means of the principles that we have used for the simpler circuits. The first step is to combine both reactances. Fig. 76 shows a circuit having a resistance, an inductance, and a

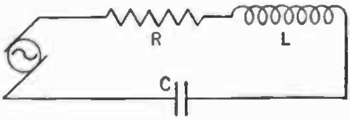


Fig. 76.

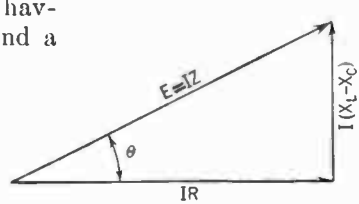


Fig. 77.

condenser in series. The solution of this is shown by Fig. 77. It should be observed that the reactance is the difference between the inductive reactance and the capacitive reactance. In this illustration the inductive reactance is larger than the capacitive reactance. For this reason, the potential drop due to reactance is represented as being in an upward direction. Here the current lags behind the voltage. If the capacitive reactance were greater than the inductive reactance, the potential drop due to reactance would be directed downward. In the latter case the angle θ would represent the amount of lead of the current. The total e.m.f. will be

$$E = I\sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2},$$

and θ may be found by

$$\tan\theta = \frac{\left(2\pi fL - \dfrac{1}{2\pi fC}\right)}{R}.$$

In series circuits in which there are a number of resistances, inductances, and condensers, the combined resistance, inductance, and capacitance may be found by applying the rules for series circuits that have already been explained. The total e.m.f. may then be found in the manner outlined above for a single resistance, inductance, and capacitance.

A Circuit Having Resistance, Inductance, and Capacitance in Parallel.—The potential difference across a number of branches in parallel is the same as that across one branch, just as we found for direct-current circuits. A parallel circuit having a resistance, an inductance, and a condenser is shown by Fig. 78.

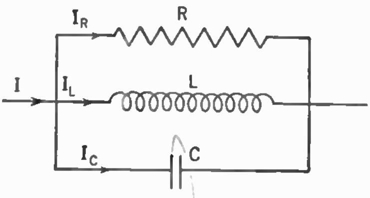


Fig. 78.

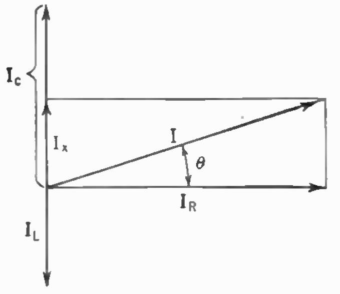


Fig. 79.

The potential difference across the resistance is E_R; across the inductance it is E_L, and across the capacitance it is E_C. If the total e.m.f. is E, then $E = E_R = E_L = E_C$. The total current in the circuit is equal to the vector sum of the individual currents in the parallel branches. Fig. 79 shows the procedure used for adding the currents. The current through the resistance, R, which is represented by I_R, is a horizontal line drawn from point O. The current through the inductance, which is represented by I_L, is drawn vertically downward from O. The current, I_C, through the condenser, is represented by a line drawn upward. The current through the combined inductance and capacitance is the difference between the two separate currents. If we call this combined current through the combined reactance I_X, then $I_X = I_C - I_L$. In the case we have selected, I_C is greater than I_L; hence I_X is directed upward. The current I_X is now added to the current I_R by means of the diagram, according to the method that was used for e.m.f.'s. The total current in the circuit is then

$$I = \sqrt{I_R^2 + I_X^2},$$

$$I = \sqrt{I_R^2 + (I_C - I_L)^2}.$$

Since the current through the resistance is in phase with the e.m.f., the angle θ, between I_R and I, is the phase angle. In the present case, the phase angle is a leading angle because the current in the capacitance is greater than that in the inductance. If the current in the inductance had been greater, the angle θ would have been a so-called *angle of lag*. The value of the phase angle may be expressed as

$$\tan \theta = \frac{I_C - I_L}{I_R}.$$

Combining Alternating-Current Curves.—The currents in parallel branch circuits may be either in phase or out of phase. In the former case, the combining of the currents is a simple matter. If we have currents in two branches, one being I_1 and the other I_2, the graphs of these currents are shown by Fig. 80. The instantaneous current in the case of I_1 is $i_1 = I_{1m} \sin \phi$, and for I_2 it is $i_2 = I_{2m} \sin \phi$.

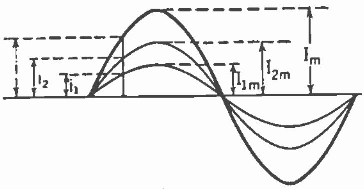


Fig. 80.

Since the currents are in phase, the value of ϕ is the same in both cases. The instantaneous value of the total current is $i = i_1 + i_2$; hence $i = (I_{1m} + I_{2m}) \sin \phi$. It is evident that $I_m = I_{1m} + I_{2m}$ and also $I = I_1 + I_2$. On the graph, the values of i_1 and i_2 are added, then plotted for the same value of ϕ. It will be noted that the resultant curve is also a sine wave having the same frequency as that of the individual currents in the two branches. The current flowing in the main circuit will therefore have the same frequency as the current in the two branches, but will have instantaneous and maximum values that are equal to the sum of these two currents. It must be realized, of course, that the total current flowing in the circuit is a *single current*, not two separate currents.

When the currents in the parallel branch circuits are out of phase, the resultant curves are again found by combining the separate currents for the given phase angle. Fig. 81 illustrates the curve of the combined current of two currents in parallel circuits, where they are out of phase by 180°. The frequency of the total current and the individual currents is the same. The value of the instantaneous current would be $i = i_1 - i_2$. Hence

$$i = I_{1m} \sin \phi_1 - I_{2m} \sin \phi_2 = (I_{1m} - I_{2m}) \sin \phi;$$

thus,

$$I_m = I_{1m} - I_{2m}.$$

If the currents are out of phase by some angle other than 180°, then the method of combining them is first to combine the cur-

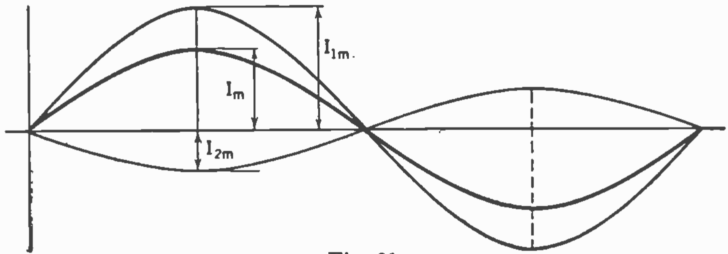


Fig. 81.

rents through the reactances, then to combine the result of this with the current through the resistance.

Resonance in Series Circuits.—A series circuit is in *resonance* when the capacitive reactance is equal to the inductive reactance. In such a case the total reactance is 0. When a series circuit is in resonance, the maximum current flows. In a circuit that has a resultant inductive reactance, this may be reduced to 0 by adding a suitable capacitance to the circuit. On the contrary, however, if the resultant reactance is capacitive, the addition of a suitable inductance will produce resonance. The production of resonance for a given frequency is one of the basic principles of radio circuits. The operation is known as *tuning;* its purpose is to produce the strongest possible current for a desired frequency.

Resonance in Parallel Circuits.—We have just learned that in a series circuit resonance occurs when the inductive reactance

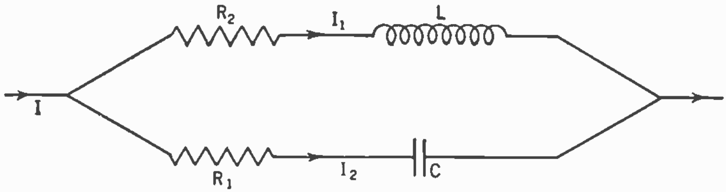


Fig. 82.

is equal to the capacitive reactance. This is the same as saying that the lagging component of the e.m.f. is equal to the leading component of the e.m.f. Under these circumstances, the impedance is a minimum, and the current is a maximum, for a given potential difference. In a parallel circuit there is resonance when the lagging component of the current is equal to the leading component. If there is an inductive reactance in one branch of the parallel circuit, and a capacitive reactance in the other, as shown by Fig. 82, resonance occurs when the impedance of the combination is a maximum, and the current through the combination is a minimum. This is shown by Fig. 83. Under the conditions of resonance for this circuit, the lagging current in the branch containing inductive reactance is equal to the leading current in the branch containing capacitive reactance.

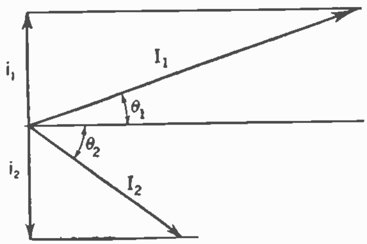


Fig. 83.

Resonance in Series-Parallel Circuits.—It has just been explained that in a series-resonant circuit, the impedance is at a minimum and is equal to the resistance of the circuit; also, that in a parallel circuit in resonance, the impedance is at a maximum. These two principles are utilized in certain types of circuits, among them such as are shown in Fig. 84. The condenser, C_2, is varied to produce resonance for a particular frequency. Since for the resonant condition in a parallel circuit the impedance is at

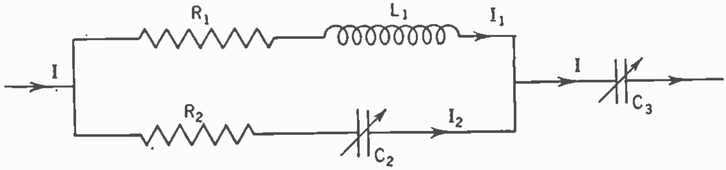


Fig. 84.

a maximum, the current will be at a minimum for this frequency, and so will be suppressed. If the condenser, C_3, is varied so that the series circuit is in resonance for a different frequency, this latter frequency will have a maximum current in the circuit. Thus, by using a series-parallel circuit, a desired frequency can be emphasized by having the series circuit in resonance, and an undesired frequency can be suppressed by having a resonant condition in the parallel portion of the circuit. This principle is extensively utilized in radio circuits as a filtering device that permits certain frequencies and rejects others.

Power in Alternating-Current Circuits.—We learned that in the case of a direct current, the power in a circuit equals the product of the current and the potential difference. If the current is measured in amperes, and the potential difference is measured in volts, the power is in watts. In the case of the alternating current, the power at any one time is equal to the product of the instantaneous current and the instantaneous e.m.f.; that is,

$$p \text{ (watts)} = e \text{ (volts)} \times i \text{ (amperes)},$$

where p is the instantaneous power, e is the instantaneous e.m.f., and i is the instantaneous current. From this it should be clear that

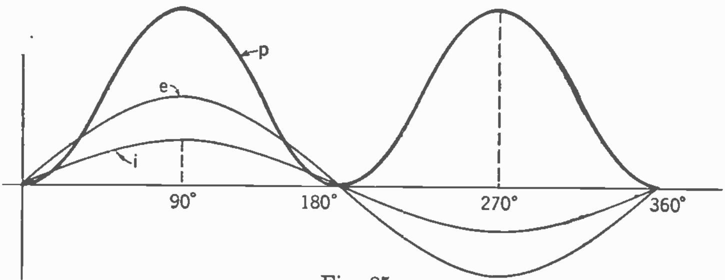


Fig. 85.

the power in an alternating current is constantly changing. Over a period of time the power will depend upon the phase relation of the current and the e.m.f. A few different instances of phase relation will show how the power is affected by the difference in phase. Let us first consider a case in which the current and the voltage are in phase. Fig. 85 shows the power, the current, and the e.m.f. curves for the case where the current and the voltage are in phase. The power curve is found by multiplying each instantaneous current by its corresponding instantaneous e.m.f. It will be observed that the power is always positive. The reason for this is that when the current is negative, the voltage is also negative, and their product is positive. In this circuit all the power is consumed in overcoming the resistance. The average power is equal to the product of the effective e.m.f. and the effective current. This, however, applies only to a circuit having resistance but no reactance. If a circuit has no resistance and no capacitance, but only inductive reactance, the curves for power, current, and e.m.f. are shown in Fig. 86. It will be recalled that in a circuit that contains only inductive reactance, the current lags 90° behind the e.m.f. Here again the instantaneous power is equal to the instantaneous e.m.f. times the instantaneous current. It may be seen from the curves that, during half the cycle, the current and the e.m.f. are opposite in sign. This causes the power to be negative, as is shown by the power curve. Negative power means that the line is returning power to the generator. In this case of pure inductive reactance, power is drawn from the generator during the

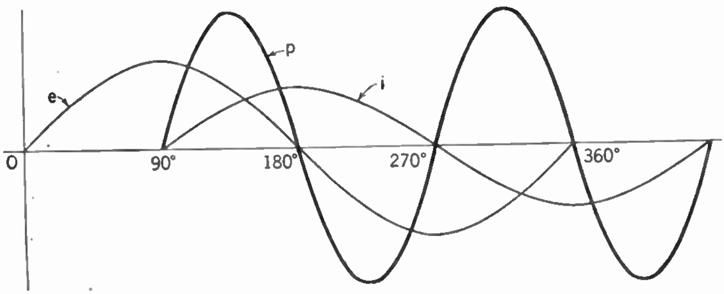


Fig. 86.

remaining half, so that the net power consumed is 0. The average power consumed by a pure reactive circuit is 0, whether it be inductive or capacitive.

The Power Factor.—Since power is consumed in a circuit having pure resistance, and since no power is consumed in a circuit having pure reactance, this suggests a method for determining the power in a circuit that contains both resistance and reactance. It is only the resistance that takes power from the generator. In Fig. 87 the current and the e.m.f. are represented with their phase angle, θ. The current is broken down into two components, one in the direction of the e.m.f., and the other at right angles to it. Only the current in the direction of the e.m.f. is needed for computing the power consumption. That part of the current which is due to the reactance plays no part in the computation of the power. The current component due to the resistance can be found from the

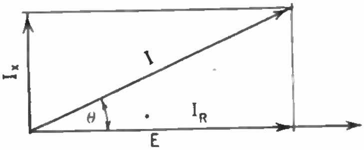


Fig. 87.

vector diagram, $I_R = I \cos\theta$. The average power is then $P = EI_R = EI \cos\theta$. The quantity *cos θ* is known as the *power factor*; it is the factor by which the product of the effective current and the e.m.f. must be multiplied in order to get the average power. It should be remembered that $P = EI \cos\theta$ is the general equation for the average power in an alternating-current circuit. It is interesting to note that the power factor takes care of all the cases we have discussed. When there is only resistance in the circuit, then the phase angle is 0 and $\cos\theta$ is equal to 1; in this case, $P = EI$. When there is only reactance in the circuit, the phase angle is 90° and $\cos\theta$ is 0, so that no power is consumed.

The Measurement of Power.—In direct-current circuits the power can be found by using an ammeter for determining the current and a voltmeter for determining the e.m.f. The power is then found by multiplying the current by the e.m.f. In alternating-current circuits the effective current can be found by means of an alternating-current ammeter, and the effective e.m.f. by means of an alternating-current voltmeter. The product of these two will, in general, *not* be the power in watts. The product of amperes and volts must be multiplied by the power factor. An instrument that gives the power directly for both direct-current and alternating-current circuits is called the *wattmeter*. It is so constructed that it includes the power factor in its reading; it is unnecessary to know this factor separately.

Alternating-Current Measuring Instruments.—In the case of direct-current circuits, we have already seen that the most commonly used type of instrument for measuring both the current and the potential difference is a D'Arsonval galvanometer that has suitable shunts and multipliers. It will be recalled that this instrument is based upon the principle of a current flowing through a coil between the poles of a permanent magnet. In the case of an alternating current, the magnetic field due to the current in the coil is constantly changing. We should expect that the coil would vibrate back and forth with the frequency of the alternating current. Due to the inertia of the coil, however, and to the continued rapid reversing of the magnetic field, the coil vibrates only slightly from its position of rest. For this reason the permanent-magnet type of instrument is used only in direct-current circuits. In the case of alternating currents, a number of devices are used for overcoming this shortcoming of the D'Arsonval type instrument. The most important of these will now be explained.

The Thompson Inclined-Coil Instrument.—An instrument that can be used for measuring low-frequency alternating currents is shown in Fig. 88. A fixed coil, *A*, is mounted at an angle to the horizontal. At the center of this coil is a soft-iron vane, *B*, which is in a plane at right angles to the coil. The vane is mounted on a vertical shaft, *C*, which is free to turn on jeweled bearings. Attached to the shaft is a pointer, *D*, which moves over a scale, *E*. When an alternating current is sent through the coil, the vane of soft iron attempts to set itself along the lines of force that were set up by the current in the coil, thus causing the shaft to turn against the restraining action of the flat coil spring, *F*, attached to the shaft. Since the vane is made of soft iron, it tends to set itself along the lines of force of the coil, irrespective of the direction in which the lines of force run. The amount of displacement of the pointer depends upon the effective value of the current flow, but is not directly proportional to it. For this reason the scale does not contain equal divisions, but is more crowded at the end where the smaller values are located. When no current flows in the coil, the spring brings the pointer back to 0.

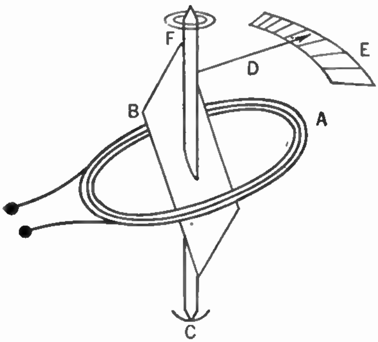


Fig. 88.

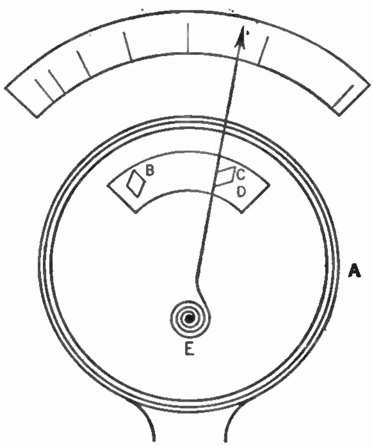


Fig. 89.

The Moving-Vane Type of Instrument.—Another principle employed for measuring alternating currents is shown by Fig. 89. An alternating current flows in a fixed coil, *A*. Inside the coil are two soft-iron vanes. One vane, *B*, is fixed; the other, *C*, is attached to a pointer mounted on an axis. The alternating current magnetizes the two iron vanes similarly, regardless of the direction of the current. Since the two pieces of iron are similarly magnetized, they repel each other and the pointer moves over the scale. The moving vane fits loosely in a small air compartment, *D*. This causes the instrument to be damped. A spring, *E*, attached to the pointer, brings it back to 0 when the current is not flowing. The scale of this instrument is also non-uniform.

The Electrodynamometer.—The two-coil type of instrument is sometimes employed for making alternating-current measurements. Such a device is known as a *dynamometer*. A diagram of the principle of this instrument is shown in Fig. 90. *A* and *B* are two fixed coils connected in series with a third coil, *C*, which is

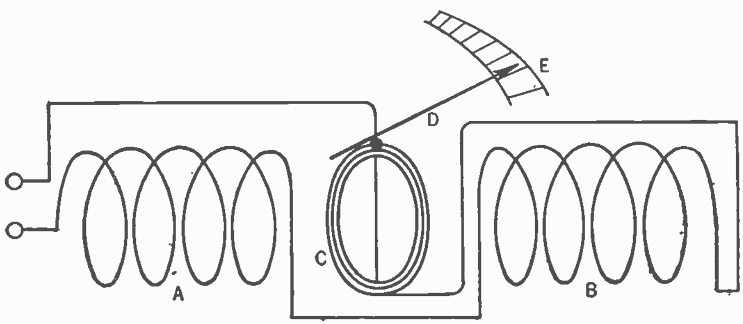


Fig. 90.

free to move about a vertical axis. A pointer, *D*, attached to the moving coil, indicates the value on a scale, *E*. A hairspring is attached to the pointer for the purpose of returning it to the 0 position when no current flows. Since the current changes simultaneously in both the fixed coils and the moving coil, the deflection is always in one direction; thus the instrument can be used for measuring alternating currents. If a shunt is used in connection with the dynamometer, the latter can also be used as an ammeter; if a multiplier is used, the electrodynamometer will serve as a voltmeter.

Hot-Wire Instruments.—Since the heating effect of a current is independent of the direction of the current, this fact may be utilized for measuring both direct currents and alternating currents. A diagram of an instrument based upon this principle is shown in Fig. 91. The current flows through a wire, *AB*. The end, *A*, is permanently fixed, and *B* is attached to the circumference of a cylinder. A pointer, *D*, connected to the cylinder, moves over the scale, *E*. A spring, *C*, tends to turn the pointer for full deflection. The wire *AB* is wound around the cylinder in such manner as to oppose the action of the spring. When the current through *AB* becomes greater, the wire becomes hotter and so expands. This causes a slack in the wire, and the spring causes the pointer to move over the scale that indicates a larger current. The hot-wire type of instrument is slow in operation and is affected by room temperatures. It usually requires frequent resetting of the pointer for the purpose of indicating 0 when no current is flowing.

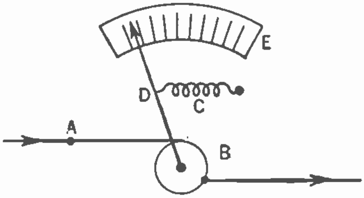


Fig. 91.

Thermocouple Instruments.—The principle of the thermocouple has already been explained. In the thermocouple ammeter, the main element is a thermocouple, as shown by Fig. 92. This type of meter is commonly used for radio frequencies; that is, for frequencies of more than 20,000 cycles per second. In the diagram, *A* is a sensitive thermocouple, usually made of two wires, one of them an antimony alloy, the other, a bismuth alloy. The current flows from one terminal of the instrument through the thermojunction, *B*, to the other terminal. The junction, *B*, is heated by the flow of the current. A sensitive D'Arsonval galvanometer is connected between *B* and the cool junction of the thermocouple. A small direct current then flows through the galvanometer, thus causing a deflection of the pointer. Being nonuniform and crowded at the lower readings, the scale is therefore read with great difficulty in this area. Another disadvantage of this form of instrument is the burning-out of the thermocouple.

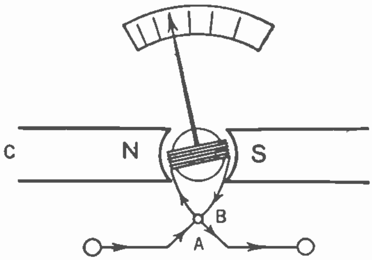


Fig. 92.

This does not affect the rest of the instrument, however; the thermocouple can readily be replaced at small cost.

QUESTIONS

1. Under what condition does Ohm's law apply to alternating-current circuits?

2. What effects are produced by an inductance in an alternating-current circuit?

3. In what way does capacitance affect the phase relationship between the current and the e.m.f.?

4. Explain the difference between resistance and reactance in an alternating-current circuit.

5. How may one calculate the impedance of a circuit that has both resistance and reactance?

6. Explain the three important factors in an alternating-current circuit.

7. What are the current-and-e.m.f. relations in a series alternating-current circuit?

8. Draw graphs that show how currents in phase can be added.

9. Explain how resonance can be established in a series circuit.

10. What is the value of the impedance in a parallel resonant circuit?

11. Explain a practical use of resonance in a series-parallel circuit.

12. What characteristic accounts for the consumption of power in an alternating-current circuit?

13. In what manner does the power factor affect average power consumption?

14. Draw a diagram that shows how a dynamometer-type instrument can be used as a wattmeter.

15. Name two instruments that can be used for radio-frequency measurements.

CHAPTER 5

ELECTRONICS

The Edison Effect.—Aside from a comparable similarity of shape that is at once apparent, further examination of a radio tube is hardly likely to cause one to realize that its action is based upon a principle discovered by Thomas A. Edison at the time when he was making early experiments in the manufacture of the incandescent lamp. Yet Edison did stumble upon that particular principle. Little did he reckon that it would later be employed in the manufacture of a device that has come to have so many and such various uses. In the early manufacture of the lamp he had invented, Edison observed that the filament was gradually eaten away, and thus eventually burned out. Careful examination showed that this invariably took place at the negative end of the filament. In order to study this action, he constructed a special tube. It was an ordinary electric lamp having a special plate that was placed inside the evacuated bulb and connected to an outside terminal. A sensitive galvanometer was connected between the plate and the positive terminal of the filament, as shown by Fig. 93. It was then observed that a current flowed from the plate to the filament. When the connection from the galvanometer was removed from the positive terminal of the filament to the negative terminal, the galvanometer thereupon indicated no current. Edison realized the importance of this flow of current through an evacuated tube, but he was unable to explain it. He made a careful record of the experiment and later it came to be known as the *Edison effect.*

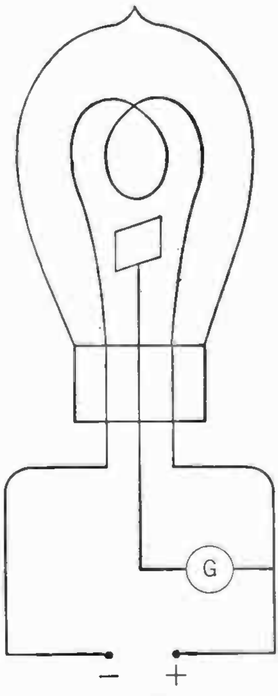


Fig. 93.

Thermionic Emission.—The Edison effect was finally explained according to the theory that electrons were being given off by the heated filament. It is profitable for us to study this extremely important concept. Any substance, when heated to a sufficiently high temperature, gives off electrons. These electrons are called *thermions*, and the action is known as *thermionic emission*. This thermionic emission has often been compared to the evaporation of water. As any substance is heated, the electrons gain energy; some break away from the body of the substance. The heating may be brought about in any manner, but in many practical cases it is done by means of heat produced by an electrical current that flows through the substance. In their property of thermionic emission, materials differ considerably. When platinum is coated with an oxide of barium or strontium, for example, its thermionic emission is increased enormously. Some substances, even at a low temperature, give off large quantities of electrons. One such substance is thorium. A filament impregnated with a small quantity of this salt is called a *thoriated filament*.

The Diode.—By making use of the Edison effect, Fleming constructed a tube like that shown in Fig. 94. Here, *F* is a wire filament that is supplied with current from a battery, *A*, of low voltage; *E* is an evacuated envelope, usually made of glass, but sometimes of metal; *T* is a metallic plate. Both filament and plate are enclosed in the evacuated envelope. The current through the filament heats it to a point where it emits a large number of electrons. This circuit is known as the *filament circuit*, or the *A circuit*. The *A* battery is usually on the order of a few volts. Another battery, *B*, of large e.m.f., is connected across the plate and the filament, the plate being connected to the positive terminal of the battery.

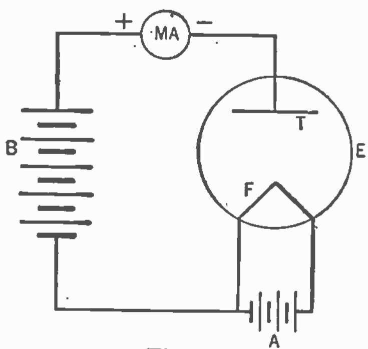


Fig. 94.

This circuit is called the *plate circuit*, or the *B circuit*. The high positive potential on the plate causes the electrons to move through the evacuated space to the plate. In Fig. 94 the milliammeter measures this plate current. If the plate is made negative, there is no plate current because the electrons are repelled by the plate. An electrode that is the source of electrons is called a *cathode.* A tube containing a cathode and plate is known as a *two-element tube,* or a *diode.*

The Diode as a Thermionic Valve.—It has just been explained that when the plate is made positive, electrons will thereupon flow from the cathode to the plate. If the plate is made negative, however, no electrons will flow through the tube. This is the same as saying that when the plate is positive, a current flows in the plate circuit; and that when the plate is negative, there is no plate current at all. Fleming realized the importance of this fact in that he called his tube a *valve.* This valve action of a diode, which causes it to make a current to flow in only one direction, is extensively used wherever a rectified current is wanted. In order to understand the general principle of the rectifying effect of a diode, we shall consider an alternating e.m.f. connected across the diode, from cathode to plate, as shown by Fig. 95. In this instance it will be observed that the *B* battery has been replaced by an alternating-current generator. Nevertheless, it is also important to recall that the e.m.f. from an alternating-current generator varies. Fig. 96 shows a graph of

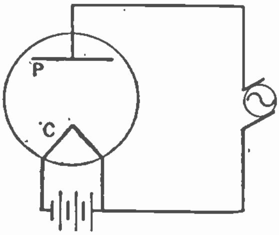


Fig. 95.

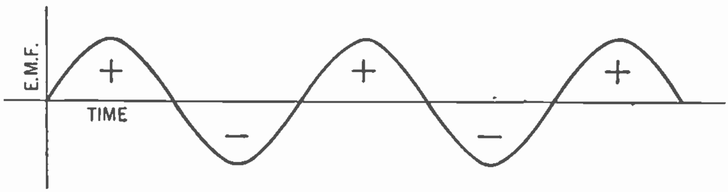


Fig. 96.

just such an e.m.f. The graph shows the time during which one terminal of the generator is positive, and also the time during which the terminal is negative. This means that the plate will be alternately positive and negative for equal intervals of time. The rectified output is shown by Fig. 97. The time intervals are the same as those shown in Fig. 96. The conclusions to be drawn from an analysis of the graph are these: (1) the current always flows in one direction; (2) it is intermittent; (3) it varies from 0 to a maximum. A more complete explanation of the part the diode plays in rectifying circuits will be found in the subsequent discussion of power supply (page 99).

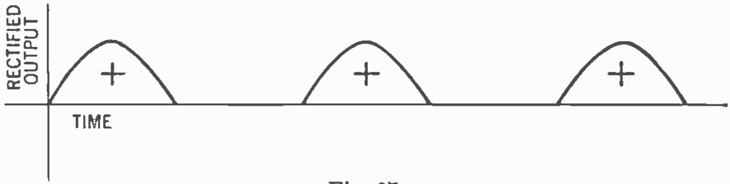


Fig. 97.

Some Characteristic Curves.—When the plate is kept at a positive potential, not all the electrons emitted by the cathode reach the plate; some of them return to the cathode, while others remain for a short time in the space between the cathode and the plate. Those electrons that remain in the space produce an effect known as the *space charge*. It will be recalled that like charges repel each other. As a consequence of this fact, the space charge has a repelling action on the electrons that attempt to leave the cathode, and it also opposes those electrons that are traveling towards the plate. This, of course, reduces the value of the plate current. The extent of the space charge depends upon the cathode temperature and also upon the plate potential. Fig. 98 shows the effect on the plate current that is due to changing the plate voltage. Such a curve is called a *characteristic curve* of the tube. As the potential on the plate is increased, more of the electrons in the space-charge region are drawn toward the plate. This reduces the effect of the space charge, and in consequence increases the plate current. This action continues until all electrons are removed from the space-charge region. Beyond this point, further increase in plate voltage does not result in an increase in the plate current. This is illustrated by point *S* on the graph. This point is known as the *saturation point*. The

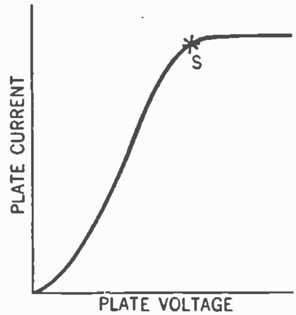


Fig. 98.

reason for this condition is that all electrons that are emitted from the cathode are already being drawn toward the plate, and consequently further increase in plate voltage cannot at all increase the current. The maximum current is called the *saturation current*. This is also sometimes referred to as the *emission current* because (as has been previously mentioned) under the condition of saturation all emitted electrons flow through the tube. If the temperature of the cathode is increased, the rate of emission of electrons from the cathode is also increased. This results in a larger saturation, or emission, current. In Fig. 99 you may observe characteristic curves for the same diode, but in this instance the cathode is operated at different temperatures. Each curve is marked with the temperature at which the cathode is to be kept while the plate voltage is being changed. T_1 is the lowest temperature, and T_5 is the highest. It will be observed that the initial part of all curves is identically the same. Curves for the higher temperatures reach their saturation points at higher voltages. After reaching the saturation point, the current for each curve remains practically constant for further increases in voltage. All this is readily understandable when we realize that an increase in the temperature of the cathode results in a higher rate of emission of electrons. This, in turn, produces a greater space charge. As a consequence of this, a higher potential on the plate is necessary for the removal of all electrons from the space-charge region.

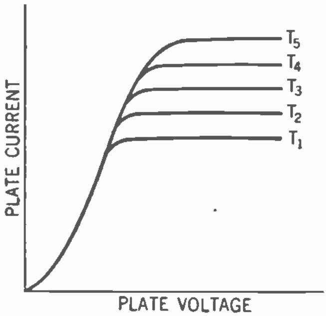


Fig. 99.

The Cathodes.—The cathode in a diode (or in any of the many other types of radio tube that will be described later) has the important function of supplying electrons for the operation of the tube. So far as concerns the cathode, one of the important problems is that of a method of heating it to the temperature required for suitable emission. The manner in which a cathode may be heated is frequently used as the basis for classifying cathodes. Those cathodes that are directly heated by the passage of a current through the material of the cathode are called *fila-*

ment cathodes; those that are heated indirectly are known as *heater cathodes.*

The Filament Cathode.—So far as concerns the filament cathode, the current flows directly through a filament made of substances that have been found to be satisfactory electron emitters. Materials most commonly used are tungsten, thoriated tungsten, and metals that have been coated with alkaline-earth oxides. If pure tungsten is used, a large current is necessary in order to heat the tungsten to a white heat so that a sufficient electron emission may be obtained. On the contrary, a filament made of tungsten that has been treated with a small amount of thorium requires a much smaller current, because the thoriated tungsten emits electrons of sufficient amount at a much lower temperature than does pure tungsten. The filament can be operated at a still lower temperature if a wire made of a nickel alloy having a thick coating of alkaline earths is used. Filament cathodes require comparatively little electric power. Where the source of electric power is limited, they are to be preferred for this reason. This would, of course, apply to nearly all battery-operated tubes because one wants to impose as little drain as possible upon the battery.

The Heater Cathodes.—An indirectly heated cathode consists of a thin sleeve coated with some satisfactory electron-emitting substance, as is shown by Fig. 100, where *C* is the cathode and *H* is a heater inside the cathode, but insulated from it. The heater is usually a tungsten wire through which a current is flowing. Its only function is to supply heat to the cathode. Electron emission from the heater is not utilized. The useful electron emission comes from the heated cathode.

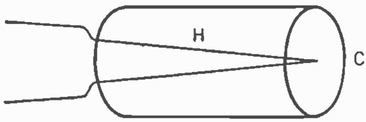


Fig. 100.

Since the heater current is not a part of the tube circuit, therefore an alternating current may be used without the resulting hum that would ensue if the cathode were directly heated. The heater-type cathode is also well adapted for use in automobile radios, because, in those, electrical interference might enter the tube circuit through the heater supply line. It also offers many advantages in flexibility of tube operation because of the separation of the heater supply current from the rest of the tube. This type also permits a closer spacing of cathode and plate; this results in a smaller voltage drop in the tube. Almost all receiving tubes for alternating-current operation manufactured today have heater-type cathodes.

The Triode.—In experimenting with the diode, De Forest added a third element to the tube. The new element, called the *grid,* was placed between the filament and the plate. De Forest called this new tube an *audion,* though today it is commonly known as a *triode.* Fig. 101 shows the construction of a simple filament-cathode triode. The filament cathode is near the axis of the evacuated envelope. The plate is a thin metal sheet having

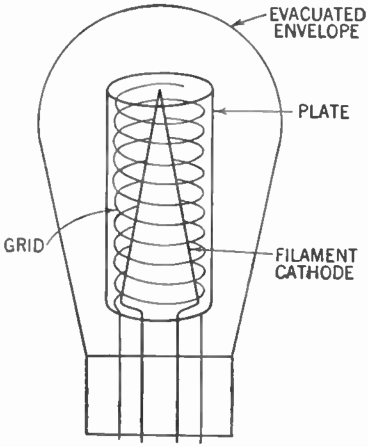


Fig. 101.

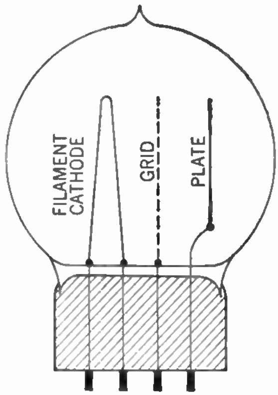


Fig. 102.

the shape of a cylinder. The grid is a mesh of fine wire between the cathode and the plate. The arrangement may readily be understood from the schematic diagram of Fig. 102. The cathode gives off electrons that travel through the tube to the plate, which is at a positive potential. If the grid is at a positive potential, it speeds up the electrons from the cathode and so prevents the building up of a large space charge. Since the grid is very near the cathode, a small potential on the grid produces a much greater effect than does a larger potential on the plate. Because the grid occupies very little space, and because there are relatively large openings in the mesh of the grid, most of the electrons do not stop at the grid, but instead pass through the mesh of the grid and continue on to the plate. A positive potential on the grid therefore greatly increases the plate current. If the grid is at a negative potential, it will repel the electrons and so slow them down in their flow from the cathode to the plate. Since the grid is so much nearer the cathode than is the plate, a comparatively small negative potential on the grid may prevent any electrons whatsoever from reaching the plate, even though the latter has a positive potential. From this we can see that the plate current can be controlled by means of small variations of the grid potential. When the grid is used in this manner it is called a *control grid*. The potential on the grid is called the *grid bias;* customarily it is negative. The battery that supplies the grid bias is called the *C*

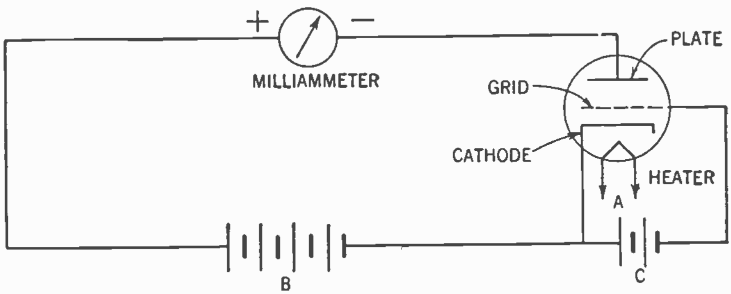


Fig. 103.

battery. Fig. 103 shows a typical circuit of a triode having a heater cathode. It will be noticed that the plate voltage is supplied by the *B* battery, the grid bias by the *C* battery, and the heater of the cathode by the *A* supply. The milliammeter measures the plate current.

Characteristic Curves of a Triode.—The characteristics of a radio tube are utilized in identifying its distinguishing features and values. There are two general ways in which the characteristics of a tube are given. The first method makes use of graphs known as *characteristic curves*. We are already familiar with this method (in connection with the characteristics of the diode that were presented in the discussion of this type tube). The second method of giving the characteristics is by means of a tabulated form arranged in terms of certain defining quantities that will be discussed later. As concerns the triode, there are two types of characteristic curve. The first type of characteristic curve is obtained by varying the direct-current voltages on the electrodes of the tube. This is known as the *static characteristic curve*. The second type is obtained by means of an alternating-current voltage on the control grid, and by varying conditions of direct-current voltage on the electrodes of the tube. These are known as the *dynamic characteristics*. The latter indicate the performance of the tube under actual working conditions.

Static Characteristic Curves.—Two kinds of curves show the static characteristics of a triode. These are known as the *plate characteristic* curves and the *transfer characteristic* curves. They give the same information, but in different forms. The plate characteristic curve is a graph of plate currents against plate

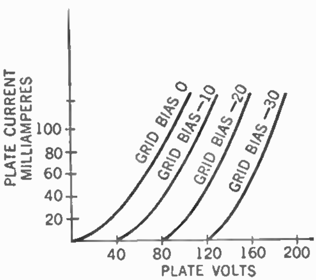


Fig. 104.

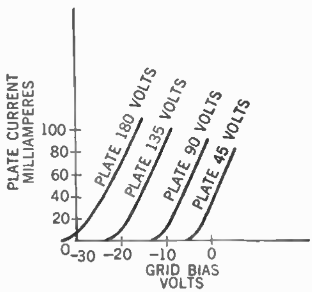


Fig. 105.

voltages for different grid-bias voltages. Fig. 104 shows a group of plate characteristic curves for a given tube. These curves are for a heater cathode tube, so that saturation is not reached for the voltages studied because the heater can be so regulated that the cathode emits sufficient electrons. A transfer characteristic curve shows the relationship of the plate current and the grid bias. These curves are sometimes called *mutual characteristic* curves. A family of transfer, or mutual, characteristic curves is shown for a given triode in Fig. 105.

The Triode as an Amplifier.—One of the most important functions of the triode is to strengthen, or amplify, weak signals. A simple circuit for the illustration of this principle is shown by Fig. 106. The input is connected to the grid. We may consider the input signal as a weak alternating current of a given frequency. The variations of potential on the grid, due to this alternating current, cause variations in the plate circuit of the same frequency, though they are of increased magnitude, as is shown by an alternating-current ammeter in the plate circuit. The resistance, R, in the plate circuit is called the load of the tube, and the value of this resistance in relation to the resistance of the tube determines the amount of amplification produced. In order to adjust conditions so that the wave form of the output voltage is precisely like that of the input voltage, the C bias and the magnitude of the input voltage must be such that only the

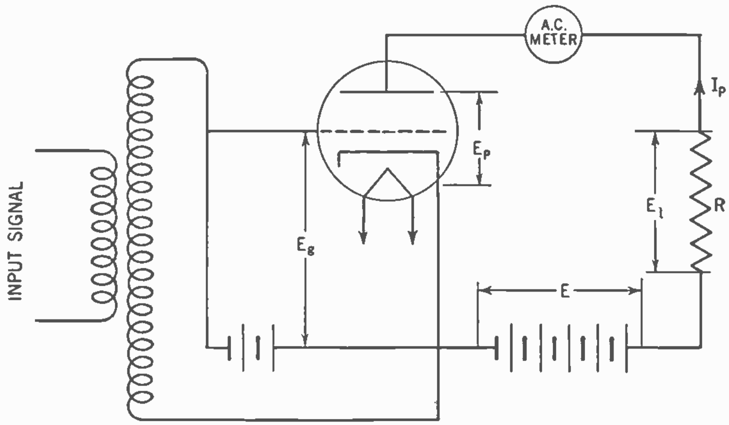


Fig. 106.

straight part of the characteristic curve is used; the load resistance must be high in value as compared with the tube resistance. In the circuit diagram, the voltage between the cathode and the plate is indicated as E_p, the voltage across the load resistance as E_l, and the voltage supplied by the B battery as E. According to Ohm's law, there is a potential drop through the resistance that is equal to the product of the plate current and the load resistance; that is, $E_l = I_pR$. The potential on the plate must be reduced by this amount, and hence, $E_p = E - E_l = E - I_pR$. In other words, a variation in the grid voltage, E_g, will produce not only a variation in the plate current, but also in the plate voltage. It is obvious, then, that the static characteristics of the tube cannot be used because they were determined by having a constant voltage on the plate. The characteristics of the tube under actual working conditions are called the *dynamic characteristics.* A curve showing these characteristics is known as a *dynamic characteristic curve.*

The Dynamic Characteristic Curve.—A dynamic characteristic curve may be obtained by using a resistance of a given value as a load resistance in the plate circuit of the tube, and then plotting, under this condition, the grid bias and the plate current, as was done for static conditions. By using different load resistances, a family of curves similar to those shown in Fig. 107 can be obtained. The static curve may also be drawn with the

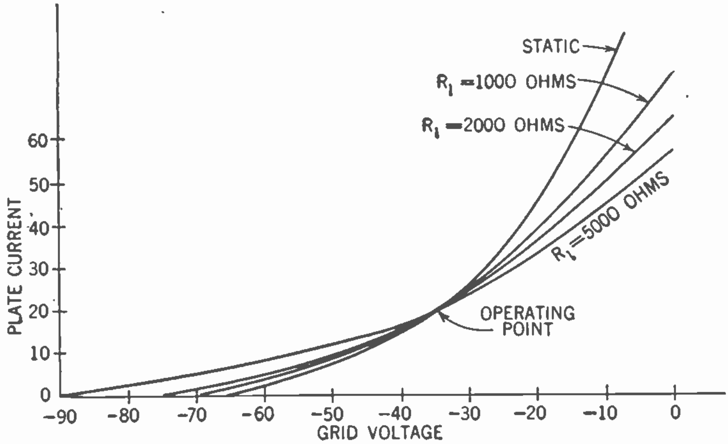


Fig. 107.

dynamic curves, as a basis for comparison. It will be noticed that the dynamic curves are much flatter and longer than are the static curves. This means that the plate current variations are much smaller under the same grid voltage variations. It should also be noted that all dynamic curves, and also the static curve, intersect at a single point. This point is called the *operating point.* At this point the characteristics are the same for *no* load as for load conditions. The curves for the larger load resistance have the smaller slope. In order to summarize the action of the triode as an amplifier, we may examine Fig. 108, which shows a dynamic characteristic curve. The operating point is near the center of the straight portion of the curve; thus the swing, or amplitude, of the grid voltage, due to the signal, reaches neither the lower nor the upper bend of the curve. The latter would bring about a dis-

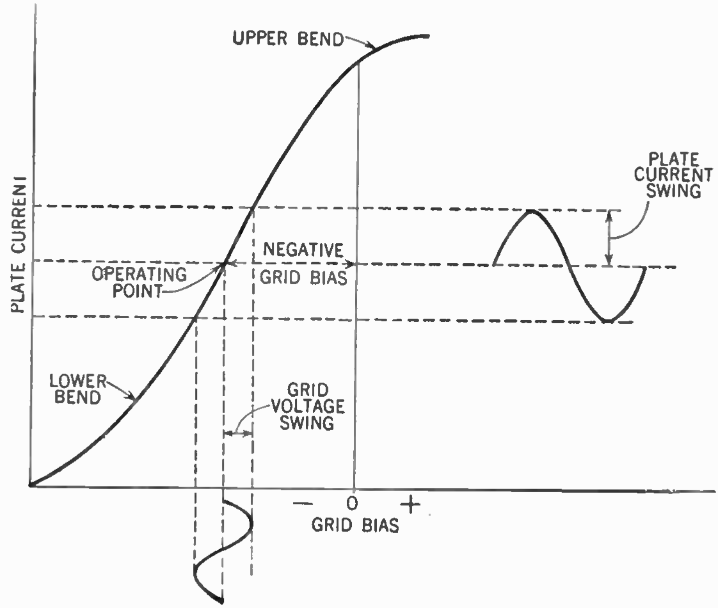


Fig. 108.

tortion of the signal. It will be observed that the plate-current swing is determined by means of the grid-voltage swing and the slope of the straight portion of the characteristic curve.

Tube Characteristics.—A radio tube has many characteristics. Knowledge of these enables us more readily to understand the tube's operation. Some of these will now be defined; others we shall postpone for consideration until we are better acquainted with certain special functions of the various types of tube. These characteristics are usually presented in table form for the various types of tube so that a proper tube may be selected for the task it is required to perform.

The Amplification Factor.—The relative power of plate voltage and grid voltage to control the flow of electrons is called the *amplification factor.* It has already been stated that a small change of the grid voltage will produce a large change in the plate current, as compared with the change in plate current that is produced by a larger plate-voltage change. One method of obtaining the amplification factor is to determine what change in grid voltage will just offset the effect of a given change in plate voltage, so that the plate current thereby remains constant. As an illustration, let us consider a tube in which the grid must be made 0.1 volt more negative when the plate is made 10 volts more positive, so that the plate current does not change. The amplification factor is, therefore, the quotient of the plate-voltage change and the grid-voltage change for this condition. This would be $\frac{10}{0.1} = 100$. The amplification factor is represented by μ.

Plate Resistance.—The plate resistance (r_p) of a radio tube is the resistance to the flow of alternating current set up by the path between cathode and plate. It is the quotient of a small change in plate voltage to a corresponding change in plate current. The value of the plate resistance is in ohms. In order to know how to calculate plate resistance, let us consider the following example: If a change of 2 volts on the plate produces a change of 0.4 milliamperes in the plate current, what is the plate resistance? The value of $r_p = \frac{2}{0.0004} = 5{,}000$ ohms.

Transconductance.—The control-grid-plate transconductance, or *transconductance* (g_m), is defined as the ratio of a small change in plate current to the change in the control-grid voltage that causes it, provided that all other voltages remain unchanged. According to Ohm's law, a potential difference divided by the corresponding current gives us the resistance in ohms. In the case of transconductance, we are dividing a current by a potential difference; thus the quotient must be the reciprocal of resistance. The reciprocal of a resistance is called a *conductance.* Since the ohm is the unit of resistance, it was decided that the unit of conductance, or the reciprocal of resistance, would be the *mho.* The word *mho* is simply the word *ohm* written backwards. The following is an example for determining the transconductance of a tube. A grid-voltage change of 0.4 volt causes a plate-current change of 0.6 milliamperes, with all other voltages constant. The value of transconductance is

$$g_m = \frac{0.0006}{.4} = 0.0015.$$

It is customary to represent transconductance in *micromhos* (one micromho = one-millionth of a mho). In this case $g_m = 0.0015$ mhos = 1.500 micromhos. Another way to consider transconductance is to regard it as a quotient of the amplification factor and the plate resistance; thus,

$$g_m = \frac{\mu}{R_p}.$$

It is important that the transconductance of the tube be high. The transconductance of tubes in actual use varies from approximately 1,000 micromhos to 5,000 micromhos. The relative merit of two tubes of the same type is indicated by the value of their transconductance. The tube having the greater transconductance is the tube of greater merit. This does not apply, of course, to tubes of different types.

The Power Output.—The power in any part of an electric circuit is the product of the current and the potential difference:

$$P \text{ (watts)} = I \text{ (amperes)} \times E \text{ (volts)}.$$

In the plate circuit of the triode, as shown by Fig 108A, the power consumed by the load resistance, R_l, is equal to the product of the plate current, I_p, and the potential difference, E_l, across the load resistance:

$$P_l = I_p \times E_l = I_p^2 R_l.$$

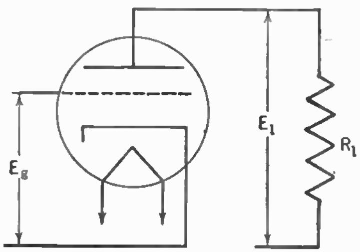


Fig. 108A.

Since the voltage change on the grid, due to the signal, is E_g, the corresponding change of potential on the plate is found by multiplying the value, E_g, by the amplifying factor, μ; that is, $E_p = \mu E_g$. Using Ohm's law on the plate circuit, we have

$$I_p = \frac{E_p}{R_p + R_l} = \frac{\mu E_g}{R_p + R_l}.$$

Therefore $$P_l = I_p^2 R_l = \frac{\mu^2 E_g^2 R_l}{(R_p + R_l)^2}.$$

This is the fundamental equation for the power output of any radio tube, provided that it is operating on the straight part of the characteristic curve.

When a radio tube is operating so that the load resistance is equal to its alternating-current resistance, the tube is delivering its maximum power. This can easily be understood by considering the analogy of a cell having an internal resistance, R_p, as shown by Fig. 109, with an external resistance R_l. When the resistance R_l is 0, the internal IR-drop in the cell is so great that the terminal voltage is 0; there is no external power, since it is all consumed inside the cell. Let us now consider the case where the resistance, R_l, is very much greater than R_p. The current is then reduced to a very small value, and very little energy is used in the circuit. If we gradually reduce the resistance, R_l, until the power consumed outside the cell is equal to the power consumed within the cell, we shall find that this takes place when the external resistance, R_l, is equal to the internal resistance, R_p. This will give the maximum external power consumption. Making use of the general expression for the power output of a radio tube,

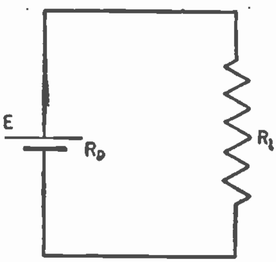


Fig. 109.

$$P_l = \frac{\mu^2 E_g^2 R_l}{(R_p + R_l)^2},$$

we have for the maximum power output

$$P_{l\,max} = \frac{\mu^2 E_g^2 R_p}{4R_p^2} = \frac{\mu^2 E_g^2}{4R_p}$$

The power supplied to the load resistance comes from the B-voltage source. The tube cannot supply power since it is not a generator. It simply acts as a regulator, in the sense that the variation in signal voltage applied to the grid allows energy to be drawn from the B supply and to be consumed in the plate circuit.

Other Tube Constants.—In addition to the tube constants already described, there are also many other constants useful for rating a radio tube. A few of these will now be briefly stated. *Plate dissipation* is the power dissipation in the form of heat provided by the plate as a result of electron bombardment. It can be found by finding the difference between the power supplied to the plate and the power delivered to the load in the plate circuit. The *plate efficiency* of an amplifier tube is the ratio of the alternating-current power output to the product of the average direct-current plate voltage and the direct-current plate current at full signal. Thus the percentage of plate efficiency =

$$\frac{\text{power-output watts} \times 100}{\text{average d.c. plate volts} \times \text{d.c. amperes}}.$$

The *power sensitivity* of a tube is the ratio of the power output to the square of the input signal effective e.m.f. It is expressed in mhos. Thus

Power Sensitivity (mhos) =

$$\frac{\text{Power-output watts}}{(\text{Effective e.m.f. of signal})^2 \text{ volts}^2}.$$

The Tetrode.—When discussing condensers, we defined a condenser as two conductors that are separated by an insulator, or dielectric. Considered from this point of view, the electrodes of a radio tube constitute a number of condensers. These include the grid-plate, the cathode-plate, the grid-cathode, and others. The capacitances of these condensers are known as *inter-electrode capacitances*. These capacitances may produce undesirable effects in the operation of the tube and the circuit in which the latter is interconnected. The most serious of these undesirable effects is caused by the capacitance between the grid and the plate in a triode. In this type of tube, an excessive capacitance that exists between the grid and the plate causes a feedback of energy from the inductive-plate circuit to the tuned-grid circuit. At the time when the triode was the only type of tube available for radio work, a large number of such tubes had to be employed in a radio receiver because the amplification factor, being very low, gave rise to serious feedback oscillations due to the grid-plate capacitance. Various circuit arrangements and oscillation-suppressing devices were employed for the purpose of ridding the receiver of these undesirable oscillations. Today this difficulty is overcome by attacking the trouble at its source. Fig. 110 shows a cutaway section of a tube, which, in addition to the three electrodes (cathode, plate, and grid), has a fourth electrode that consists of a fine spiral, or mesh, of wire between the control grid and the plate. This tube, with its four electrodes, is known as a *tetrode*. The additional electrode of the tube is known as a *screen grid*. Since the latter is placed between the control grid and the plate, it acts as an electrostatic shield and thus reduces the grid-to-plate capacitance. The screen grid is grounded through a fixed condenser. Since this condenser offers an easy path for an alternating current, it is called a *by-pass condenser*. It must be realized that by having the condenser between the screen grid and the ground, the direct-current circuit is not grounded. The screen grid shields the control grid from oscillations on the plate, and thus harmlessly by-passes them to the ground; in this manner it prevents the feedback found in the regular triode. The screen grid, although at a positive potential, is at a much lower potential than is the plate; hence the electrons are attracted to the plate with greater force than to the screen grid. The plate resistance of a tetrode is extremely high; in consequence of this, the amplification factor is also high because it is equal to the product of the plate resistance and the transconductance.

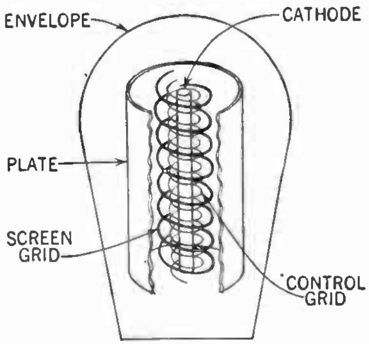


Fig. 110.

The Pentode.—In a radio tube, electrons that strike the plate, if moving at sufficiently high velocities, dislodge other electrons from the plate. This secondary emission takes place in triodes, but since the amplification factor in such tubes is small, there is no appreciable effect. In the case of a tetrode, which has a large amplification factor, this secondary emission becomes a serious problem. The electrons from the secondary emission hinder the regular flow of electrons to the plate, and may even go to the screen grid, thus causing further trouble. When amplification with the tetrode is attempted beyond a certain point, the secondary emission interferes with the proper operation of the tube. This, therefore, seriously limits the amplification

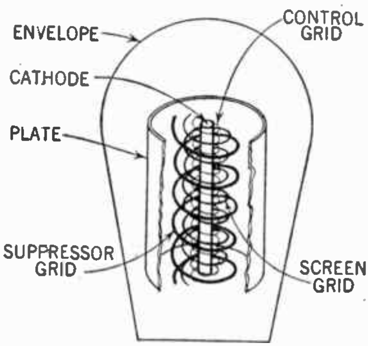


Fig. 111.

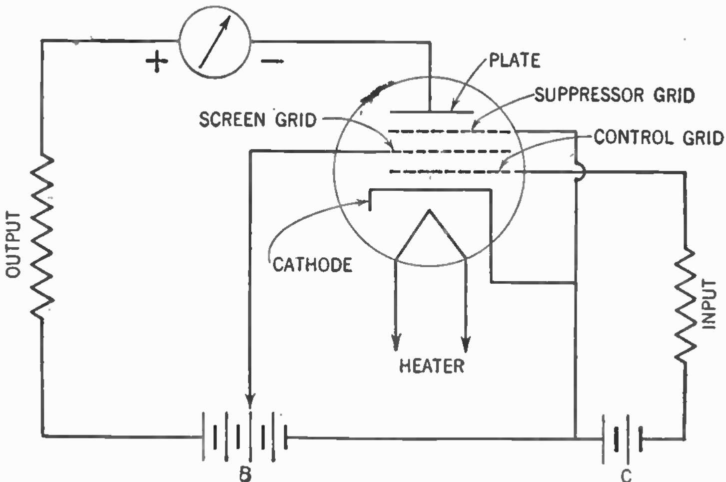


Fig. 112.

of the tetrode. This effect of secondary emission is overcome by the addition of a fifth element to the tube. The element so added is known as a *suppressor grid*. The tube is then known as a *pentode*, that is, a five-electrode tube. The suppressor is placed between the screen grid and the plate. A cutaway section of the pentode is shown in Fig. 111. The suppressor is usually connected to the cathode as shown by the wiring diagram of the pentode in Fig. 112. Because of its negative potential with respect to the plate, the suppressor repels the electrons given off by secondary emission from the plate and thus avoids the difficulties encountered in the tetrode. The pentode can therefore obtain a higher power output by means of a lower grid-driving voltage.

The *Variable-μ* Tube.—When screen-grid tubes are used there is danger that strong signals from near-by stations will force the grid voltage to the point where it is off the straight part of the characteristic curve. As a consequence, the alternating plate current is cut off. This results in bad distortion that is due to undesired modulation. This defect is known as *cross modulation*. It is overcome in a tube called the *variable-μ*, or *supercontrol*, tube. It accomplishes its result by flattening out the bottom end of the characteristic curve. In Fig. 113, the characteristic curve of an ordinary screen-grid tube is given, and also the characteristic curve of the variable-μ tube. The flat characteristic of the variable-μ curve is evident when one contrasts this with the sharp cut-off of the ordinary screen grid. It is clear that large negative potentials on the grid do not force the plate current to 0; thus cross modulation is avoided. This result is accomplished by the winding of the grid. The latter is so wound that the spaces between the turns are unequal, being smaller at certain places than at other places. Where the turns are farthest apart, the spacing is considerably greater than that in the control grid of the ordinary screen-grid tube. At ordinary voltages this tube functions in the usual manner, but when the grid voltage becomes excessively great, the electrons can still pass through the larger spaces in the grid. This does not occur in the control grid of the ordinary screen-grid tube. Because of this, on high negative signal voltages

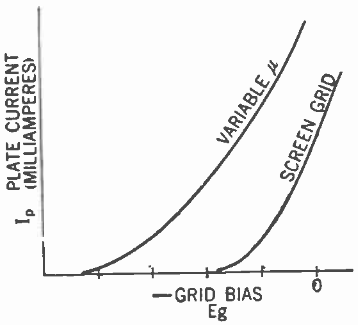


Fig. 113.

there is no cut-off in the variable tube as there is in the ordinary screen-grid tube.

The Beam-Power Tube.—In the beam-power tube, the suppressor grid is replaced by grouping electrons in such manner that they repel the secondary emission electrons of the plate and so drive them back to it. The beam-forming plate, as shown by Fig. 114, is at the same potential as is the cathode. The screen grid of the tube is spiral wound like the control grid. This alignment of the screen and the grid causes the electrons to flow in sheets. This builds up a low-voltage electronic space charge near the plate so as to repel the secondary emission electrons. The tube has another advantage in that the screen current is very small because the turns of the screen are shaded by the turns of the control grid. This makes the tube very efficient, since there is so little loss of current in the screen circuit. The tube also has a very high sensitivity, as is shown by the large amount of power it can deliver for a small grid voltage. It is therefore useful where a power tube is required.

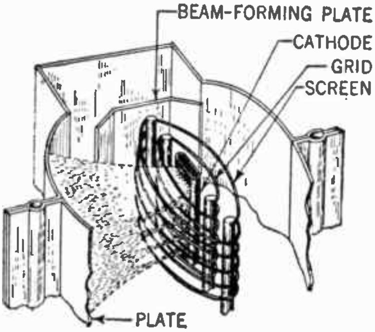


Fig. 114.

Multi-Unit Tubes.—In the early days of radio, only two types of tube were available: the *diode* and the *triode*. These tubes had to be used for many different purposes. The same style of tube had to be used for rectification, for detection, and for amplification, under widely varying conditions. As time went on, the tendency was to develop special tubes, each designed to meet individual problems. Although the general principles of these tubes have already been described, nevertheless each tube has some particular feature that makes it desirable for the purpose to which it is to be put. Some of these tubes are really only several tubes enclosed in a single envelope to conserve space. In these instances there may be several cathodes, or the same cathode may be shared between tube units. Some of these multi-unit tubes contain a large number of electrodes and consequently may serve both as a diode and triode at one and the same time.

QUESTIONS

1. What determines the rate of thermionic emission from the filament of the diode?

2. Why is a thoriated filament used instead of pure tungsten?

3. Draw the circuit of the diode and explain how it functions.

4. Explain how alternating current can be rectified by the use of a diode.

5. What happens to the negative half of the cycle when an alternating current is rectified by a single diode?

6. What is meant by the *space charge?* How does it affect the operation of a diode?

7. Why is the saturation current sometimes referred to as the *emission current?*

8. How does the current in the filament change the saturation point?

9. Explain the difference between a tube having a filament cathode and one having a heater cathode.

10. Draw the diagram of a triode circuit and explain the function of the grid.

11. How do the dynamic characteristic curves for a triode differ from its static characteristic curves?

12. Explain the meaning of *grid bias;* of *operating point;* of *grid-voltage swing;* of *plate-current swing.*

13. If in a triode tube a negative potential of 5 volts on the grid produces an increase of the same number of milliamperes in the plate circuit as does an increase of 45 volts on the plate, what is the value of the amplification factor? **Ans.** The amplification factor is 9.

14. A grid-voltage change of 0.6 volt causes a plate-current change of 1.2 milliamperes with all other voltages constant. Calculate the transconductance, and express it in its correct unit. **Ans.** 0.002 mhos.

15. What is meant by *inter-electrode capacitance?*

16. What inter-electrode capacitance is most important?

17. Explain the function of the screen grid in the tetrode.

18. What is the function of the suppressor grid in the pentode?

19. In what manner does the characteristic of the variable-μ tube differ from the ordinary screen-grid tube?

20. What causes the increased efficiency in the beam-power tube?

CHAPTER 6

THE POWER SUPPLY UNIT

Voltage Requirements of a Radio.—In order to operate a radio receiver or transmitter, some source of electric power is necessary. Special voltage ranges are required for filament cathodes and heaters, for plate potentials, and for grid biases. Filament cathodes, plates, and grids require direct-current voltages; heaters may be operated on alternating-current voltages. Tubes used for different purposes may require a wide range of voltages. The filaments, or heaters, employ low voltages, while the plates are usually operated at high voltages. The grid biases are of intermediate values, though they are negative. Various voltages required may be supplied by batteries.

Batteries for a Radio.—Though batteries can adequately supply voltage requirements, they do have many drawbacks. For the B-voltage supply, many cells in series are necessary in order to give the high voltage demanded for the plates of the tubes. The current drain on such a battery is not very great. On the contrary, the A battery, which supplies the filaments of the tubes, may consist of a few cells in series, since only a small potential difference is required. The current drain on these, however, is very great. The B battery must be comparatively large because of the many cells necessary for furnishing the large voltage. Though the A battery need have only a few cells for meeting the voltage demand, nevertheless each cell must have plates of large area in order to meet the current requirements. In consequence of all this, both the A battery and the B battery must be large and cumbersome. Batteries also wear out in a comparatively short time, and besides, they are costly and difficult to replace. Deterioration of batteries takes place even when they are not in use; this, of course, results in inefficient operation. As batteries become older, or as they run down, their voltage ratings change; this, in turn, brings about uneven and unsatisfactory operation of the tubes they are supplying. If storage batteries are used, they require frequent charging. This means that at certain intervals the radio set must be kept out of operation. The care of such a battery is exacting; failure to take proper precautions may result in the destruction of the battery itself. Furthermore, storage cells contain acids or alkalies that are injurious to clothing and other fabrics.

Elimination of the Battery.—From the foregoing we can see the desirability of eliminating the battery as the source of power supply in the radio set. In most present-day receiving sets, all batteries have been entirely eliminated. This is true of all sets except the portable ones. Since most homes are today supplied with a 110-volt alternating current, and because this source of supply is commonly utilized for all our other electrical needs, we shall see how it can also be adapted for supplying the necessary voltages that are required for radio use. In the case of the 110-volt direct-current supply, the problem is somewhat different from that of 110-volt alternating-current. When the supply voltage is 110-volt alternating current, three separate problems must be met. The first is that of changing the voltage to the desired value; the second, that of rectifying the alternating current; the third, that of eliminating variations in the rectified current.

The A-Voltage Requirements.—Most tubes that operate from an alternating-current supply line are of the indirectly heated type cathode. It will be recalled that the cathode receives from a separate heater the heat necessary for raising its temperature to the proper emission point. The voltage required for operating the heater is on the order of a few volts. Since this voltage can be an alternating current, all that is required is a step-down transformer. This is called a *filament transformer*. The current from the secondary of the transformer flows through the heater filament and so causes it to become hot. The cathode receives its heat by convection and radiation from the heater filament. If the power for the A-supply is to be received from a 110-volt direct-current line, the heater-type tube is also employed because the voltage in the direct-current line from the direct-current generator is not altogether constant. It has a ripple that causes serious fluctuations in the filament type cathode and so results in a hum that is caused by the unequal electron emission from the filament.

The B-Voltage Supply.—The plate of the radio tube must be supplied with a high direct-current voltage. This therefore requires the solution of all three problems that have been mentioned. The 110-volt alternating current can be increased to about 300 volts alternating current by means of a *step-up transformer*. The transformer used for this purpose is known as a *power transformer*. The next problem is that of rectifying the current. Under our discussion of vacuum tubes, we mentioned that a diode can be used as a rectifier. A more detailed discussion of rectification is given in the paragraphs that follow.

Half-Wave Rectification.—As previously described, the diode consists of two elements: the cathode and the plate. In order to heat the cathode, there must be a low voltage supply. This can be obtained from the alternating-current voltage supply by means of a step-down transformer. Fig. 115 shows a transformer whose

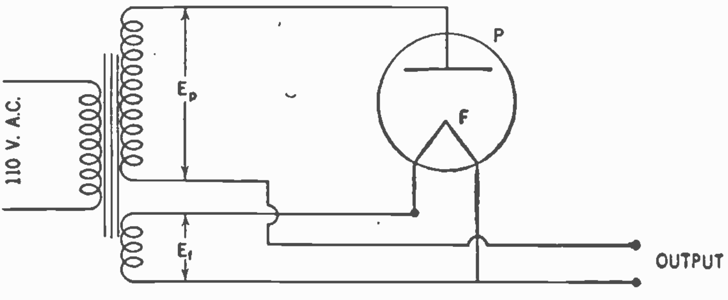


Fig. 115.

primary is connected to the ordinary 110-volt alternating-current house line supply. This type of transformer has two secondary windings. The one with the few turns gives a reduced voltage so that the current for the filaments of the tube may be supplied. The one having the larger number of windings is connected to the plate of the tube. Thus the 110-volt alternating current that has been stepped up to about 300 volts by means of the transformer is rectified by the tube. It must be realized, however, that during the positive part of the cycle, the plate is positive, and the electrons flow from cathode to plate; during the negative half of the cycle, the plate current is 0. Fig. 116 shows the input of the tube and also the rectified output. From a comparison of the two graphs it may be seen that only half the cycle is utilized. Rectification of this kind is known as *half-wave rectification.* A

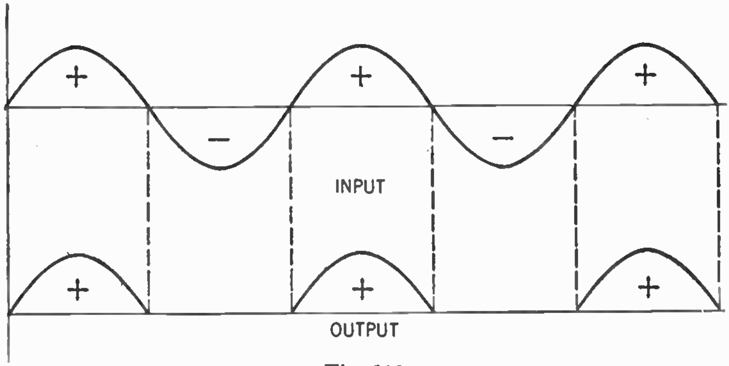


Fig. 116.

single ordinary type diode can produce only half-wave rectification.

Full-Wave Rectification.—Obviously it is preferable to utilize the entire cycle of the alternating-current input. When accom-

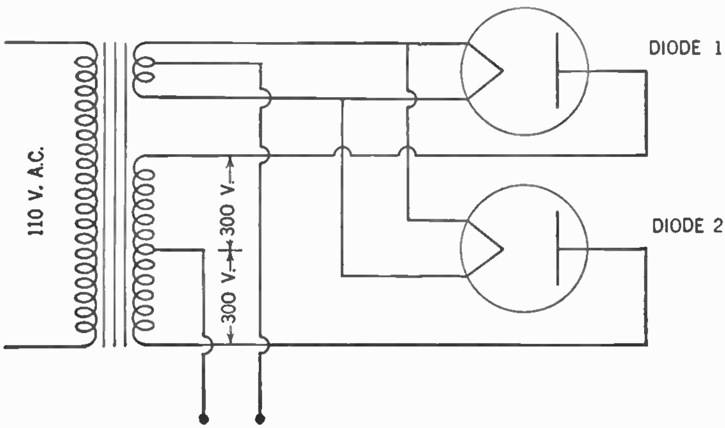


Fig. 117.

plished, this is known as *full-wave rectification.* It can be worked out in several ways. Fig. 117 shows how two separate diodes may be used for producing full-wave rectification of the alternating-current input. The two filaments of the diodes are heated from a current that is supplied from a step-down transformer. The ends of the secondary of a step-up transformer are connected to the plates of the two diodes, as shown. The centers of the two secondary windings are tapped; these are the terminals of the rectified output. From this it is apparent that during half a cycle the plate of Diode 1 is positive, and that the current flows through this tube. During the same time, however, the plate of Diode 2 is negative, and consequently no current flows through this tube. During the second half of the cycle, the plate of Diode 2 is posi-

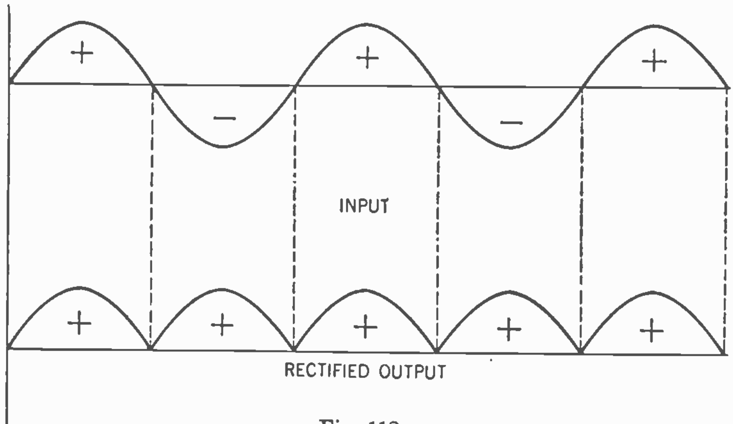


Fig. 118.

tive and that of Diode 1 is negative. As a result, current flows only in Diode 2 during this half cycle. Thus the entire cycle of the input current is utilized, and we have full-wave rectification. This condition is illustrated by the graphs shown in Fig. 118. These show the alternating-current voltage input and the rectified output from the combination of the two diodes. It may be observed that both parts of each cycle of the supply current are utilized. Though the current is fluctuating in the output, there is no interval during which the current is not flowing, as in the case of half-wave rectification. Today it is more common to use a single tube instead of two separate tubes for full-wave rectification. The details of a full-wave rectifier tube can be learned from Fig. 119. It may be seen that the tube contains two plates, but only one filament. Upon comparing this circuit with that shown in Fig. 117, it may be observed that the two plates in the single tube are connected in the same manner as are the plates in the two separate tubes. When either plate is positive, the same filament supplies the electrons for the action of the tube. The input and output are the same as those for the two separate tubes, as shown by Fig. 118.

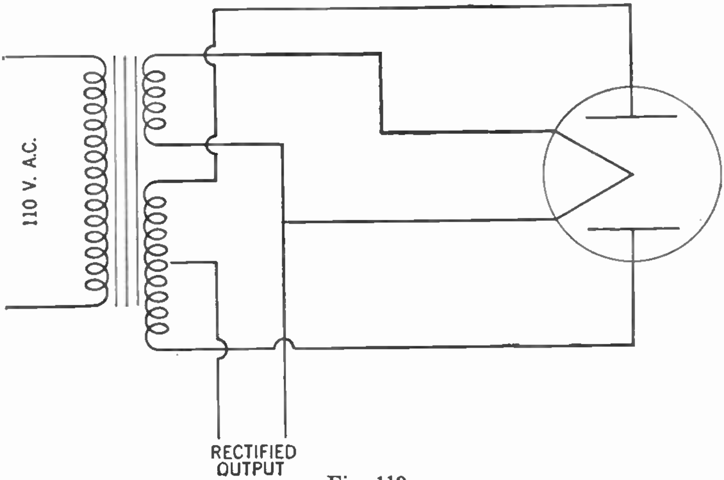


Fig. 119.

Filter Circuits.—Now that we have a high rectified voltage, all that is necessary is to keep this voltage constant. A circuit

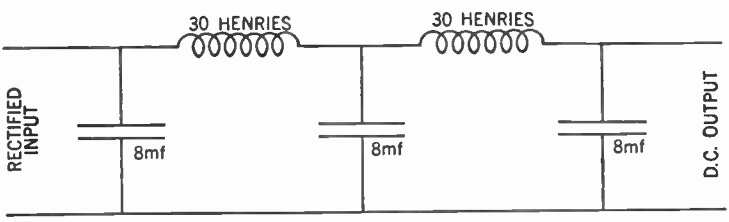


Fig. 120.

employed for the purpose of making even the fluctuations in this current is known as a *filter circuit*. (See Fig. 120.) The rectified output from the rectifying tube is connected to the arrangement of series inductances and parallel condensers. These inductances consist of coils of wire wound about iron cores; they are known as *choke coils*. This particular type of filter circuit is called a *smoothing filter*. Since the choke coils are in series with the load circuit, they offer a large impedance to the fluctuating voltage, and so tend to level off the peaks in the voltage fluctuation. The

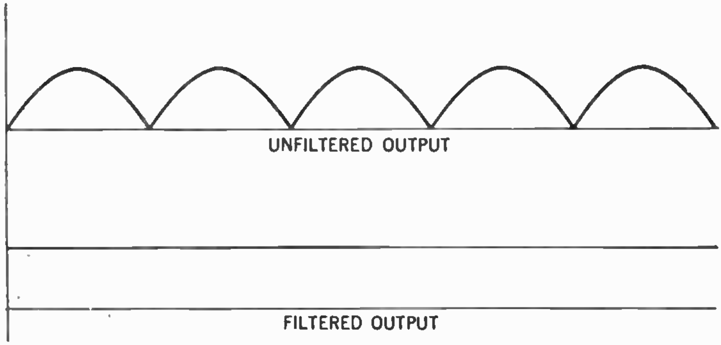


Fig. 121.

smoothing effect of the parallel condensers results from their storing up electrical energy on the peaks, then releasing it back to the circuit on the voltage dips. This procedure tends to keep the voltage constant. Graphs of both the unfiltered and filtered full-wave rectified output are shown in Fig. 121. It may be seen from

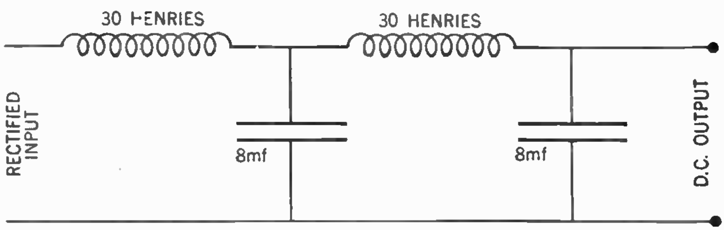


Fig. 122.

this that we now have a steady direct current. The smoothing filter circuit of Fig. 120 is known as a *condenser input filter*, since a condenser is there placed next to the rectifier tube. Fig. 122 shows a *choke input filter*. It should be observed that in this arrangement a choke coil is placed nearest to the rectifier tube.

The Voltage Divider.—Now that we have a high, steady direct-current voltage, it is also often necessary to have some means of taking off specific voltages of different values for the various requirements of the tube's circuit. This is done by means of the voltage divider that was described in the discussion of the theory of direct currents. (See page 34.) A voltage divider having a resistance of 20,000 ohms is shown in Fig. 123; there it is placed across the 300-volt output of a filtered circuit. It should be observed that by tapping off at various points we can obtain the required B voltage for the different kinds of tube used in a radio circuit. The voltage divider must be so built, however, as to take care of the amount of power it will be required to sup-

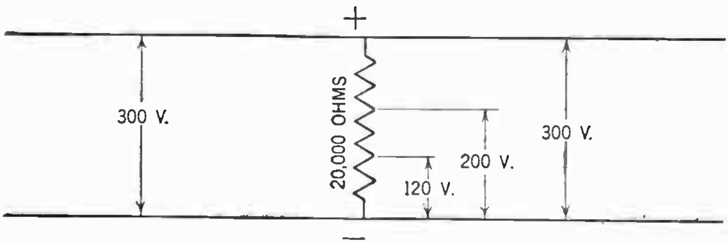


Fig. 123.

ply to the plate circuits of the various tubes. The power rating of the voltage divider, computed in the usual manner, is given in watts.

The C-Voltage Supply.—The grid voltage may be obtained without the use of a battery by means of two different methods. By means of the first method, it is obtained from the voltage divider that has just been discussed. According to the second method, it is obtained by means of a voltage drop across a resistor in the cathode circuit. This latter method is known as the *cathode bias*, or *self-bias*, method. It must be realized that the aim is to make the control grid negative with respect to the cathode by means of the required number of volts. Fig. 124 illustrates the first method of obtaining the grid bias from the control grid. By checking the diagram it will be noted that the grid is connected to a point on the voltage divider which is more negative than the point where the cathode is connected. We shall now examine the second method of obtaining the grid bias. In the self-biasing method we utilize the voltage drop produced by the cathode current that flows through a resistor connected between the cathode and the negative terminal of the plate supply. A typi-

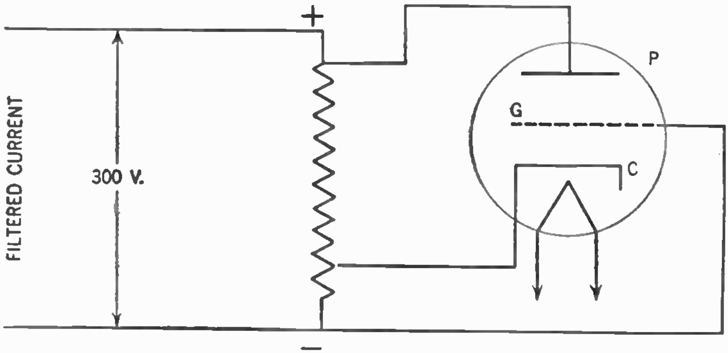


Fig. 124.

cal self-biasing circuit is shown in Fig. 125. It is evident that here the grid has a negative bias because it is connected to the negative potential end of the resistance, *R*. In the case of a triode, the current through the resistance is the plate current. The cathode

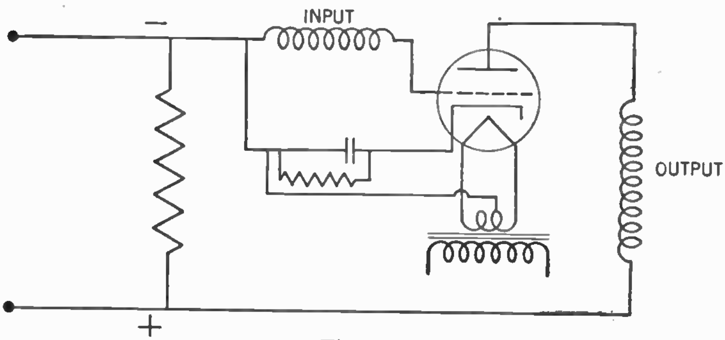


Fig. 125.

current for a tetrode is the sum of the plate and screen currents. By using Ohm's law, the size of the resistance for self-biasing can be calculated as follows:

$$R \text{ (ohms)} = \frac{E}{I} = \frac{\text{Grid bias in volts}}{\text{Cathode current in amperes}}.$$

As an illustration: If a grid bias of 6 volts is required for a triode whose plate current is 4 milliamperes, what resistance must be used for self-biasing?

$$R = \frac{E}{I} = \frac{6}{0.004} = 1{,}500 \text{ ohms.}$$

Since the plate current is fluctuating, this tends to produce an unsteady grid bias that is highly undesirable because it produces distortion of the input signal. In order to avoid this difficulty, a condenser of large capacitance is put in parallel with the resistance. This is known as a *by-pass condenser*. The function of such condensers in smoothing out the fluctuations in a circuit has already been discussed. (See page 103.)

Screen-Grid Supply.—The positive screen voltages for screen-grid tubes can be obtained from suitable taps on the voltage

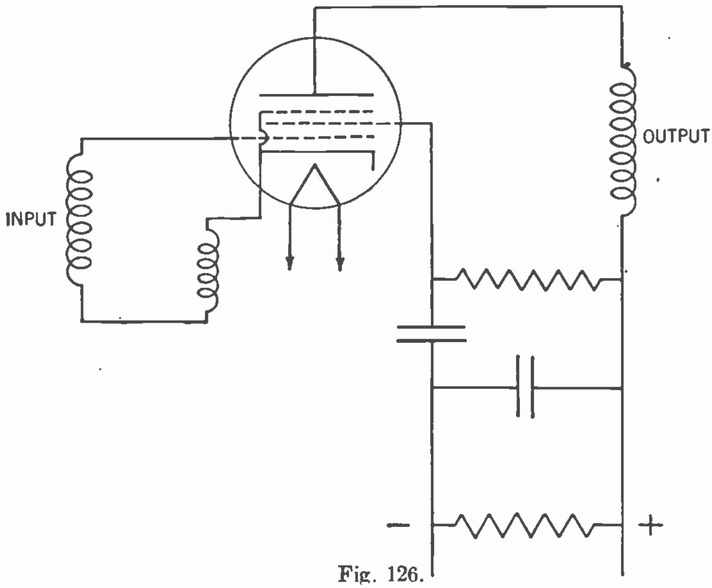


Fig. 126.

divider. In the case of pentodes and beam-power tubes, the positive screen voltage may be obtained from the B supply through a series resistor. Fig. 126 shows a circuit that supplies the voltages for the screen of a pentode.

Complete Voltage Supply.—We have already discussed various methods of obtaining the necessary voltages for the heaters, plates, and grids required for different types of tube. At this point it is well to examine a typical circuit that supplies the usual range of voltages for tube operation that are obtained from the 110-volt alternating-current supply line. Fig. 127 shows a circuit by means of which the ordinary 60-cycle 110-volt alternating current is used for supplying the requirements of the tubes for an ordinary type receiver. It will be noticed that the transformer has three secondary windings: one for supplying the low voltage for the heaters, a second for stepping down the voltage that supplies the filament of the rectifying tube, and the third for the high voltage. The rectifier tube is a two-plate, or full-wave, rectifier. The

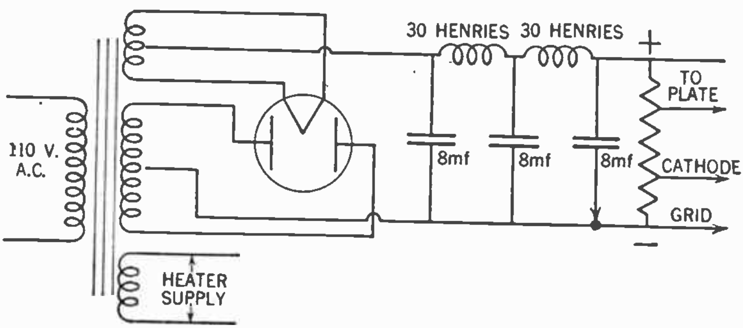


Fig. 127.

smoothing filter circuit is a condenser-input filter. The voltage divider is tapped for B supply and grid bias. Separate taps may be made for the plate voltage for detectors and amplifiers that require different voltages. The grid bias is also obtained directly from the voltage divider. Although there are many variations of this circuit, it exemplifies the important steps used for obtaining the required direct-current voltages for tube operation from alternating-current supply lines. These steps will be repeated here in order to emphasize general principles of power supply. The order given is in sequence from the 110-volt alternating current to the final direct-current voltages. The main steps are: (1) change of alternating-current voltage by means of the power transformer; (2) rectification by means of a rectifying device; (3) smoothing by means of a filter circuit; and (4) voltage apportionment by means of the voltage divider.

Ionization.—The rectifying tubes that we have just described are known as *hard tubes* because they are highly evacuated. In the process of manufacturing them, the air is pumped out and chemicals are then often introduced into the tube for the purpose of absorbing any air that remains. Plainly, this high evacuation of the tube greatly increases its resistance. This high resistance wastes power and causes heat dissipation. It reduces voltage and gives poor voltage regulation. In cases where the current requirements are not very great, this is no serious problem. Where large currents are required, however, the hard tube is highly inefficient. In this type of tube all the current through the tube consists of electrons that have been emitted by the cathode. If, however, a small quantity of some inert gas is introduced into the tube, then a considerable change takes place in the current that flows through the tube. For the same voltage as is used in the hard tube, the current is considerably greater. The reason for this can be understood by considering the nature of the gas in the tube. The gas, like all other substances, is made up of atoms. The atom of the gas consists of a positive nucleus, and electrons which are held by the nucleus due to the attraction of unlike charges. When an electron becomes detached from an atom, the remaining part of the atom has a resultant positive charge. The atom in this condition is known as a *positive ion.* Since the electron has an insignificant mass as compared with the atom, the positive ion in consequence has a mass many times greater than that of the electron, but it does have the same magnitude of charge. The repulsion of the positive charge on the plate, and the attraction of the negative charge on the cathode, cause the positive ion to acquire a velocity. As the heavy positive ion moves with this acquired velocity, it may collide with another atom. If this occurs, it loses one of its own electrons and thus the atom it collides with also becomes a positive ion. This process is known as *ionization by impact.* Electrons detached from the atoms are known as *negative ions.* Since the tube is now filled with both positive

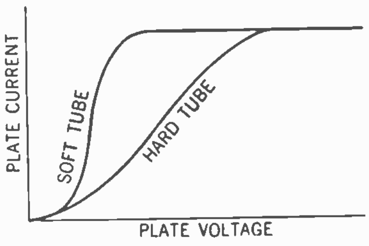


Fig. 128.

and negative ions, the current no longer consists only of the electrons given off by the cathode, but includes the newly formed ions as well. Tubes of this type, usually filled with argon, neon, helium, or mercury vapor, are known as *soft tubes.* The characteristic curves of a hard tube and of a soft one are shown in Fig. 128 for purposes of comparison.

The Ionization Potential.—Examination of the characteristic curves of both soft and hard tubes reveals some interesting facts. It may be observed that both curves are identical until a certain plate potential is reached. At this point the soft tube begins to show a considerably larger current than does the hard tube, for the same plate voltage. This is readily understandable if we realize that the positive ions must acquire sufficient velocity to cause ionization, and that this velocity depends upon the plate voltage. The minimum plate voltage required to produce ionization is known as the *ionization potential.* The numerical value of the ionization potential differs for different gases. As is revealed by the characteristic curves, a surprising fact is that the saturation current is the same for both kinds of tube. Although the ions that are produced in the soft tube must augment the current, nevertheless the effect is so small that it is negligible. We are then faced with the question as to why the current in the soft tube is greater than that in the hard tube between the ionization potential and the saturation point. This query is readily answered if we recall the existence of the strong negative space charge in the hard tube. In the case of the soft tube, the positive ions neutralize this charge and thereby cause the plate current to be increased.

Gaseous Rectifiers.—For high potential work, the hard diode is necessary because in the soft tube the gas becomes ionized by the high reverse potential and thus causes current to flow in the reverse direction. For low potential work, the soft tube is more desirable because the voltage drop in the tube is smaller and therefore the voltage regulation is more satisfactory than is that of the hard tube. In addition to the advantage in voltage regulation, the gaseous rectifier can handle much more current without becoming hot than can the vacuum rectifier. This is due to the fact that the gaseous rectifier has a much lower resistance because of the elimination of the space charge. Tubes based upon this principle are frequently used for battery charging. Two popular gaseous rectifying tubes are the *Tungar* and *Rectigon.*

Mercury-Arc Rectifier.—A very important gaseous rectifier is one that makes use of mercury vapor. Known as a mercury-arc rectifier, this device is illustrated in Fig. 129. Here, instead of having a filament supply the electrons, a pool of mercury is the source of them. When the tube is operating, a large part of the current is concentrated at the surface of the pool of mercury. This causes the mercury to become hot and so to give off electrons. In order to start the rectifier, it is necessary to close the switch, *S*, which is connected to an auxiliary pool of mercury. The tube

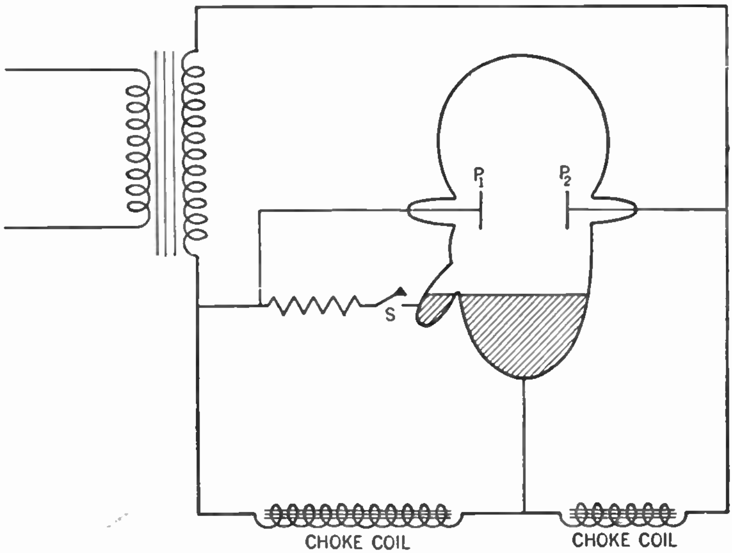


Fig. 129.

is then tipped until the mercury in the cathode comes in contact with that in the auxiliary anode. After straightening the tube again, an arc is established, the mercury is heated, and electron emission is started. The switch is then opened and the tube operates as has been explained. The two choke coils are needed in order to keep the discharge going through the tube during the reversal in the input voltage. Tubes that combine this principle with that of emission from a heated filament are quite satisfactory. Mercury vapor rectifier tubes of this type can supply much larger currents than can ordinary rectifying tubes of the same size.

Thyratron.—All tubes so far discussed are of the two-element, or diode, type. In the case of gaseous tubes it has been found advantageous to use a grid too, thus making the tube a triode. If the grid of this tube is made sufficiently negative, the electrons are prevented from leaving the filament, despite the fact that the plate may be positive. There is a value of the grid voltage for every plate voltage that will permit the current to flow. If the grid voltage is further reduced, the electrons move toward the plate at a higher speed. When the potential reaches the ionization potential of the gas in the tube, a large increase is brought about in the current, due to the neutralization of the space charge by the positive ions. If the negative potential on the grid is then increased, this has no effect upon the plate current. The only way in which the grid can again control the plate current is when the plate voltage is reduced to 0. This may be explained by the fact that after ionization has commenced, the positive ions grouped around the grid act as a positive space charge and so offset the action of the grid. From the description of this tube we can see that either all the current flows or none at all. If we place an alternating-current voltage on the plate and a fixed bias on the grid, then when the plate has reached such a point in the positive half-cycle that it offsets the action of the negative grid, the plate current will flow. In the second half of the cycle the plate becomes negative and the plate current ceases to flow. Hence, by adjusting the bias on the grid, the point in the cycle at which the current starts can be controlled, but it will nevertheless flow through the remainder of that half-cycle. If, however, an alternating current is placed on the grid as well as the plate, and the phase between them is controlled, any amount of average current, from zero to the maximum emission current, can be taken from the tube. Thus, by properly adjusting the phase difference between the plate and the grid, the supply of current can be controlled. A tube based on this principle of a controlled grid is known as a *thyratron*. Such tubes are being put to many uses in broadcasting stations and elsewhere in radio systems where large controlled rectified current is required.

The Voltage Doubler.—It is sometimes possible to increase the rectified voltage to a value twice as high as that of the peak voltage without using a transformer. This kind of rectifying circuit is known as a *voltage doubler*. Fig. 130 shows a voltage doubler that has a single rectifying tube. This tube combines two separate diodes in one envelope. The circuit is made use of in transformerless receivers. The heaters of all tubes in the set are connected in series. The action of the doubler may be understood by examining the wiring diagram. During the positive half-cycle of the input, one of the diodes passes current and positively charges the lower of the two condensers. As positive charge accumulates on the lower plate of this condenser, a positive voltage builds up across the condenser. On the next half-cycle of the

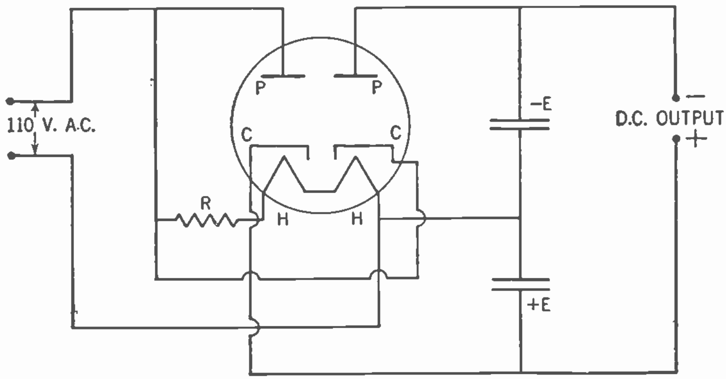


Fig. 130.

input, the other diode passes current and so builds up a negative voltage across the upper condenser. Each condenser is charged up to E_m, the peak value of the input voltage. From the arrangement of the condensers we can see that the total potential across the two together is $2E_m$, which is twice the peak voltage of the alternating-current supply.

The Copper-Oxide Rectifier.—A simple and durable rectifier is the *copper-oxide rectifier*. It consists of a copper disk, on one side of which a film of cuprous oxide has been formed. If lead plates are pressed against the two opposite faces of this disk, it will be found that current flows more readily in the direction from the copper oxide to the copper than it does in the opposite direction. It can therefore be used as a rectifier. In order to care for the required current and voltage, a number of such disks are connected in series-parallel arrangement. Rectifiers of this type have a long life and operate well without attention. The copper oxide rectifier may be used for a wide variety of purposes. These include battery charging, magnet operation, loud-speaker excitation, and so on. This rectifier may also be used for both half-wave and full-wave rectification. A common method of full-wave rectification is the use of the Graetz Bridge shown in Fig. 131. In this the circuit consists of four copper-oxide rectifiers connected in series in a closed loop. The terminals of the alternating-current input are connected to those opposite junctions of the loop where the two unlike elements are joined. When the junction *A* is positive, the current flows along the path *ABDC;* when *C* is positive, the cur-

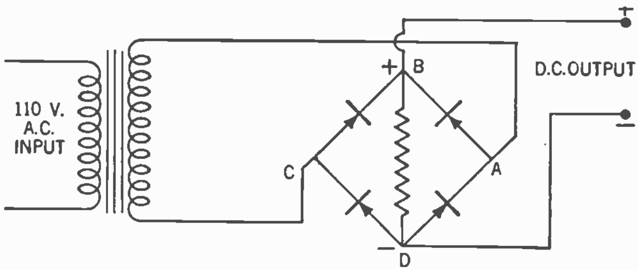


Fig. 131.

rent flows along *CBDA*. Thus junction *B* is always positive with respect to junction *D*.

Universal Power Supply.—Although 110-volt alternating current is today available almost everywhere, some localities are still supplied with 110-volt direct current. A transformer will not function on direct current. If the power transformer is eliminated from the B supply unit, and the 110-volt alternating current or direct current is connected directly to the rectifier tube and filter circuit, it will work equally well with both kinds of current. Such a unit is known as a *universal supply unit* because it works equally well on either alternating current or direct current. It has the added advantage of being more compact and lighter because power transformers are large and heavy. On this account, and also because of its cheapness of construction, this principle is used in midget sets. Although the voltage is limited to 110 volts, many new type tubes work efficiently at this voltage. The only problem left is that of the heater supply. In place of filament transformers, the filaments may be put in series. Because most sets have an insufficient number of tubes for taking care of the entire 110-volt drop, an extra resistor is put in series, as shown by Fig. 132. The resistor takes care of that portion of the potential drop that has not been taken care of by the resistance of the heater filaments. The resistor, known as a *dropping resistor,* is in

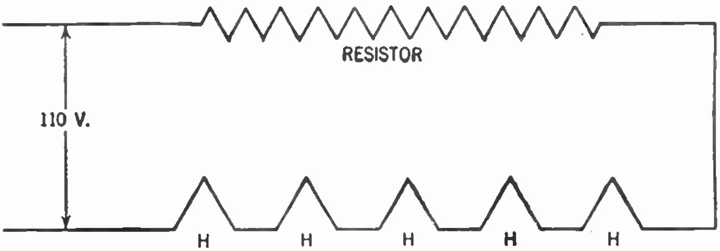


Fig. 132.

most sets kept external to the set itself because of the heat it produces.

The Automotive Supply Unit.—Increased use of the automobile radio made it necessary to design a voltage supply from a 6-volt source such as that of the automobile storage battery. In general, this is accomplished by means of a Ruhmkorff coil (al-

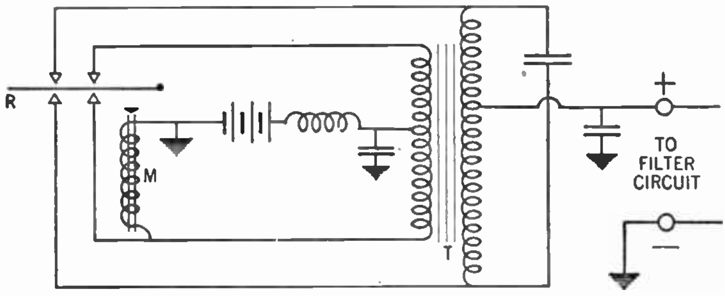


Fig. 133.

ready described on page 44) and a suitable rectifying and filter circuit. Fig. 133 shows a synchronous vibratory power supply that requires no rectifying tube. When the battery circuit is open, the reed, *R*, is halfway between the two pairs of contact points. When the battery circuit is closed, the magnet, *M*, draws the reed toward the lower contact points and thus a current flows in the lower half of the primary coil of the transformer, *T*. This flow induces a voltage in the secondary coil of the transformer. Simultaneously, the magnet coil is short-circuited; the reed swings back, and by its inertia is carried until it is in touch with the upper contact points, so that a current thus flows in the upper half of the primary coil of the transformer. In this manner a voltage is induced in the secondary coil of the transformer. The secondary coil output is rectified, due to the second set of contact points that are in synchronism with the interruption of the primary coil circuit. Thus a high-voltage rectified current is obtained. A filter circuit then smooths out this rectified output.

The Dynamotor.—Portable power for transmitters and large-size receivers is often obtained by means of a double-armature–high-voltage generator known as a *dynamotor*. The device gets its name from the fact that the second armature winding acts as a motor that drives the dynamotor. Usually operated from 12-volt or 32-volt storage batteries, it generates from 200 volts to more than 1,000 volts. A modification of the dynamotor, known as a *genemotor*, is extensively used for transmitters. The genemotor has exceptionally good voltage regulation and efficiency.

QUESTIONS

1. What are the principal voltage requirements of a vacuum-tube receiver?

2. By means of a diagram, explain the difference between half-wave and full-wave rectification.

3. What are some disadvantages of using batteries for tube operation?

4. Name the important steps in obtaining B voltage from a 110-volt alternating-current line.

5. Explain the advantage of heater-type tubes in eliminating line disturbances.

6. How is the current for the filament of the rectifier tube obtained?

7. Draw a diagram of a full-wave rectifying tube and explain how it functions.

8. If the resistance of a voltage divider is 25,000 ohms, and if it is connected across a 250-volt direct-current line, where should it be tapped in order to obtain 120 volts for the plate of an amplifier tube?

Ans. Across 12,000 ohms.

9. Explain the function of the filter circuit.

10. Name two methods of obtaining control grid bias.

11. Draw a diagram that makes clear the principle of self-biasing.

12. If a bias of — 3 volts is required for a control grid of a triode that has a plate current of 6 milliamperes, what resistance must be used for self-biasing?

Ans. 500 ohms.

13. What is the cause of the greater plate current in a gaseous tube?

14. Why is the saturation point identical for a gaseous tube and a vacuum tube?

15. What are the outstanding characteristics of a thyratron?

16. What principles are utilized in the voltage-doubler circuit?

17. Name some advantages of the copper-oxide rectifier.

18. What electrical apparatus may be eliminated by using the voltage-doubler?

19. How can a receiver be built to operate on either an alternating current or a direct current?

20. Explain a method that may be used for obtaining B voltage from a 6-volt storage battery.

CHAPTER 7

SOUND AND ELECTRICAL ENERGY

The Nature of Sound.—In order to produce a sound, it is necessary to have some object in vibratory motion. A bell that has been struck by a hammer or clapper can be seen to vibrate as it gives out its sound. The same is true of a tuning fork that has likewise been struck, or a violin string that has been bowed. A vibrating body does not always produce a sound, however; this can be shown by means of the following experiment: An electric bell is placed inside an air-tight vessel. When the bell is rung, it can be clearly heard. The air is now pumped out of the vessel and the bell is again rung. Though the clapper of the bell can be seen to vibrate as before, no sound is heard. Sound will pass through any material medium, but it will not pass through a vacuum. In fact, sound travels more readily in liquids and solids than it does in air. Experience has taught us that we can hear sounds more easily under water than in the air, and that sounds originating at a great distance can be heard by putting one's ear to the ground. The velocity of sound in air is approximately 1,100 foot-seconds; in water, 4,808 foot-seconds; and in steel, 15,510 foot-seconds.

The Nature of Sound Waves.—It is apparent that since sound travels through solids, it is not some part of the medium itself that travels from the vibrating body to our ear. We are then led to the conclusion that it is a distortion, or *configuration*, of the medium which "travels" from the source of the sound. Such a configuration is known as a *wave;* its motion through a medium is known as *wave motion*. Sound is not the only phenomenon that involves wave motion. We are all familiar with the configuration on the surface of a pond set up when a stone falls into quiet water. These surface waves travel out in all directions along the surface of the pond. Light also travels through space in the form of waves. In fact, as we shall presently discover, radio communication, too, depends upon wave propagation. Though the various waves we have just mentioned differ considerably from one another, nevertheless they also have many characteristics in common. It will be valuable to consider some of these general properties of waves, not only in order to obtain a better understanding of sound, but also for the purpose of later discussing radio waves more understandingly and more profitably.

The General Characteristics of Waves—Since the water wave is so familiar, we shall use it as the point of departure for our discussion. If a train of water waves is set up on the surface of a quiet pond, as previously suggested, we observe that a block of wood floating on the surface of the pond moves upward and forward on the *crest* of the wave, but backward and downward in the *trough* of the wave. Even after several waves have passed, we notice that the block has not changed its average position. This verifies the fact that it is the wave, or configuration, and not the medium, that is in motion. This is true of all kinds of waves. Fig. 134 shows a train of water waves traveling with a velocity v. The

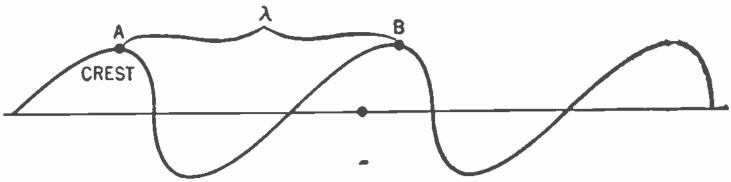


Fig. 134.

shape of the wave is known as the *wave form*. A complete crest and trough is known as a *wave length*. A more concise statement would be, that the wave length is the distance from any point in a crest to the corresponding point in the next crest. In the diagram, the distance AB is the wave length. The number of waves passing a given point per second is known as the *frequency*. The velocity of a wave propagation is equal to the frequency multiplied by the wave length:

$$V = N\lambda,$$

where V is the velocity, N is the frequency, and λ is the wave length. The greatest displacement of any part of the medium from its undisturbed position is known as the *amplitude* of the wave. As Fig. 134 shows, CB is the amplitude of the water wave.

Production and Characteristics of Sound Waves—In order to understand the mechanics of the production of a sound wave, we shall consider the simple case of a vibrating prong of a tuning fork. Though other cases may be more complicated and so more difficult to explain, nevertheless the principle underlying them all is essentially the same. In the first illustration shown in Fig. 135, we have a prong of a tuning fork at rest; the vertical lines represent air molecules. In the second illustration, the prong has moved forward. This forward movement caused the molecules adjacent

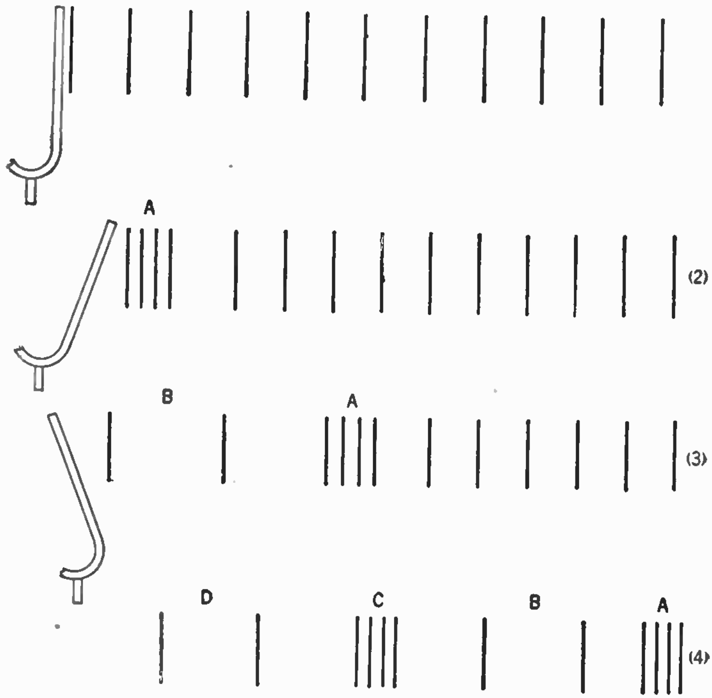


Fig. 135.

to the prong also to be crowded forward and thus form a condensation at *A*. The prong has gone backward in the third illustration. This movement caused the molecules to spread apart and so brought about the rarefaction shown at *B*. This action is, of course, repeated over and over again. Meanwhile the molecules in motion have communicated this motion to the adjacent molecules, and thus waves are propagated through the medium. In the fourth illustration we may observe condensations at A and C, and rarefactions at B and D. The distance AC is one wave length. The frequency of the sound wave is known as its *pitch*. The maximum distance any molecule moves from its rest position is the *amplitude* of the wave. The amplitude of a sound wave is exceedingly small as compared with its wave length. The latter varies from about 1 centimeter up to many meters, while the former is on the order of 10^{-8} centimeters. The amplitude of a sound wave determines its *intensity*.

The Character of Audible Effects.—In a study of radio, we are primarily interested in those effects of sound that are associated with the human ear. The human ear does not, by common knowledge, respond to all sounds. A dog, however, responds to a whistle purposely made so as to have no audible effect upon a human being. Many sounds that have no effect upon the ear are constantly occurring; these can be detected, though, by certain mechanical and electrical devices. The lowest pitch the human ear can recognize is one of about 30 vibrations per second; the highest, which may range from 18,000 to 22,000 vibrations per second, varies for different persons. Sounds that have a pitch greater than the upper limit of audibility are known as *supersonic* sounds. Sounds having a pitch as high as 250,000 vibrations per second have been detected by means of delicate instruments. Another factor of a sound wave associated with hearing is its *loudness*. The loudness of a sound is related to its intensity.

Definition of the *Bel* and the *Decibel*.—The intensity of a sound is measured in terms of the energy of the sound waves that every second pass through a unit area perpendicular to the direction in which the sound is traveling. The unit is the *microwatt* per second per square centimeter. The human voice has a range of approximately 0.01 to 10,000 microwatts/centimeter^2/second. Though sound intensity is given in microwatts/centimeter^2/second, the comparison of two sound intensities nevertheless is given in terms of a unit known as the *bel*. Since most practical applications are concerned with the *ratio* of loudness, this unit is therefore widely used. If the ratio of the intensities of two sounds is 10, they are said to differ by 1 *bel*. The bel is, therefore, a measure of the *level* of sound intensity. When a certain sound is 100 times as great as another, the difference of the intensity level is 2 bels. If the difference of intensity level is 3 bels, then the sounds have an intensity ratio of 1000 times. The number of bels is given by the following formula:

$$\text{Number of bels} = \log_{10} \frac{I_2}{I_1},$$

where I_2 and I_1 are the intensities of the two sounds that are being compared. The smallest difference in sound intensity levels that the human ear can detect is one-tenth of a bel. This figure, used as a unit by those who do acoustical work, is known as a *decibel* (*db*). In recent years sound-level meters have been used for making surveys of everyday noises; the noise values have been recorded in decibels. A general idea of the range of these can be obtained from the following typical examples: a whisper = 10 dbs; the average home = 30 dbs; a crying baby = 50 dbs; a subway car = 100 dbs; thunder = 120 dbs; an air-raid siren at 100 feet = 140 dbs.

What Is an *Audiogram?*—Careful studies of audibility have only recently been made. As a result of extensive and elaborate

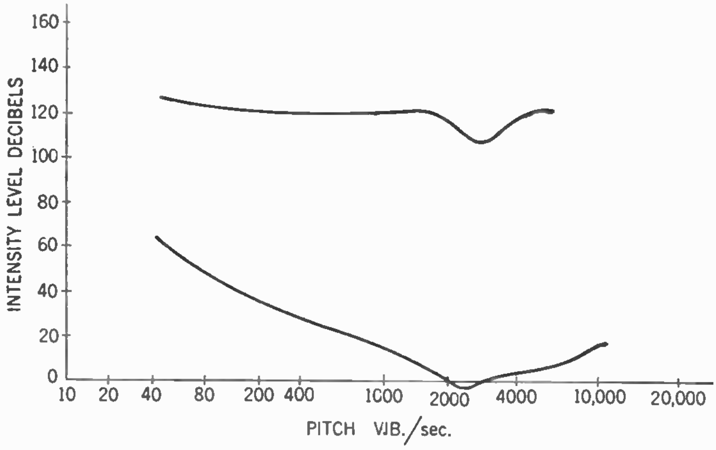


Fig. 136.

measurements recently made by telephone engineers, we now have definite information concerning the audibility possibilities of the normal ear. The audiogram of such an ear is shown by Fig. 136. In this figure the lower curve indicates the variation of the lower limit of audibility; the upper curve shows the variation of the upper limit of audibility. It should be noted that the human ear is most sensitive to sound waves whose range is between 2,000 vibrations/second and 4,000 vibrations/second. These factors are of extreme importance in radio work because they must always be taken into consideration when designing sound converters and reproducers.

The Telephone Transmitter: The Carbon Microphone.—Radio owes a large debt to the telephone industry, not only for its electrical concepts but also for the invention of equipment used for converting sound energy into electrical energy, and conversely. During the early period in which radio communication was being developed, existing telephone equipment was taken over bodily by the new science. On this account, and because modern equipment for the purpose has in most cases merely been developed from earlier forms, the simple transmitter must here be explained as a device for converting sound energy into electrical energy. Fig. 137 shows the essential features of an ordinary telephone transmitter. *A* is the mouthpiece; *B* is a diaphragm; *C* and *D* are two polished carbon plates; *E* indicates loosely packed granules of carbon; *F*, a cell. The sound wave enters through the mouthpiece. Alternating condensations and rarefactions cause the diaphragm to vibrate back and forth with the same frequency as that of the sound wave. The carbon plate, *C*, is so attached to the diaphragm that the two move together. The plate, *D*, is so rigidly attached that it cannot move. Upon examination of the electric circuit, we discover that the current flows from the cell to plate *C*, then on through the carbon particles to plate *D*, and thence back to the cell. We should now be able to understand the action of the transmitter. Whenever a condensation forces the diaphragm inward, then the plate, *C*, also moves inward and so compresses the carbon particles. This latter action brings about a reduction in the resistance of the circuit, and, therefore, an increase in the current. On the contrary, however, whenever a rarefaction reaches the diaphragm, then the pressure is reduced, and as a result, the diaphragm moves outward, thus pulling the plate, *C*, along with it. This latter action causes the carbon particles to separate and so increases the resistance; this decreases the current. Thus, in the

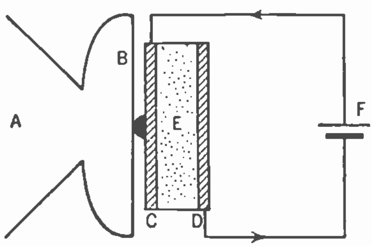


Fig. 137.

circuit, the sound wave causes a fluctuating current that is characteristic of a particular sound wave. The telephone transmitter is also known as a *single-button carbon microphone.*

The Improved Carbon Microphone.—The ordinary single-button carbon microphone, or telephone transmitter, has a range of satisfactory performance that ranges from approximately 2,000 vibrations to 3,000 vibrations per second. This range is quite satisfactory for telephonic communication, which depends only upon the normal range of the human voice. The demands of radio-

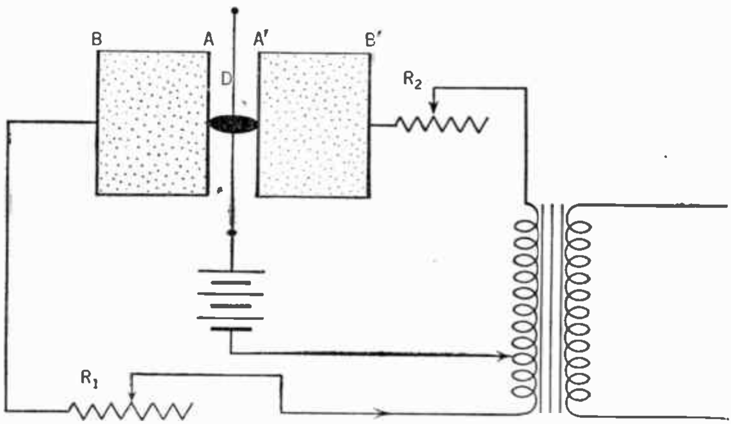


Fig. 138.

communication, however, are much greater in both range and discrimination. In this instance we are concerned not only with the normal human voice but also with many other sounds that vary widely in many respects. It is necessary to record faithfully all kinds of musical instruments and the singing voice, as well as unusual noises. We are compelled to cover the entire range of audible pitch and intensities within the limits of audibility. Since the ordinary carbon microphone has a range limited to that of the normal human voice, plainly it is not satisfactory for any broadcasting at all, except where the input is confined to ordinary speech. Fig. 138 shows an improved form of the microphone, known as the double-button carbon microphone. When this microphone is used, the sound waves cause the diaphragm, *D*, to move to and fro because of their various condensations and rarefactions. The two polished carbon plates, *A* and *A'*, are attached to the diaphragm; two similar plates, *B* and *B'*, are fixed. If one imagines the diaphragm to move to the right, this causes the carbon particles between A' and B' to be more closely packed together and so results in a reduction of resistance and an increase of current in the circuit that passes through $A'B'$. On the contrary, however, the particles that lie between A and B become further removed from one another, and so decrease the current in this circuit. Examination of the diagram shows that the current through $A'B'$ passes through the upper half of the primary of a transformer. The lower half of the primary is at the same time being supplied by the current that passes through AB. It may be seen that, as the current increases in part of the primary coil, it consequently decreases in the other part. Since the two currents flow in opposite directions in the coil, according to Lenz's law the direction of the induced e.m.f.'s in the secondary coil, due to both parts of the primary, are the same. As a consequence of this, the double-button carbon microphone is approximately twice as effective as is the single-button carbon microphone. The rheostats, R_1 and R_2, are used for making the current in the two circuits the same, so that there may be no magnetic effect of the primary coil when the diaphragm is at rest. Thus, changes in the battery voltage produce no effect because they change both currents equally. In both sensitivity and range, this microphone is far superior to the single-button type. It is also, of course, less subject to distortion.

The Condenser-Type Microphone.—Where high-quality pick-up is required, a microphone based on a principle that differs from that of the carbon microphone is sometimes used. As shown by Fig. 139, P is a fixed metallic plate, and D is the diaphragm of the microphone. Together, the two act as plates of a condenser. It will be recalled that the capacitance of a condenser is inversely proportional to the distance between the plates. This being true, as the diaphragm moves back and forth, due to the sound waves that fall upon it, the capacitance of the condenser varies. This variation also causes a change to take place in the charge on the condenser, and so results in a current that flows from one plate of the condenser to the other. A potential of some 200 volts is maintained between

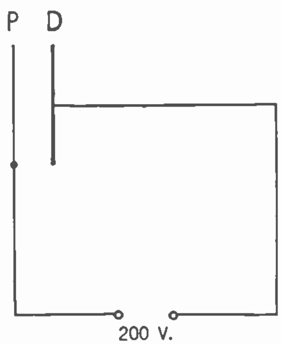


Fig. 139.

the diaphragm and the plate in order to keep the condenser charged. The fluctuating current set up by the microphone circuit is characteristic of the sound waves that fall upon the diaphragm.

The Microphone Coupling.—After the sound has been transformed into current fluctuations by means of the microphone, it

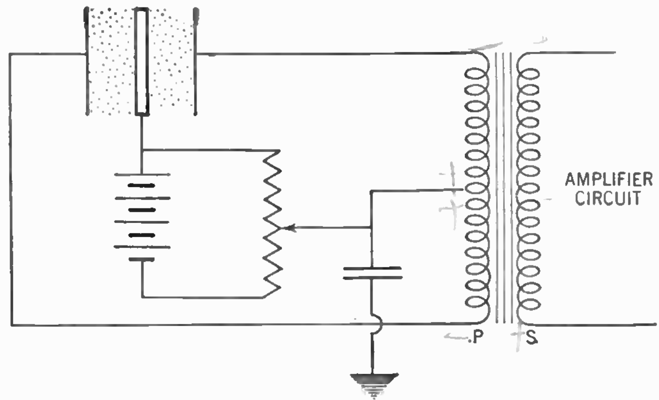


Fig. 140.

must be coupled to the transmitting circuit. Fig. 140 shows the transformer coupling for a double-button carbon microphone cir-

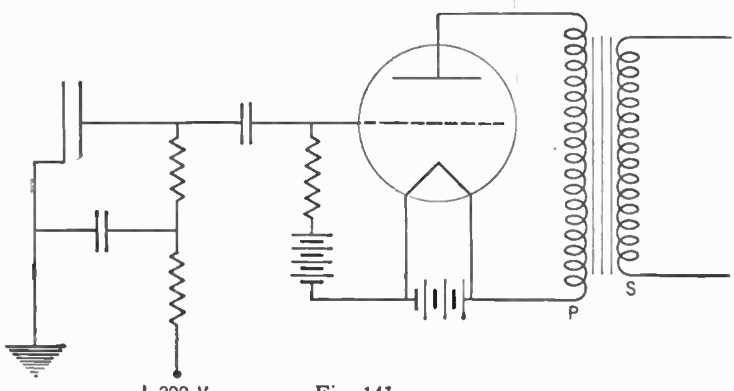


Fig. 141.

cuit. In the case of a condenser type microphone, the fixed plate of the microphone is connected to the grid of a triode tube, as shown by Fig. 141. The fluctuations of the potential in the microphone circuit cause changes in the potential on the grid; the latter has a negative bias. The plate current flows through the primary of a transformer. The induction in the secondary coil of the transformer is produced by the fluctuations in the plate current. The latter are much greater than those of the microphone current fluctuations.

Construction of the Telephone Receiver.—Having examined the method by means of which sound energy is changed into electrical energy, we shall now consider how electrical energy can be changed into sound energy. Again we must look to the telephone for the principle that will enable us to effect such a transition. The ordinary telephone receiver is very simple in construction. From Fig. 142 we see that its important parts are a permanent magnet, *M*, around the poles of which are wound two coils, *C*. The diaphragm, *D*, is an iron disk. When a fluctuating

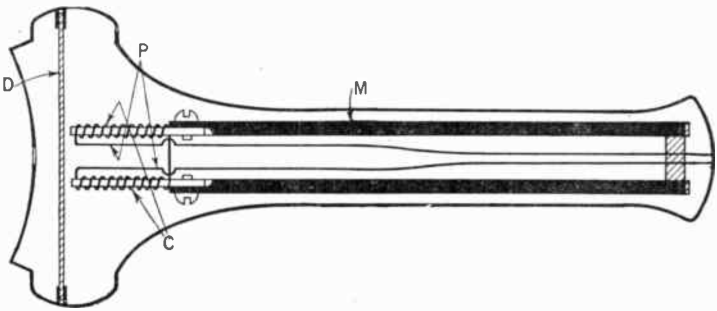


Fig. 142.

current flows through the coils, the magnetic field thereupon set up causes the poles of the magnet to become alternately stronger and weaker. This, in turn, varies the attracting force exerted upon the iron diaphragm, and so causes it to vibrate with the same characteristics as the fluctuations of the current. Vibrations of the diaphragm give rise to sound waves. If fluctuations in the current were originally produced by sound waves that fall upon the diaphragm of a transmitter in the same circuit, then the receiver diaphragm will also vibrate with the same frequency and thus produce sounds identical with those originally recorded by the transmitter.

The Loud-Speaker.—In the early days of radio, the ordinary telephone receiver was modified into the headset. Popular demand, however, soon brought about the invention of a device so powerful that the receiver would not have to be held close to the ear. This device, originally known as a *loud-speaker*, has since been improved in many different ways by means of using basically different principles. Before we try to understand these principles, let us consider those qualities that any good loud-speaker should possess.

Essential Qualities of a Loud-Speaker.—A loud-speaker should be free of wave-form distortion. By this we mean that the sound wave produced should follow, in detail, the fluctuations of the current. It should also be reasonably free of frequency distortion; that is, it should respond equally well to all frequencies within the audible range. Still another requirement of a loud-speaker is that its response be proportional to the strength of the fluctuating current. In other words, there should be no volume distortion over the range of frequencies required. Very few loud-speakers, indeed, can meet these three qualifications. It is common practice to design the audio-amplifying system so as to take into account the weaknesses of the loud-speaker itself. The net result of all this is to produce an audible output that has all the characteristics of the perfect loud-speaker. In addition to these general characteristics, a loud-speaker must be sturdy and also not too bulky.

The Parts of a Loud-Speaker.—A loud-speaker has three essential parts: (1) the motor, or *driving unit*, (2) the *diaphragm*, and (3) the *horn*. The motor converts electrical vibrations into the mechanical vibrations of the diaphragm. The diaphragm causes the air to vibrate, thus setting up a sound wave. The horn acts as a means of setting in motion a suitable volume of air. In some loud-speakers the horn and diaphragm are combined into a single unit that is somewhat modified in appearance.

Types of Loud-Speaker Motor.—The driving unit, or motor, of a loud-speaker can be based upon any principle by means of which motion is produced by a varying current that passes through it. The most efficient unit is one in which the least amount of variation of the current produces the largest amount of motion of the diaphragm. There are two principal types of loud-speaker. The first is known as a *magnetic speaker;* the second as a *dynamic speaker.* Neither name is very satisfactory, since the work of both is produced by magnetic effects, and since both also move under the action of a force. For this reason we shall define the two types of speakers on the basis of their actual construction. The magnetic speaker depends upon the motion of a piece of iron. In this type the varying current, that passes through coils wound on the pole pieces of a permanent magnet, causes the poles of the magnet to attract a soft piece of iron. In the dynamic speaker, the motion is produced in a coil by means of the interaction of the field of a magnet and of a magnetic field set up by the varying current that passes through a conductor.

An Explanation of the Magnetic Loud-Speaker.—As has already been explained, the magnetic loud-speaker is a moving-iron type of instrument. Three principal forms of driving unit use the moving-iron principle. These are (1) the *iron diaphragm,* (2) the *balanced armature,* and (3) the *inductor-balanced armature.* The iron-diaphragm magnetic loud-speaker uses the same principle as does the ordinary telephone receiver, though it has a much larger magnet, coil, and diaphragm for handling the greater energy required of a loud-speaker. A cross section of this type of driving unit is shown in Fig. 143. The poles of the magnet act on the diaphragm even when no current is flowing in the coils. This keeps the diaphragm constantly under stress and so limits its amplitude of vibration. If the unit is to be sensitive, the air space between the poles and the diaphragm must be a small one. Within these limitations, it is plain that if the air gap between the magnetic poles and the diaphragm is made too small, the amplitude thereby suffers and this results in poor volume. On the contrary, if the gap is made too large, the loud-speaker will not be at all sensitive. Since a diaphragm made of iron is not very flexible, it consequently has a poor frequency response. Though this was at one time a popular type of loud-speaker, it is no longer in use because of the defects just mentioned.

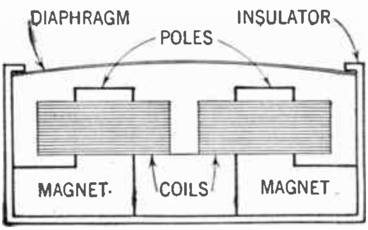


Fig. 143.

In order to overcome the defects of the iron diaphragm, an arrangement like that shown in Fig. 144 was eventually devised. At its center, a piece of soft iron is mounted upon a pivot. It is located half-way between the poles of a permanent magnet. A coil is wound upon this pivoted piece of iron. The fluctuating current flows through this coil. When no current is flowing, the iron takes a central position because it is equally attracted by both poles. For this reason it is known as a *balanced armature*. When the current flows in the coil, one end of the iron becomes a north pole and the other a south pole. Though the force of the poles of the permanent magnet on these poles is opposite in direction, nevertheless the effect upon both ends of the iron coil is such as to rotate it in the same direction about the pivot. One end of the iron coil is connected to the diaphragm by means of a lever. Thus the motion of the diaphragm is much greater than that of the piece of iron. By means of this method, the motion of the diaphragm can be made large without sacrificing the strength of the attracting force of the magnet. An added feature is that the diaphragm does not have to be made of iron, and can therefore be made of some lightweight material such as mica or aluminum. The balanced-armature driving unit gives a very satisfactory performance and is used in many battery-operated sets. In order to obtain good sensitivity, the gap between the poles of the permanent magnet must be made small so as to give a low reluctance to the magnetic circuit. This causes serious trouble when a sound of large intensity is to be reproduced, for when the armature turns through such a large angle its ends strike the pole pieces and thus cause a rattling sound. This defect can be avoided by using the design shown in Fig. 145. The principle upon which this armature operates can be understood by noticing that the wire in which the fluctuating current flows is wound in one direction around the north pole of the permanent magnet, and in the opposite

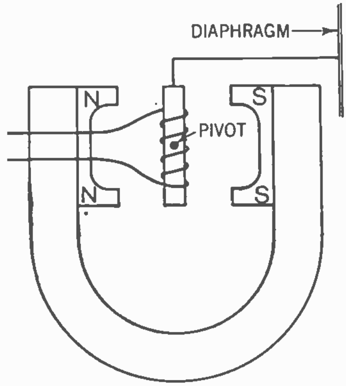


Fig. 144.

direction around the south pole. Wound in this manner, the current flowing as indicated in the diagram will strengthen the north pole at *A* and weaken the south pole at *B*. Thus the magnetic field at *A* becomes stronger, and the magnetic field at *C* becomes weaker. The reverse situation occurs when the current flows in the opposite direction. Between the poles at *A* and *B* are bars of soft iron that are fastened together and supported by two springs so that they may be free to move between the poles of the magnet. For the fluctuating current shown in the diagram, the induction in the iron is such as to produce a force that moves the armature unit to the right. A current change in the reverse direction would cause the armature to move to the left. This driving unit is known as an *inductor-balanced* armature. The air gap between the poles can be made very small because the armature moves at right angles to the distance between the poles, and because there is no danger of the armature's coming into contact with the poles. Since the air gap is small, the sensitivity of this type of loud-speaker is very great.

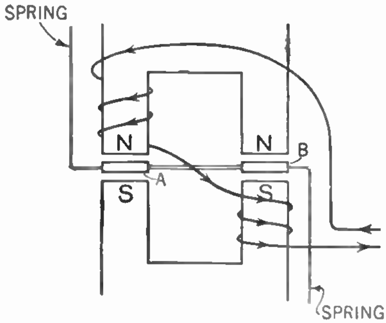


Fig. 145.

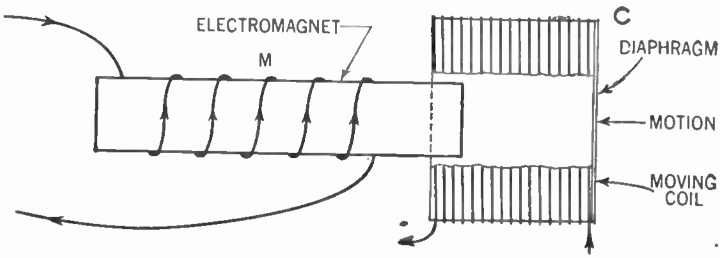


Fig. 146.

The Dynamic Loud-Speaker.—The dynamic loud-speaker has a moving-coil driving unit, the construction of which is shown by Fig. 146. A direct current flows through the coil of an electromagnet, *M*. The fluctuating current flows through the coil, *C*, which is free to move along the direction of the axis of the electromagnet. The diaphragm is attached to the moving coil. The fluctuating current in coil C sets up magnetic fields that react with the field of the electromagnet. Since the current in the coil of the electromagnet always flows in the same direction, a current in one direction in coil C produces a force that moves the coil away from the magnet. A current in the opposite direction produces a force that draws the coil toward the magnet. Due to this, coil C is given a to-and-fro motion that is characteristic of the

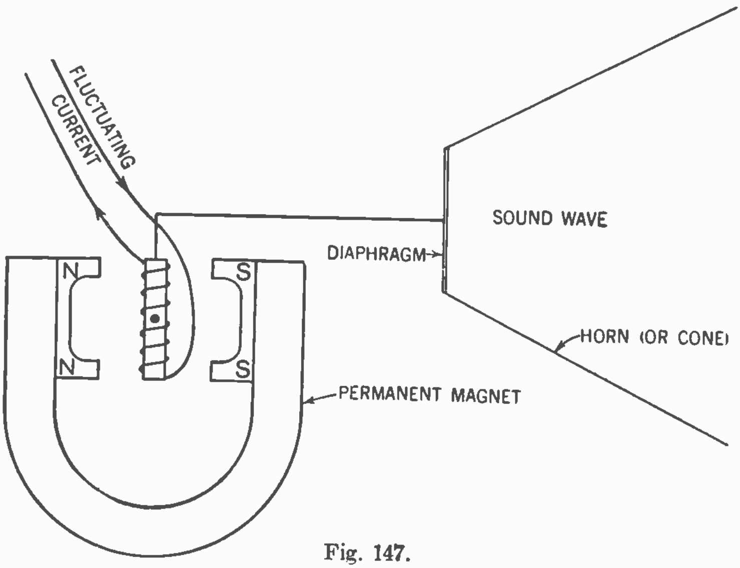


Fig. 147.

fluctuating current which flows through it. The diaphragm that is attached to the coil will have a similar motion and so produce condensations and rarefactions in the air in such manner that the resultant sound waves are similar to the sound waves that produced the fluctuating current. Since the coil moves along the axis of the electromagnet core, it may vibrate through large amplitudes without striking anything. This is one of the greatest advantages of this type of driving unit. It may be used for loud reproduction of the lowest notes without danger of its striking pole pieces.

The Function of the Diaphragm.—The vibrating iron in the magnetic-type loud-speaker, and the vibrating coil in the dynamic loud-speaker, do not have sufficient surface to set in vibration a volume of air large enough to produce a sound of desirable loudness. It is therefore necessary for them to drive a sound producer that has the characteristics required for setting up a wave of sufficient loudness. This is usually accomplished in one of two ways. The first method is by causing a flat diaphragm to vibrate at the neck of the horn. Fig. 147 shows a balanced-armature driving unit that operates a horn-type loud-speaker. The horn so used is commonly one of the *exponential* type. An exponential horn is one in which the cross-sectional area doubles for equal lengths along the horn. It has been found that such a horn permits the sound to progress from the diaphragm to the outside air with a minimum of interference. An alternative method of setting a sufficient amount of air in vibration is by attaching a paper cone to such a driving unit as has just been mentioned.

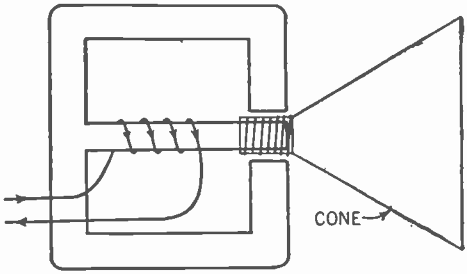


Fig. 148.

A dynamic-cone loud-speaker is shown in Fig. 148. Note that the electromagnet is an iron-clad one. The high efficiency of such a magnet was explained in the discussion of electromagnetism. The moving coil is attached to the cone that produces the sound wave as the coil is moved by the fluctuating current.

Horn *versus* Cone.—A loud-speaker must have three essential characteristics: (1) *sensitivity*, (2) *cut-off*, and (3) *distortion*. Sensitivity and distortion have already been discussed. Cut-off means the point above which frequencies are not satisfactorily reproduced by the speaker, and also the point below which low frequencies cannot be faithfully reproduced. In most cases, cones can be made so as to compare favorably with the exponential horn, so far as concerns cut-off and distortion. The exponential horn that has a relatively small diaphragm energy transmits a very large proportion of this energy to the sound wave. For this reason an exponential horn having a moving-coil driving unit gives exceptionally loud sounds without distortion. On this account an electrodynamic loud-speaker that has an exponential horn is to be preferred for public address systems and other instances where sound without distortion must be carried to a large audience. For home receivers, where compactness is desired, the cone loud-speaker is more satisfactory because the horn must be long and large in order to reproduce low notes properly. Where low notes are concerned, the front and back of the cone produce waves that interfere with one another; this interference may bring about improper reproduction of the low notes. In order to overcome this difficulty, baffles are constructed around the loud-speaker so that the two waves have no chance to interfere with each other.

The Condenser-Type Loud-Speaker.—The condenser type loud-speaker depends upon the force of attraction and repulsion between oppositely charged bodies. The general principle of this type loud-speaker is shown by Fig. 149, where *P* is a fixed plate and *D* is a thin diaphragm. The space between the two plates is a dielectric. The fluctuating voltage is connected across the two plates. The diaphragm is attracted to the fixed plate by the force of attraction of unlike charges on the two plates. In order to make the loud-speaker sensitive, the plates must be kept extremely close together and the substance placed between the plates must have a large dielectric constant. The plates are kept polarized by means of a voltage that is greater than any value of the fluctuating voltage. The diaphragm, therefore, vibrates with the characteristics of the fluctuating voltage and so produces sound waves. A loud-speaker designed on this principle is simple of construction, cheap to build, and has a minimum of moving parts likely to get out of order. This type condenser, however, has not yet been so fully developed as to be sensitive enough to replace the magnetic or dynamic speakers.

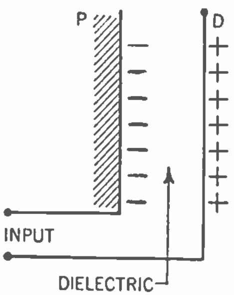


Fig. 149.

The Phonograph Record.—Early phonograph records were made by having the sound set a diaphragm in vibration. Attached to the diaphragm was a sapphire point that cut a spiral groove of varying depth in a wax disk. This plan of recording the sound was known as the "hill and dale" method. In order to reproduce the sound, a steel needle attached to a diaphragm was made to follow the groove; the up-and-down motion of the needle caused the diaphragm to produce condensations and rarefactions in such manner that the original sounds were reproduced. In another type of phonograph, the needle vibrated from side to side and the diaphragm was vertical. Today the sound is picked up by a microphone and then amplified by means of a vacuum tube. This amplified current magnetically operates a recording needle that makes the trace in wax. Sounds are also reproduced electrically by means of the radio receiving set. For this purpose a magnetic pick-up (shown in Fig. 150) is necessary. A needle pivoted between the poles of a magnet follows the spiral groove in a phonograph record. In this way the needle vibrates to and fro, guided by the impressions on the disk, and so induces a fluctuating current in a coil in which the needle is mounted. This fluctuating current, amplified by the vacuum tubes, then passes to the driving unit of a loud-speaker, and there the sound is again produced.

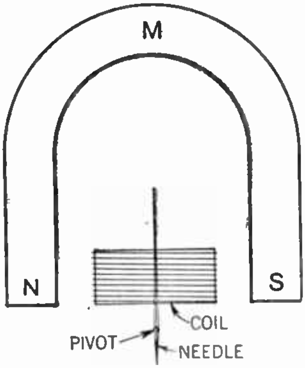


Fig. 150.

QUESTIONS

1. What is meant by the *pitch* of a sound wave?
2. Draw a diagram that indicates the wave length of a water wave.
3. What is the fundamental wave equation?
4. What determines the intensity of a wave?
5. Name the parts of a sound wave.
6. What do we mean by the *audible range?* Give an example.
7. What is the unit of sound intensity?
8. Explain the meaning of *bel* and *decibel.*
9. What is an *audiogram?*

10. Explain the importance of the audible range and sound levels in radio communication.

11. What significance does the decibel have, other than being a unit of sound intensity level?

12. Explain the difference between the single-button and double-button microphone.

13. On what principle does the condenser-type microphone work?

14. What are the two types of driving unit in a loud-speaker?

15. Explain the operation of one type of magnetic loud-speaker.

16. In what way is the dynamic loud-speaker superior to the magnetic loud-speaker?

17. What are the essential characteristics desirable in a good loud-speaker?

18. Compare the advantage of the horn and cone loud-speaker.

19. What is meant by an exponential horn?

20. Draw a diagram and explain the operation of a magnetic pick-up for a phonograph.

CHAPTER 8

PRODUCTION OF ELECTROMAGNETIC WAVES

The Production of Waves.—We have learned that a wave is a distortion, or configuration, of the medium in which it occurs. The wave passes through the medium while the medium as a whole remains at rest. The production of the wave is brought about by some disturbing force, such as a stone dropped into a pond of water for a water wave, or a vibrating tuning fork or violin string for a sound wave. In the case of water waves, the configuration, or wave, may readily be observed. We shall now consider some instances where the wave cannot so easily be perceived. Sound waves, as we know, will not travel through a vacuum. This is not true, however, of light waves. Light comes to us from the sun and stars through millions of miles of empty space. This space is a much more nearly perfect vacuum than any that man can produce. In view of this fact, the question then arises: Through what medium is the light wave propagated? A proper answer to this question is important in any study of radio since radio waves behave just as light waves do. The medium for light and radio waves in empty space has never yet been discovered. Nor has it yet been determined whether or not there is any such medium at all.

Electromagnetic Waves.—Since no material medium appears to be involved in the propagation of light and radio waves, accordingly we must modify our concept of a wave. We must visualize a configuration in space that travels throughout space just as a water wave or a sound wave travels through a material medium. Fortunately it is not difficult to make this visualization. We shall, however, first have to recall some of the facts concerning electric and magnetic fields that were presented in the chapter entitled *Principles of Electricity*. In the space that surrounds an electric charge, there is an electric field. This field can be represented by electric lines of force. Fig. 151 shows the electric field in the vicinity of a positive and negative charge. It should be observed that the lines of force go from the positive to the negative charge.

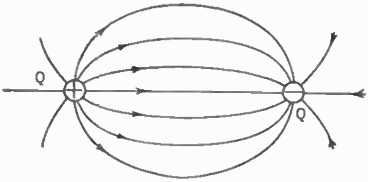


Fig. 151.

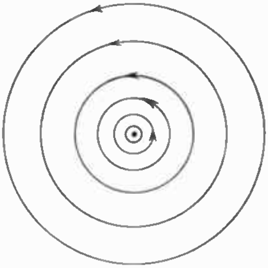


Fig. 152.

If the charge is in motion, there is also a magnetic field in the space that surrounds the moving charge. We should recall that the magnetic field surrounding a conductor that carries a current consists of circular lines of force concentric with the center of the conductor (Fig. 152) for a current that flows out of the paper. It must be realized, however, that both electric and magnetic fields exist at the same time wherever a current is flowing. Fig. 153 shows both the magnetic field and the electric field for a current that flows out of the paper. It should be observed that the electric field consists of radiating lines, while the magnetic field consists of concentric circles. The electric lines are at right angles to the magnetic lines at all points. Thus far we have considered a steady current that flows in the conductor. If the current were to change in the wire,

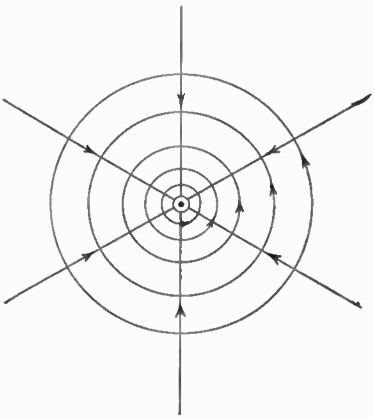


Fig. 153.

this would produce a change in both the electric and the magnetic fields. An alternating current of high frequency in the wire would produce a rapidly changing electric and magnetic field in the space that surrounds the conductor. Thus the vibrating electrons in the wire set up a configuration in space that is analogous to the configurations in a material medium that are set up by a vibrating tuning fork. Such a configuration, or wave, is known as an *electromagnetic wave*.

The Types of Electromagnetic Wave.—In the case of light, the electromagnetic wave is set up by the electron changes that take place in the atom. In radio, on the contrary, the electromagnetic wave is produced by a high frequency alternating current. Both light and radio waves travel with the same velocity, namely, 186,000 miles per second, or 3×10^{10} centimeters per second. So far as we know, the only difference between light and radio waves is that of their frequency. It has already been said that $V = N\lambda$, where V is the velocity of the wave, N is its frequency, and λ is the wave length. The velocity of all electromagnetic waves is 3×10^{10} centimeter/seconds. Their frequencies, however, extend over a large range. They include not only visible light rays and radio waves, but also such invisible light radiations as infra-red rays, ultra-violet rays, X-rays, and gamma rays. We purposely call attention to the fact that radio waves are only one type of a wide variety of electromagnetic waves. Furthermore, we shall limit our discussion to radio waves. Though the exact extent of the frequencies of radio waves is not known, nevertheless it is generally believed that they range approximately from 10 kilocycles to 60,000 kilocycles. (A *kilocycle* is 1,000 cycles per second.) Only a small portion of this range of frequencies is used in broadcasting. The frequencies of broadcasting stations in the United States range between the limits of 550 to 1,500 kilocycles. The remaining portion of the radio waves is reserved for foreign broadcasts, government communications, ship-to-shore telephone, television, amateur and experimental radio, and other special uses.

The Propagation of Radio Waves.—Let us now discover how a radio wave is established by a high-frequency alternating current. Fig. 154 shows a high-frequency generator connected to two vertical wires. At the time when the terminal connected to the upper wire is positive, the lower terminal is negative. The electric field in the vicinity of the wires is shown by the electric lines of force. The two wires, therefore, act as the plates of a condenser. In order to simplify the situation, and also to approach more nearly the conditions actually employed in practice, we shall eliminate the lower wire and use the ground as the other plate of the condenser, as shown by Fig. 155. As

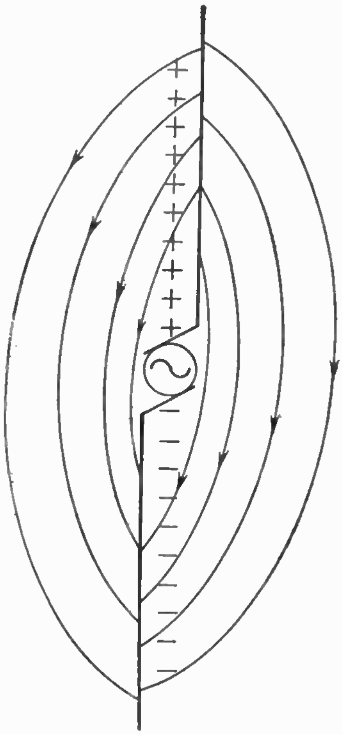


Fig. 154.

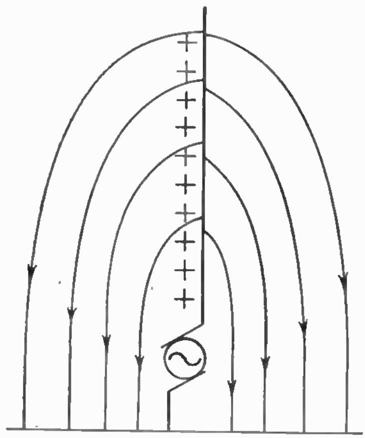


Fig. 155.

the alternating current in the circuit varies from a maximum in one direction to a maximum in the opposite direction, the electric field is also varying in the same manner. As the current in the wire reaches its 0 value, the energy in the electric field attempts to return to the wire. If the frequency is great, however, before it has time to return, a new field is established in the opposite direction. This latter field repels the original field off into space. This field, so propagated into space, is known as the *radiated field*, in order to distinguish it from the original induced field. (See Fig. 156.)

Now, since a changing electric field is equivalent to an electric current, the changing electric field produces a magnetic field. This magnetic field is perpendicular to the electric field. The two fields are changing simultaneously with the changing current. The configuration is shown by Fig. 157. It should be observed that the

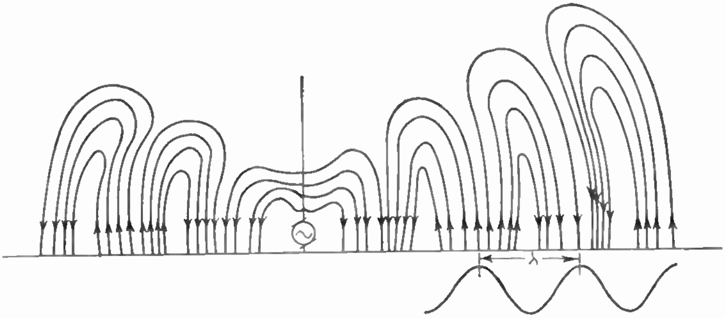


Fig. 156.

electric component is represented by E and the magnetic component by H. The two components of the wave are at right angles to each other, and the wave is propagated in a direction at right angles to both. This wave, produced by the high-frequency current, is the electromagnetic, or radio, wave which travels through

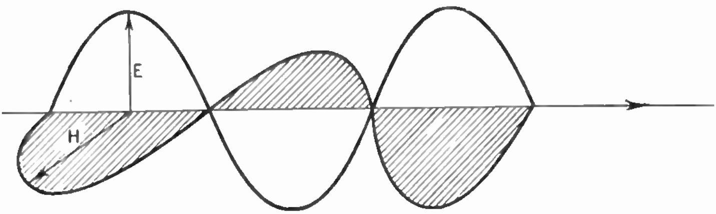


Fig. 157.

space with a speed of 3×10^{10} centimeter/seconds. If the frequency of the oscillating current is too small, then most of the energy of the electric and magnetic fields returns to the wire. On the contrary, if the frequency is large, then most of the energy is radiated into space, since there is not sufficient time for the energy in the fields to return to the wire before the reverse field is set up by the changed direction of the oscillating current.

The Vacuum Tube as an Oscillator.—In order to produce the oscillating currents necessary for the production of radio waves, induction coils were at first employed. Since these could supply only a relatively small amount of energy, alternating-current dynamos of high frequency were substituted. Because the desired frequency was so great, the generators were of very complex design and consequently had numerous disadvantages. With the perfection of the vacuum tube it was realized that the tube could be used as a generator of high-frequency currents. At the present time, therefore, the vacuum tube has supplanted all other methods of generating oscillating currents for transmitters. Fig. 158 shows the wiring diagram of a triode that is being used as an oscillator. The inductance, L_1, and the condenser, C_1, form an oscillating circuit. If an oscillation were set up in such a circuit,

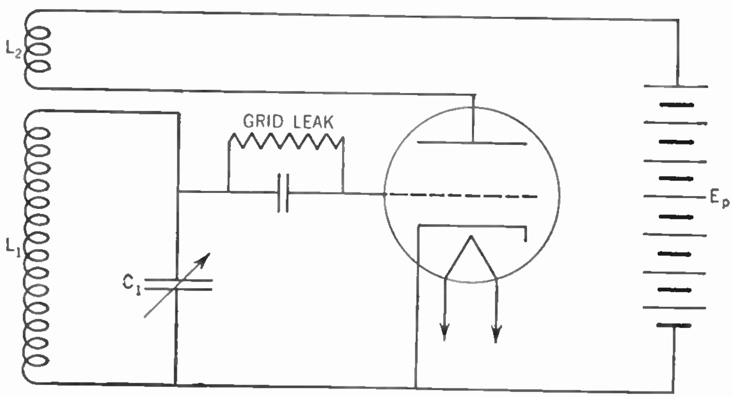


Fig. 158.

the oscillations would be damped and would die out, as is shown by the graph in Fig. 159. This condition results from the dissipation of energy. But the alternating voltage across the condenser, C_1, is connected to the grid of the triode tube. This causes variations of the same frequency in the plate circuit. Inductance L_2, in the plate circuit, is inductively coupled with inductance L_1. The fluctuating plate current through inductance L_2 induces a current of the same frequency in inductance L_1, and this is the same frequency as the original oscillatory current in L_1. This principle is known as *feedback*. By varying L_1 or C_1, or both, the frequency of the oscillations can be set at any desired value. The circuit containing L_1 and C_1 is commonly called the *tank*. Due to the effect of feedback, the oscillations in the tank, instead of damping out, as shown by Fig. 159, are sustained, as shown by Fig. 160.

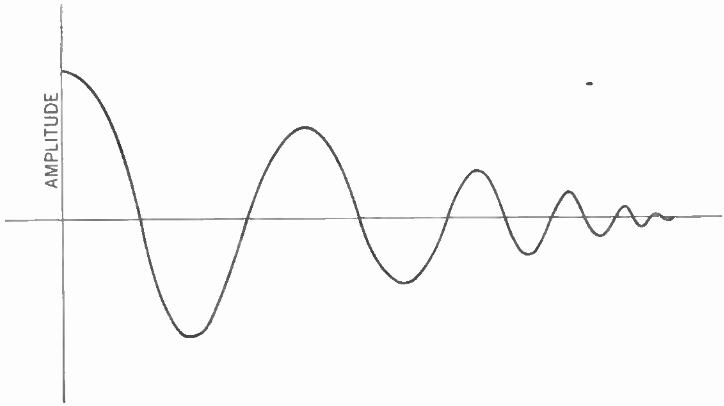


Fig. 159.

The Grid Leak.—As shown by the oscillator circuit of Fig. 158, we have explained how the oscillation is maintained by feedback. Since the tank circuit receives no outside signal, however, this

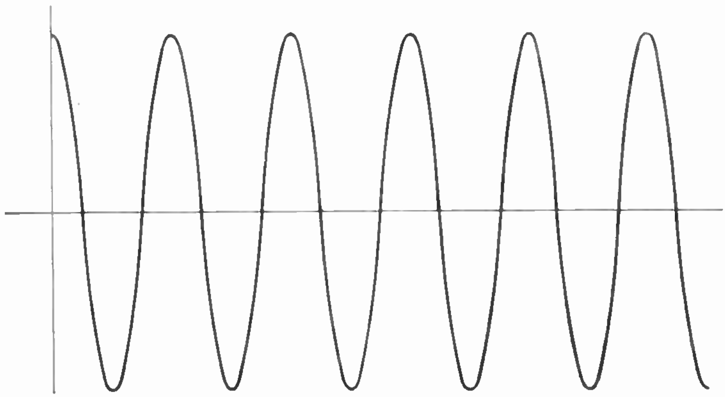


Fig. 160.

question presents itself: How does the oscillation first start? This matter may readily be understood if we examine the resistance in parallel with the by-pass condenser connected to the grid. This resistance is exceptionally large; it is usually 1 *megohm*, that is, one million ohms. The current through this resistance, commonly known as the grid leak, is zero to start with because no cell is connected to the grid. When the grid potential is zero, a large plate current flows; this results in a large induction in the coil of the tank circuit. This produces a potential on the grid which modifies the plate current. In this manner the oscillation is set up in the circuit and there maintained as previously explained.

The Frequency of an Oscillating Current.—The frequency of the current in a circuit that contains inductance and capacitance is given by the relationship $f = \frac{1}{2\pi\sqrt{LC}}$. Though it is possible to vary the frequency by changing the inductance, nevertheless it is common practice to use a variable condenser for this purpose. Since the resistances of the tank circuit and of the tube have an effect on the frequency, consequently a slight correction must be made in the formula just given. For this reason it is well to keep the resistance of the tank circuit as low as possible. Since practically all the resistance is in the inductance coil, the value of the resistance can be reduced by using a small inductance. This means a small L to C ratio.

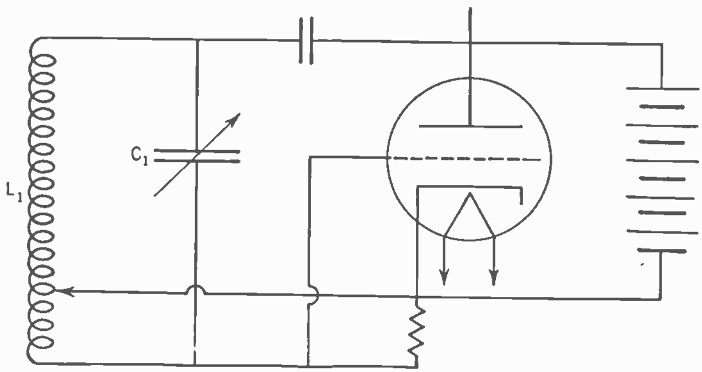


Fig. 161.

The Hartley Circuit.—Although there are many different oscillator circuits, nevertheless most of them are simply modifications of a few basic circuits. One of these latter, known as the Hartley circuit, is shown in Fig. 161. This is a self-oscillating circuit arranged on the magnetic feedback principle. Comparison of this circuit with that shown in Fig. 158 reveals that the general principle of the two is the same, except that the coil L_2 (known as the

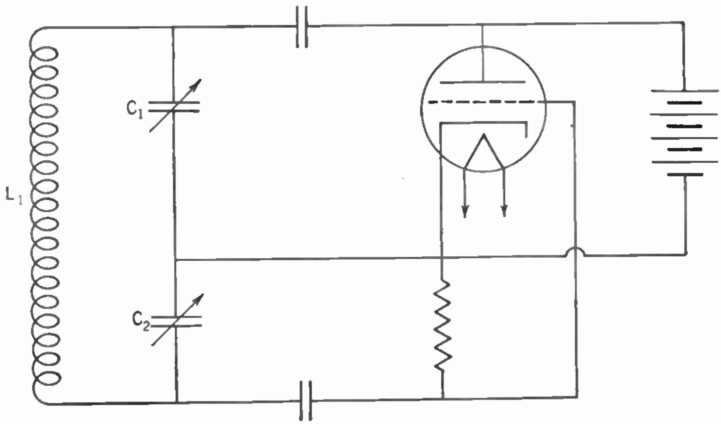


Fig. 162.

tickler coil) is eliminated in the Hartley circuit. Instead, a single coil that can be tapped is used; part of it is in the plate circuit,

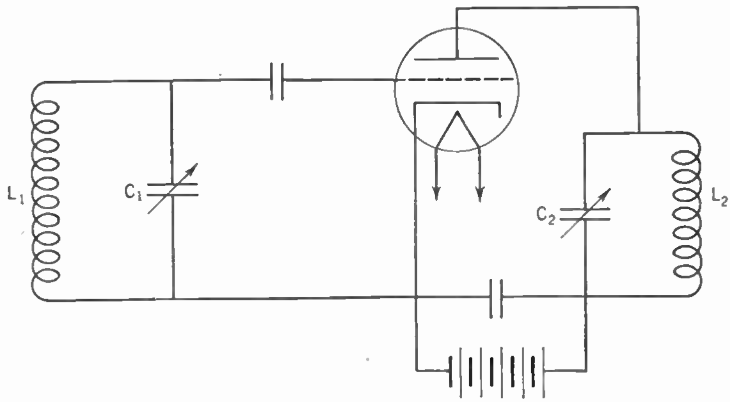


Fig. 163.

another part in the grid circuit. The magnetic coupling between the two sections of the coil provides the feedback; this can be adjusted by moving the tap on the coil.

The Colpitts Circuit.—The Hartley circuit is based upon the principle of *inductive feedback*. Another method of producing feedback is by means of a *capacitive effect*, of which the Colpitts circuit, shown in Fig. 162, is an example. The voltage across the tank circuit is divided into two parts by means of series condensers C_1 and C_2. The instantaneous voltages across these condensers are opposite in polarity with respect to the cathode. The feedback can be controlled by varying the ratio of the capacitances, C_1 and C_2.

The Tuned-Plate–Tuned-Grid Circuit.—Another circuit that makes use of the capacitive feedback principle is shown in Fig. 163. The capacitive feedback takes place in the tube's–grid-plate capacitance. In this circuit, oscillations are set up by tuning the plate and grid circuits. For this reason it is known as a *tuned-plate–tuned-grid oscillator*. This circuit has a fairly good frequency stability because of the high impedance plate load.

Piezo-Electricity.—When certain crystals, such as those of quartz and Rochelle salt, are compressed, the opposite ends, or faces, become oppositely charged. Electricity produced by means of mechanical pressure on a crystal is known as *piezo-electricity*. Crystals that exhibit this property are known as piezo-electric crystals. The electricity produced by this means differs in no respect from that produced by other means. When a piezo-electric crystal is stretched, the charges are reversed. This property is reciprocal; that is, the crystal lengthens and shortens as the charges are reversed on the faces of the crystal.

The Crystal as an Oscillator.—If a quartz crystal has metal foil coatings on opposite faces, and if it is connected in such a circuit as is shown in Fig. 164, the crystal oscillates when the frequency constants of the circuit are properly adjusted. It should be observed that this is the tuned-plate–tuned-grid circuit in which the crystal is substituted for the tuned inductance and capacitance in the grid circuit. This type of oscillator is known as a *crystal oscillator*. When the tuned inductance and capacitance are used in the grid, the oscillation is said to be self-excited.

Crystal-Controlled Oscillators.—Transmitting stations are required by law to transmit at specified frequencies. Each station must maintain its own frequency within a small margin of error. As one means of doing this, the quartz crystal is an excellent device. The constancy of a quartz crystal is exceptional. A clock that loses one second a day, that is, one second out of every 86,400 seconds, is regarded as a very fine timepiece. In contrast with this fact it is interesting to note that a quartz crystal varies only about one second in every million seconds. Today all broadcasting stations use quartz crystals for the purpose of keeping their transmitting frequencies constant. The thickness of the crystal determines its frequency. The thinner the crystal is cut, the greater

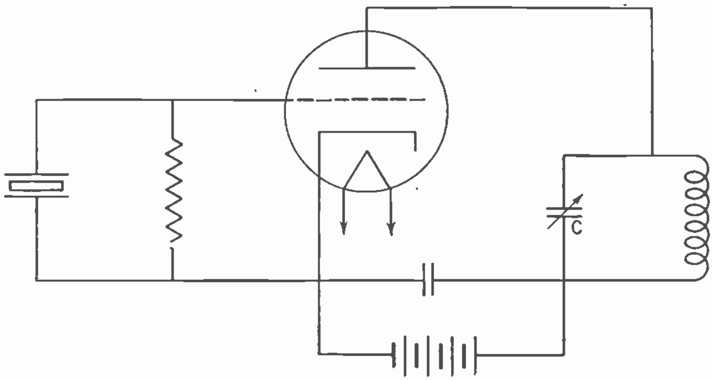


Fig. 164.

is its frequency. A quartz crystal about 0.1 centimeter thick will vibrate at about 3,000 kilocycles. Temperature also has an effect upon the natural frequency of a crystal. Such being the case, the control crystal must be kept at a constant temperature. Broadcasting stations maintain the control crystals at a constant temperature by means of electrical heating coils that are operated by thermostats. In addition to their use as control oscillators, piezoelectric crystals are also used in loud-speakers and phonograph pick-ups.

The Master Oscillator.—If the crystal of a crystal oscillator is made to oscillate too strongly, as, for example, when it is used with high plate voltage and large feedback, the amplitude of the mechanical vibration will become great enough to crack or puncture the crystal. Also, when high crystal currents are used, they are accompanied by increased heating that tends to change the frequency. For these reasons the power employed must be limited. In order to meet the requirements of a large power output to the antenna, broadcasting stations have replaced the large oscillating tube by a smaller oscillator and a separately excited amplifier. For this purpose a crystal oscillator is used; this keeps the oscillations at constant frequency, and in consequence the output of the amplifier remains constant. A crystal amplifier with a power amplifier is shown in Fig. 165. Such a circuit, known as a

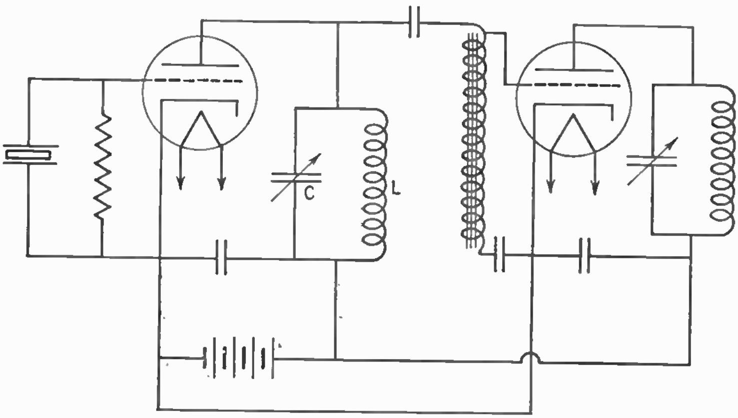


Fig. 165.

master oscillator circuit, is used by all broadcasting stations and other transmitters that require large antenna power.

Tetrode and Pentode Crystal Oscillators.—A triode crystal oscillator has already been described. (See page 145.) Since the power output of a crystal oscillator is limited by the permissible crystal current, it is in consequence advisable to use a tube of high power sensitivity, such as a tetrode or a pentode. By using tubes of this latter type, more power can be obtained with a given crystal current than can be obtained with a triode. Furthermore, for a given power, the crystal voltage for the tetrode or pentode can be less than that for the triode; this brings about a smaller heating effect upon the crystal, and so prevents frequency changes that are due to temperature variations. A typical tetrode or pentode oscillator circuit is shown in Fig. 166. The grid plate capacitance may be too low to give sufficient feedback. In this case a feedback condenser, *C*, shown with dotted lines in the diagram, may be required. For best operation, the screen voltage is usually half that of the plate voltage.

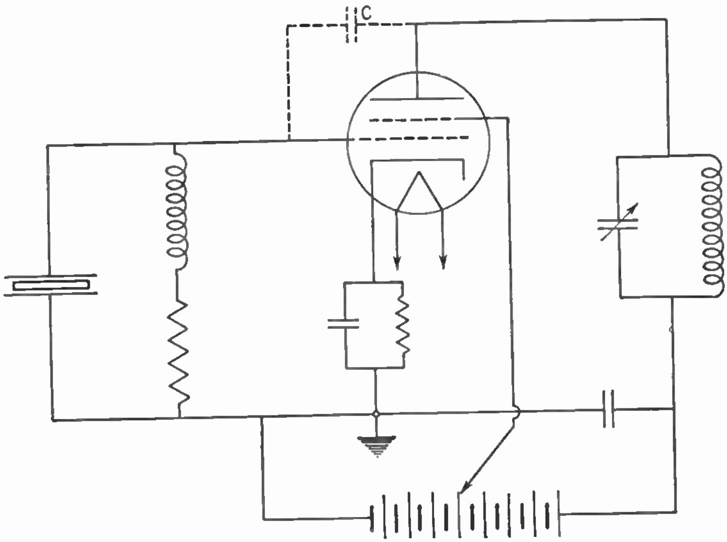


Fig. 166.

Amplification.—Having discussed methods of producing oscillating currents of desired frequency, we shall now consider how these currents may be set up in the antenna. One method of doing this is to connect directly to the antenna. This is not commonly done because the radio wave, in order to be reasonably strong, must be produced by an oscillating current of large power as compared with the original current in the oscillator circuit. In order to increase the power, it is necessary to amplify the relatively feeble current of the oscillator. Principles employed in accomplishing this result will be explained in the discussion of radio frequency amplification.

Keying.—In the transmitter circuits already explained, the wave sent out is a continuous wave of constant amplitude. This is usually known as the *carrier wave*. In radio telegraphy, the interruption of this wave gives rise to the dots and dashes of telegraphic communication. This process of interrupting the wave is known as *keying*. Necessary qualifications for satisfactory keying are (1) that the power output be zero when the key is up, and (2) that full power reach the antenna when the key is down. It is also essential that no transient currents be set up upon closing or opening the key. These transient currents cause clicks that produce interference with other transmitting stations. Any stage of the transmitter may be keyed by opening or closing the plate power circuit. Due to the fact that the positive lead is at the same potential as the plate, the key should be connected in the negative lead; there is also danger of shock, due to the high plate voltage that may be brought about when the key is connected to the positive lead. A more satisfactory manner of keying is the so-called *blocked-grid* method. In this instance, keying is brought about by applying sufficient negative bias to a control, or suppressor, grid that cuts off the plate current flow when the key is open, and by removing this blocking bias when the key is closed. In radiotelephony, the carrier wave is modulated in accordance with the sound that is to be transmitted.* Modulated wave transmission will be explained in a subsequent chapter.

* The transmitting circuits that have here been described are designed for instructional purposes only. The United States Government forbids transmission of radio signals except by licensed operators, and then only according to the regulations of the Federal Radio Commission.

QUESTIONS

1. Explain the difference between the radiated field and the induced field.

2. What is the *wave equation?*

3. State the conditions necessary for setting up an electromagnetic wave.

4. What are the two components of an electromagnetic wave?

5. How fast do radio waves travel?

6. What is the length of the wave given out by the transmitter of a broadcasting station whose frequency is 1,050 kilocycles?

Ans. 285.7 meters.

7. Describe the action of the feedback in a vacuum tube that is used as an oscillator.

8. Explain what is meant by the *tank*.

9. What is the principle of the Hartley circuit?

10. What circuit is based upon capacitive feedback?

11. Draw a diagram, then explain the tuned-plate–tuned-grid circuit.

12. What is piezo-electricity?

13. What is the function of the quartz crystal in the transmitter circuit?

14. Explain the principle of the master oscillator.

15. Draw a diagram that shows how a tetrode may be used as an oscillator.

16. What is meant by *keying?*

17. What qualifications are essential for satisfactory keying?

18. Explain the principle that underlies the blocked-grid method of keying.

19. What is the difference between radio-telegraphy and radio-telephony?

20. What is meant by the *carrier wave?*

CHAPTER 9

RECEPTION OF ELECTROMAGNETIC WAVES

Induction in the Receiver Antenna.—As the electromagnetic wave travels out from the antenna of the transmitter, any vertical conductor has an alternating e.m.f. induced in it by the changing magnetic component of the wave. This vertical wire might serve as the antenna of a receiving set. Every radio wave, no matter how feeble it may be, will induce an alternating e.m.f. in the receiver antenna, and, consequently, an alternating current. Near-by stations, of course, and also those of greater power, will produce greater effects by means of their radiated waves. This will at least limit us to a much smaller number of electrical oscillations; nevertheless there are still too many oscillations for satisfactory communication.

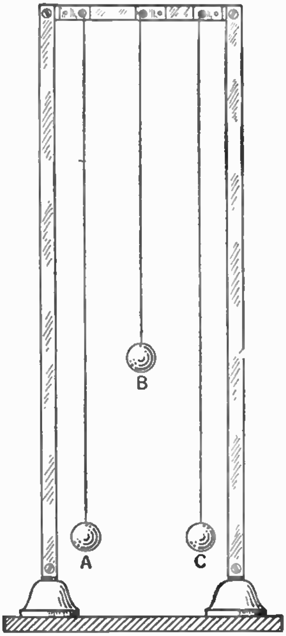


Fig. 167.

Resonance.—In order to limit reception to a single desired frequency, we make use of the principle of *electrical resonance*. Before we consider the subject of electrical resonance, it will be helpful to consider a few cases of *mechanical resonance*. The three pendulums shown in Fig. 167 are suspended from a flexible frame. It should be observed that pendulum A and pendulum C are of the same length, while pendulum B is of a different length. Let us displace pendulum A and allow it to swing through a fairly large amplitude. In a short time we shall notice that pendulum C starts to move; finally it swings with an amplitude as great as the original amplitude of A. Upon examining pendulum B, we observe only a very slight motion. The energy has, of course, been transmitted through the flexible frame. It can be shown that the frequency of a pendulum's swing depends upon its length. If two pendulums have the same length, as have pendulum *A* and pendulum *C*, they also have the same natural frequency. A pendulum of shorter length, such as pendulum *B*, will have a greater frequency. From this experiment we conclude that there is a large transfer of energy between bodies that have the same natural frequency, and that there is practically no transfer of energy between bodies that have different frequencies. Therefore, resonance is the phenomenon of the transference of energy from one system to another, where each has the same natural frequency. The transference of energy under resonant conditions is enormously greater than under other conditions. A striking example of mechanical resonance can be exhibited by the Frahm resonant top shown in Fig. 168. This top consists of a heavy wheel that is mounted in a frame. Attached to the frame is a group of reeds that are free to vibrate. A string is used for spinning the top; the latter can be held by means of a handle. The top is first given a rapid spin. It then gradually slows down until its rate of rotation, that is, its frequency, just equals the natural frequency of the shortest reed. At that time the shortest reed vibrates vigorously through a large amplitude, though all the other reeds are barely moving. As the top continues to slow down, the reeds vibrate in succession at the time when the top has the same rate of rotation as their natural frequency. The longest reed, which has the smallest natural frequency, is last to vibrate. In any consideration of sound, many illustrations of resonance also appear. If, for example, one tuning fork in the vicinity of another is set in vibration, the second fork will start to vibrate

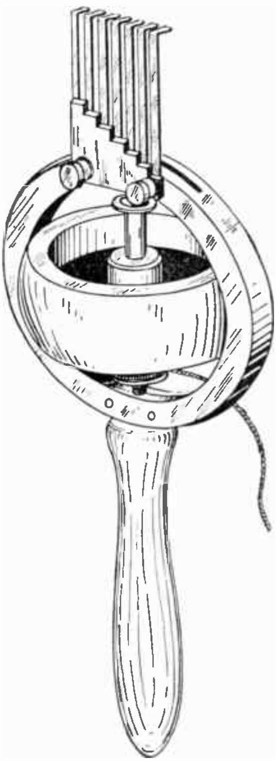


Fig. 168.

of its own accord, provided only that it has the same pitch as has the first fork. If a violin string so vibrates that it gives out a note of some given pitch, the string of the same pitch in a near-by piano will also start to vibrate sufficiently to give out the same note. There are cases on record where a note produced by a violin was sufficient to cause a wine glass having the same natural frequency to vibrate with such intensity that the glass was shattered.

Electrical Resonance.—In the topic on alternating circuits, some characteristics of resonant circuits were discussed. Fig. 169 shows a series resonant circuit. Here a constant voltage is maintained across the terminals of the circuit. The frequency of

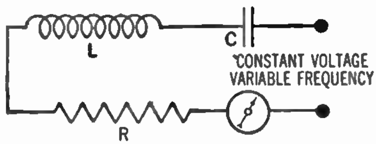


Fig. 169.

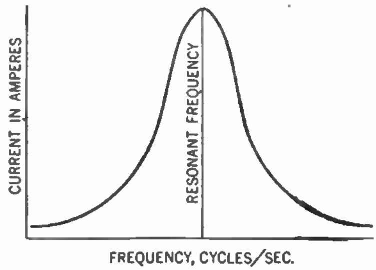


Fig. 170.

the impressed voltage is gradually increased, and the current is observed by means of a high-frequency ammeter. A graph of current and frequency is shown in Fig. 170. It should be observed that the current rises sharply to a maximum at one particular frequency. The circuit is said to be resonant at this frequency, and the latter is known as the *resonant frequency*. The similarity between this situation and that of the resonant pendulum may easily be seen. The pendulum responds to one particular frequency, *i.e.*, its natural frequency, and the electric circuit also responds to a particular frequency, *i.e.*, its resonant frequency. In order to cause a pendulum to be resonant to a given frequency, we change its length. In the case of an electric circuit, the resonant condition is obtained by *tuning the circuit*.

Tuning a Series-Resonant Circuit.—In the series-resonant circuit, the current is a maximum. We have previously seen that in order for this condition to be met, the impedance must be at a minimum, since $I = \frac{E}{Z}$. If the resistance is a fixed value, the only factor in the impedance that can be adjusted is the reactance. Since the inductive reactance and the capacitive reactance are in opposite sense, *i.e.*, since one is positive and the other negative, we can make their combined effect equal to zero by choosing the same magnitudes for them. Fig. 171 shows the vector diagram for a series-resonant circuit. It is therefore evident that the impedance is equal to the resistance; *i.e.*, $Z = R$. Since R is fixed, the current is at a maximum under this condition. The capacitive reactance of a circuit has been shown to be equal to $\frac{1}{2\pi fC}$, and the inductive reactance to be $2\pi fL$.

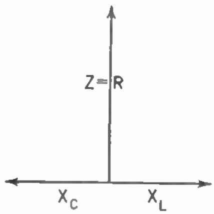


Fig. 171.

In the case of resonance,

$$X_L = X_C, \quad \text{or} \quad 2\pi fL = \frac{1}{2\pi fC}.$$

Solving for f, we have:

$$f^2 = \frac{1}{4\pi^2 LC}, \quad \text{or} \quad f = \frac{1}{2\pi\sqrt{LC}}.$$

This is one of the most important equations in radio theory. The entire principle of tuning is based upon this equation. It is possible to tune a circuit to a given frequency by changing the value of L, or of C, or of both. At various times in the development of radio equipment, all these methods of tuning have been used. To-day most tuning is done by varying C by means of a variable, or tuning, condenser such as was described in our discussion of condensers. (See page 53.)

Sharp Tuning.—We have seen that the value of the resistance does not enter into the expression for the resonant frequency. It must not be thought, however, that the resistance plays no part in tuning a circuit. If, in the circuit shown by Fig. 169, we use different resistances and then observe the currents for different frequencies, we obtain values as shown by the graphs in Fig. 172.

Since the capacitance and inductance have not been changed, the resonant frequency is the same in all the curves. The shapes of the curves are, however, very much different. In the case of the lowest resistance, the curve is sharply peaked at the resonant frequency. The curves for the other resistances are much broader near the resonant frequency. The effect of this on tuning can be seen by selecting a curve of a tuning circuit having small resistance, and another having large resistance, both of which are shown in Fig. 173. Both circuits are tuned to the frequency of station WOR, which has a frequency of 710 kilocycles. In both curves a horizontal line is drawn for the purpose of indicating the lower level of audibility. Upon examining the graphs, we observe that for the low-resistance circuit, frequencies from 680 to 740 kilocycles are audible, while in the high-resistance circuit, the range is from 640 to 780 kilocycles. The sharply tuned circuit has a range of 60 kilocycles, and the broad tuned circuit has a range of 140 kilocycles. In order to appreciate the significance of this, let us locate on both graphs the position of the two broadcasting stations nearest in frequency to WOR. These are WEAF and WJZ, which have frequencies of 660 and 770 kilocycles, respectively. In the graph of the circuit of small resistance, we observe that both these stations produce effects far below the lower limit of audibility. It is apparent, therefore, that these stations will not be heard when the set is tuned for WOR. On the contrary, in the circuit of great resistance, both these stations produce audible effects when the set is tuned for WOR, which is obviously very undesirable. Sets with insufficiently sharp tuning have, with the reception of the given station, annoying background effects produced by stations with adjacent frequencies.

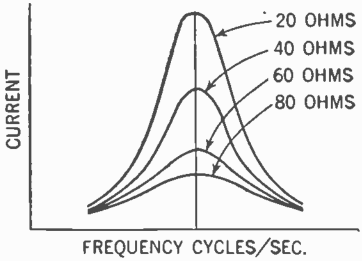


Fig. 172.

The Parallel-Resonant Circuit.—In the series-resonant circuit, the current is a maximum for the resonant frequency. We have seen that when we tune this circuit, only the desired frequency is allowed to pass. Under the theory of alternating currents, it was stated that a circuit with a capacitance and an inductance in parallel can also be a resonant circuit. In this parallel-resonant circuit, the impedance is a maximum and the current is a minimum. For this reason the parallel-resonant circuit is sometimes called the *anti-resonant circuit.* When we tune the parallel-resonant circuit for a given frequency, all frequencies pass except

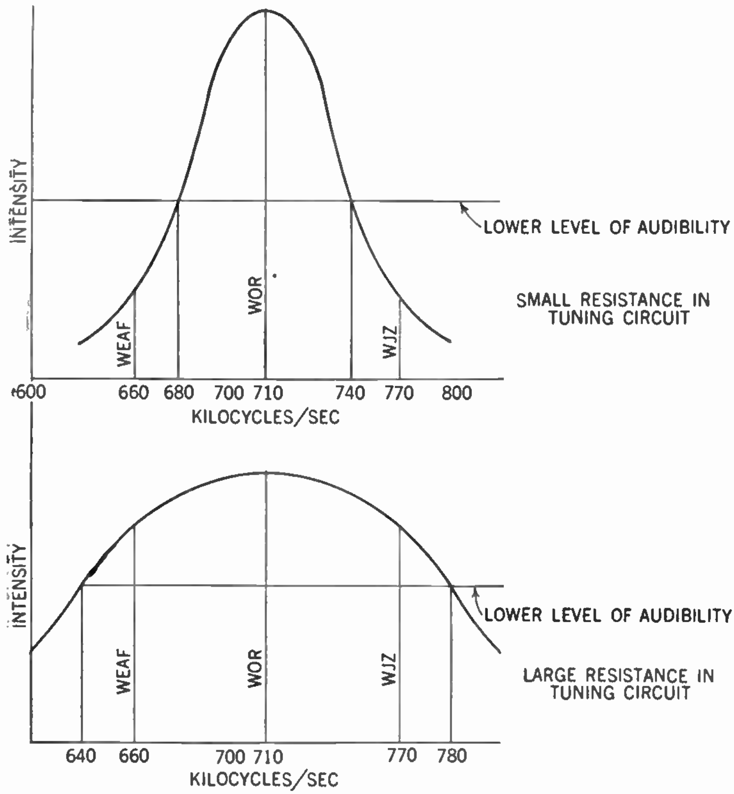


Fig. 173.

the resonant frequency. These two principles are sometimes combined in an antenna or aerial circuit so as to accept or reject certain frequencies.

Wave Traps.—Since a parallel-resonant circuit rejects certain frequencies, it is called a *wave trap.* The use of wave traps is shown by Fig. 174. In circuit A, the wave trap, or rejector circuit, is in parallel with the acceptor circuit. When both circuits are tuned for a given frequency, the rejector circuit offers a large impedance to the given frequency and low impedance to all other frequencies. Thus all frequencies except the given one pass readily to the ground. The acceptor circuit allows a large current of the given frequency to flow to the set, but does not permit much current of any other frequency to flow. This type of circuit is known as a *band-pass filter.* Although we have referred to a "given frequency," actually that frequency and also some neighboring frequencies will pass, depending upon the sharpness of tuning. That is why the circuit is called a "band-pass" filter, since it actually passes a band of frequencies. In circuit *B,* the wave trap is in series with the tuning circuit. When the rejector circuit is tuned to a given frequency, a large impedance is offered to the flow of this frequency, but all other frequencies can readily pass. The acceptor circuit works in the usual manner. A circuit of this type is called a *band-stop filter.* This device is used where a particularly strong station interferes with the reception of other stations.

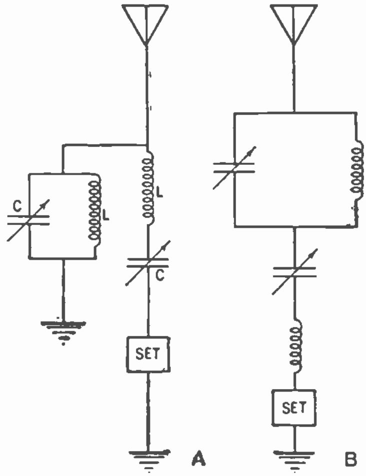


Fig. 174.

The *Q*, or the *Merit*, of a Coil.—We have seen how resistance in the tuning circuit produces broad tuning. Sharpness of tuning is known as *selectivity.* Since most of the resistance of the tuning circuit is in the coil, the selectivity depends almost entirely upon the resistance of the coil. The smaller the resistance of the coil, the more satisfactory will be its performance. This factor of a coil is known as its *merit,* or *Q,* and is defined as *the ratio between the inductive reactance and the resistance.* Its value is therefore

$$Q = \frac{X_L}{R} = \frac{2\pi fL}{R}.$$

This must not be confused with *electric charge*. Unfortunately the latter is represented by the same symbol. It must also be realized that this resistance is not the ordinary direct-current resistance. Since the frequency of the currents employed is extremely high (on the order of many kilocycles), the rapidly changing magnetic field induces opposing e.m.f.'s of varying amounts over the cross section of the conductor. At the center of the conductor, the counter-e.m.f. is greatest; it is least at the outer portion of the conductor. For this reason most of the current flows *on or near the surface*. Since this is equivalent to reducing the cross-sectional area of the conductor, its resistance is increased. This tendency of a high-frequency current to flow near the surface of the conductor is known as the *skin effect*. In high-frequency currents the resistance is higher, due to the skin effect and other causes. This resistance, known as the alternating-current resistance, is the one used for computing the Q of the coil.

Coupling.—We have seen that the lower the resistance of the tuning circuit, the sharper the tuning and the greater the selectivity. In the circuits just described, the antenna-ground circuit forms a part of the tuning circuit. Since the resistance of the antenna circuit is of necessity usually quite large, it is impossible to attain the condition of low resistance for the tuning circuit so long as the antenna remains in the tuning circuit. One method of overcoming this difficulty is to remove the antenna from the tuning circuit. This can be accomplished by making use of the principle of *mutual inductance*. In Fig. 175 the tuning circuit is shown coupled to the antenna-ground system. It should be noted that since the antenna is not a part of the tuning circuit, in consequence it does not contribute to the resistance of the tuning circuit. This results in greater selectivity. The frequency in the secondary circuit is exactly the same as that in the antenna. The induced voltage may be greater than the voltage in the antenna because the mutual inductance acts as a step-up transformer. The radio-frequency transformer is similar to the low-frequency transformers described in

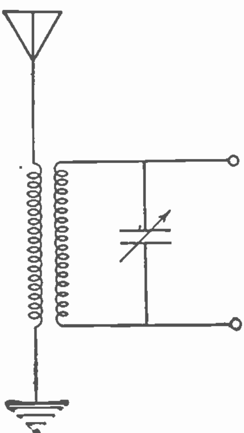


Fig. 175.

the paragraphs on electrical theory (page 45), except that it has an air core and contains no magnetic material. This method of connecting the tuning circuit to the antenna ground system is known as *transformer coupling.*

The Crystal Detector.—The frequencies of ordinary radio waves are on the order of many kilocycles per second. Alternating currents set up by these waves are also of this same order of frequency and are known as *radio-frequency currents.* We are familiar with the fact that only vibrations between 30 and 20,000 per second can be heard. Alternating currents of this range of frequency are called *audio-frequency currents.* Even if the radio-frequency currents were able to cause the diaphragm of the receiver to vibrate, we should still be unable to hear the sound because it would be far above the upper limit of audibility. As a matter of fact, the change in the current for radio-frequency takes place in something like one-millionth of a second. This is entirely too short a time in which to overcome the inertia of the diaphragm that produces the sound. The problem, therefore, is so to modify this radio-frequency current as to enable it to cause the diaphragm to vibrate and thus produce sounds. One of the earliest and simplest methods of accomplishing this result was by the use of a *crystal.* It was found that certain crystals, such as those of galena, carborundum, zincite, and iron pyrites, when placed in contact with a conductor, will readily permit current to flow in one direction but not in the opposite direction. There is usually only one spot on the crystal that is sensitive in this manner. A fine wire, known as the *cat-whisker,* is moved over the crystal until the sensitive spot is found. The most commonly used crystal for this purpose is galena. A complete crystal receiver is shown in Fig. 176. It should be observed that transformer coupling with the antenna-ground system is employed. The crystal is in series with the earphones. The alternating current from the tuning circuit is changed into a pulsating direct

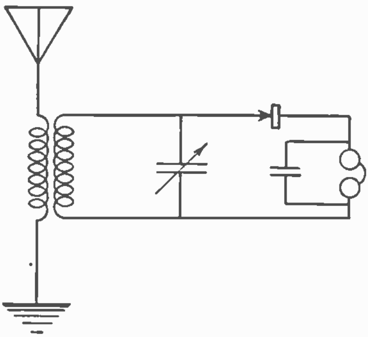


Fig. 176.

current. A condenser in parallel with the earphones is charged by the pulsating current. We have already seen that the pulses of the current, being on the order of one-millionth of a second in duration, cannot cause the diaphragm of the earphones to vibrate. When these individual pulses have sufficiently charged the condenser, however, it can then send sufficient current through the coils of the earphones to cause the diaphragm to be attracted. It must be realized that a considerable number of such pulses are required for charging the condenser; thus the interval during which the current flows through the coils of the earphones is greatly increased. This accomplishes the purpose we set out to achieve, namely, to change the radio-frequency into a form that will cause the diaphragm to respond. The fixed condenser connected across the earphones is not always necessary because the many turns of the earphones produce a capacitive effect.

The Diode as a Detector.—In many respects the crystal detector is somewhat unsatisfactory. The wire must always be in contact with the sensitive spot on the crystal. If the crystal is jarred, it may so move that the sensitive spot is displaced and in consequence the detector will not function. Dirt and moisture also may spoil the contact with the crystal. Plainly, the functioning of a crystal is undependable. With the advent of the diode, crystals were replaced by two-electrode tubes. A receiving circuit using a diode as a detector is shown in Fig. 177. The functioning of a diode as a rectifier has already been explained in the chapter on electronics. (See page 78.) This rectifying action, which is similar in principle to that of the crystal, gives the diode the quality of a detector. The diode is far more reliable as a detector than is the crystal because it is quite positive in its performance and not subject to the many capricious factors that we have just mentioned in connection with the crystal.

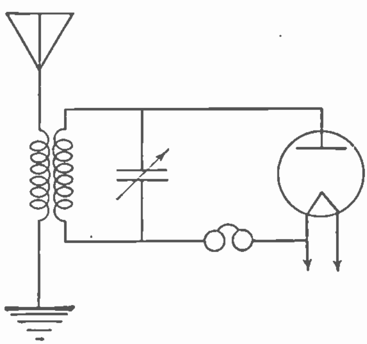


Fig. 177.

The Triode as a Detector.—Though diodes are occasionally used as detectors, it is the more common practice to use the triode for this purpose. The use of a triode as a detector is shown by Fig. 178. The grid bias is established by means of the C battery. The negative grid bias is necessary because the negative portions of the alternating current of the tuned circuit are themselves insufficient to cause a cut-off of the plate current. We did not experience this difficulty when the diode was used because no matter how small the negative fluctuations might be, nevertheless a complete cut-off took place. By the use of a suitable grid bias, however, the combined negative voltage of the fluctuating current and the grid bias causes complete cut-off of the plate current, and the triode thus functions as a detector. In addition, the changes in the voltage, due to the alternating current in the tuned circuit, are amplified by the tube. As a consequence of this, the vacuum tube is more satisfactory than the crystal because the former not only acts as a detector but also amplifies the signal received, while the latter simply functions as a detector and does not amplify the signal at all. For this reason the vacuum tube detector is the most satisfactory device for this purpose.

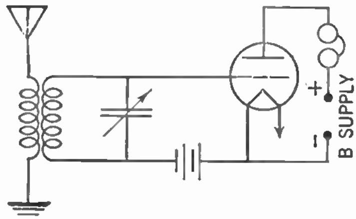


Fig 178.

Grid Leak and Condenser Detection.—In order to employ the triode as a detector without the use of a C battery, the circuit

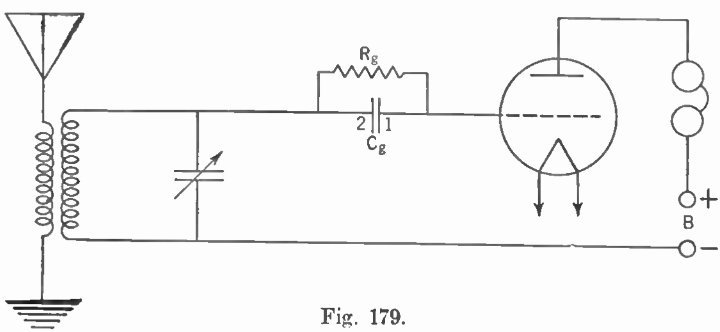


Fig. 179.

shown in Fig. 179 can be used. A fixed condenser, C_g, is connected to the grid. When the potential of the tuning circuit is negative, Plate 2 of the grid condenser is negative and electrons are driven away from Plate 1. Since only the grid is connected to Plate 1, the electrons are driven on to the grid, thus making it negative. This reduces the plate current. On the positive half of the cycle in the tuning circuit, Plate 2 becomes positive and electrons are thus drawn to Plate 1. These electrons are drawn away from the grid, thus leaving it positive. This increases the plate current. Since the grid is positive, it attracts the electrons; some of them attach themselves to the grid. The electrons are not able to escape, due to the condenser, C_g. In consequence, the grid acquires a permanent negative charge. On each cycle of the current in the tuning circuit, however, further negative charge is accumulated by the grid of the tube. If this were permitted to continue, eventually the negative charge on the grid would be so great as completely to stop the plate current. In order to prevent this condition, a path must be supplied in order to allow some of the electrons to escape from the grid. This device is a high-resistance, R_g, connected in parallel with the condenser, C_g. This resistance, which is on the order of a million ohms (1 megohm), is called the *grid leak* because it permits the excess electrons to leak off the grid. By selecting a suitable grid leak and condenser, the grid can be maintained at the proper negative potential.

Summary of Reception of the Electromagnetic Wave.—By referring to Fig. 179, we should be able to follow the steps in the reception of the wave. The magnetic component of the wave induces an alternating e.m.f. in the antenna-ground system. The alternating current set up in the antenna circuit induces an alternating e.m.f. in the secondary coil of the mutual inductance that is used as a coupling between the antenna-ground circuit and the tuned circuit. By adjusting the variable capacitance, the circuit can be tuned so that the maximum current is obtained for the frequency of the wave we want to receive. Under these conditions, the circuit is resonant only to the frequency of the desired wave; the waves of other frequencies, though intercepted by the antenna, produce practically no effect in the tuned circuit. The radio-frequency current of the tuned circuit is rectified by means of a crystal or a vacuum tube so that the resulting current is capable of causing the diaphragms of the earphones to respond and thus produce a sound wave. The crystal or vacuum tube, when used for this purpose, is called a detector. The energy in the circuit is only sufficient to operate earphones; larger energy is required for operating a loud-speaker. In order to increase the energy of the detector circuit, amplifying circuits must be used. The next two chapters explain the principles of amplification. It must be realized, however, that until now we have explained only the reception of an electromagnetic wave. The details of the transmission and reception of the *modulated* electromagnetic wave used in modern radio will be explained in later chapters.

QUESTIONS

1. According to what principle does the electromagnetic wave produce a current in the aerial-ground system?
2. What is the nature of the current in the aerial-ground system?
3. Will all radio waves induce currents in an aerial? Explain.
4. Give an illustration of resonance in a mechanical system.
5. What is meant by the *resonant frequency?*
6. In a series-resonant circuit, what is the value of the current for the resonant frequency? **Ans.** The current is a maximum.
7. What are you attempting to do when you tune a series-resonant circuit?
8. What is the value of the resonant frequency for a given circuit?

   Ans. The resonant frequency is equal to $\frac{1}{2\pi\sqrt{LC}}$
9. What effect is produced by the resistance at resonance?
10. Draw diagrams that show the difference between sharp tuning and broad tuning.
11. What are the disadvantages of broad tuning in a receiver?
12. Why is the parallel-resonant circuit called an anti-resonant circuit?
13. What is meant by a *wave trap?*
14. Draw a diagram of a band-pass filter. Explain the latter's function.
15. Explain how an antenna circuit may be arranged so as to minimize the effect of a near-by powerful station.
16. What is meant by the Q of the coil?
17. Why is the alternating-current resistance of a coil greater than the direct-current resistance?
18. What is meant by the *skin effect?*
19. What is the advantage of coupling the tuning circuit to the antenna instead of having the antenna as a part of the tuning circuit?
20. Compare the crystal and the vacuum tube in their use as a detector.

CHAPTER 10

RADIO-FREQUENCY AMPLIFICATION

The Need for Amplification.—Today almost all radio receivers make use of a loud-speaker. In the circuits we have previously discussed, earphones were used for the sound producer. This was because the amount of energy in the receiving circuit was too small to operate a loud-speaker; the latter requires considerably more energy than do earphones. The energy intercepted by the aerial of the receiver is extremely small. In order to obtain sufficient energy for operating a loud-speaker, the energy received must be greatly augmented by the receiver circuit. This latter process is known as *amplification.* Amplification can be brought about by means of two different methods or by a combination of both. The frequency of the currents set up in the aerial of the receiving circuit are on the order of hundreds of thousands of cycles per second. These frequencies are known as *radio-frequency.* We have already learned how the detector changes these frequencies into audible frequencies that range from approximately 30 to 20,000 cycles per second. Currents of these latter frequencies are known as *audio-frequency* currents. Amplification can be accomplished by amplifying the radio-frequency currents before they reach the detector. Nearly all receivers have some radio-frequency amplification. If the audio-frequency currents are amplified, the amplification is known as *audio-frequency amplification.* It should be explained that the detector must precede the audio-frequency. Most receivers make use of both forms of amplification. Transmitters also require amplification because usually a large amount of energy is needed in the transmitting antenna. In this present chapter the methods of radio-frequency amplification will be discussed. Some of the problems of audio-frequency amplification will be taken up in a following chapter.

The Triode as a Radio-Frequency Amplifier.—The general action of a triode as amplifier has been explained in the discussion of electronics. (See page 84.) It should be recalled that a change in the grid voltage produces a large effect upon the plate current. The circuit pictured in Fig. 180 shows one triode as a radio-frequency amplifier used along with another triode that serves as a detector. The secondary of the antenna coupling is connected to the grid of the amplifying tube. The amplifying circuit is tuned by the variable condenser connected across the

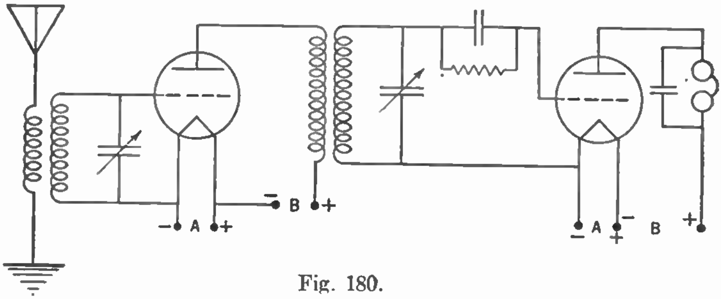


Fig. 180.

secondary of the antenna coupling. The amplifying circuit is inductively coupled to the detector circuit. Thus the incoming signal is amplified before it is rectified by the detector.

The Stages of Amplification.—A single amplification, such as is shown in Fig. 180, is usually neither sufficient nor desirable. Ordinarily, several stages of radio-frequency are employed in radio

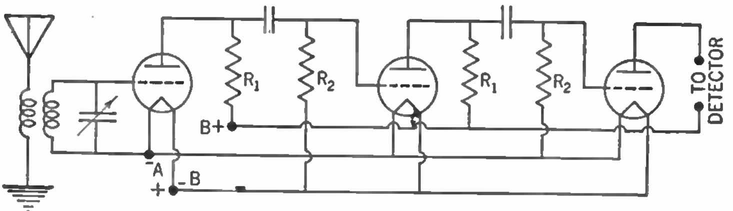


Fig. 181.

receivers. The stages of radio-frequency amplification can be coupled in a number of ways. A three-stage amplifying circuit is pictured in Fig. 181; in this figure the successive amplifying tubes are coupled by means of resistances. This method of coupling is known as *resistance coupling.* The variation of the plate current in the resistance, R_1, produces a varying voltage that actuates the grid of the next amplifying tube. The grid is made self-biasing by means of the resistance, R_2 that is connected to the negative terminal of the cathode. The condenser, C, keeps the large plate voltage of the amplifying tube from being impressed on the grid of the following tube. So far as concerns a pure resistance, the voltage for any given current is independent of the frequency; therefore, for the resistance coupling, the voltage amplification would be the same if there were no capacitance or inductance in the plate circuit. Though the resistance, R_1, can be made comparatively free of inductance and capacitance, nevertheless a comparatively large capacitance exists between the plate and the cathode in a triode. The presence of this capacitance will result in the varying voltage in R_1's being less than if no capacitance were present. This reduces the efficiency of the device as an amplifier. The grid-cathode capacitance also acts as a parallel condenser across the resistance, R_2. Since the inter-electrode capacitance of the tube has a large reactance at low frequencies, therefore the amplifying action is not seriously affected at audio-frequencies, but at the much higher frequencies of the broadcast band. The defects just mentioned are so pronounced that resistance coupling is in these instances undesirable.

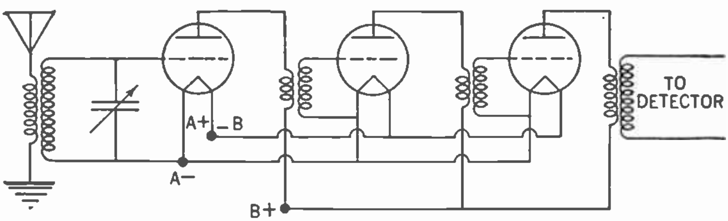


Fig. 182.

The Transformer Coupling.—Another method of coupling the stages of the radio-frequency amplification is by means of transformers. Transformers that have air cores are of the radio-frequency type. The secondary windings have a greater number of turns than do the primary; because of this, the transformers are of the step-up type that increase the input voltages. A radio-frequency amplifier having three stages of amplification, and a transformer coupling, is shown in Fig. 182. In this instance the signal is fed into the grid of the first amplifier tube. The output voltage across the load in the plate circuit of the tube is then stepped up and fed into the grid of the next tube by means of the transformer. The last stage of radio-frequency amplification delivers the amplified signal to the detector circuit. The transformer coupling is quite generally used for radio-frequency amplifiers.

The Tuned Radio-Frequency Amplification.—We have already seen how the tuned circuit, by using the principle of resonance, permits any signal of desired frequency to pass through it, but nevertheless tends to stop all other frequencies. This ideal condition is never completely achieved, of course; some unwanted frequencies always pass through the circuit. If the stages of the radio-frequency amplifier are tuned to the frequency of the tuning circuit, then further elimination of undesired frequencies is thus brought about. Tuning of the stages of amplification may be accomplished by means of a variable condenser that is similar to the one used in the tuning circuit. Amplification that makes use

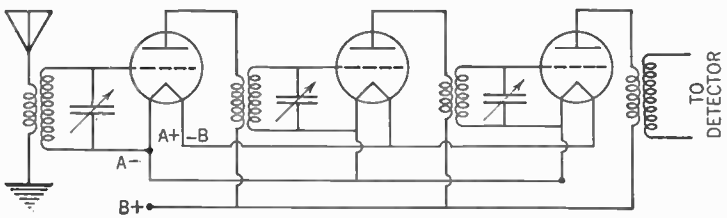


Fig. 183.

of the principle of tuned circuits is known as *tuned radio-frequency amplification*. The circuit of three stages of tuned radio-frequency amplification is shown by Fig. 183. The use of a number of stages of tuned radio-frequency amplification greatly increases the selectivity of the receiver. Each additional stage causes the tuning curve more closely to approach the condition of sharp tuning that has already been described in the explanation of resonance curves. (See page 154.)

Condenser Ganging.—In the tuned radio-frequency amplifier, each stage must be separately tuned to the desired frequency. This requires a separate control for each stage. Since this is very inconvenient, methods have been so worked out that a single knob controls the condensers in all stages, once they have been properly adjusted. One method commonly used is to have on each condenser shaft a pulley driven by a flexible belt from the main driving pulley. A single tuning-knob thus simultaneously turns the rotor shafts of all tuning condensers. A much more simple method of accomplishing the same result is to mount the rotors of all the condensers upon a single shaft; thus all condensers are simultaneously controlled. A condenser of this type is known as a *gang condenser*. Any number of sections, or gangs, may be in a single condenser.

The Parallel Operation of Tubes.—Whenever it is necessary to obtain more power than one tube is capable of delivering, two or more tubes may be connected in parallel. Thus the total power output of the combination is equal to the sum of the power outputs of the individual tubes. When tubes are operated in parallel, the corresponding elements are connected together; *i.e.*, all the plates together, all the filaments together, and all the grids together. Parasitic oscillations are frequently set up when tubes are connected in parallel. This is particularly true for high frequencies. These parasitic oscillations are extra oscillations that occur at frequencies other than the tuned ones. The effect of parasitic oscillations is to consume power; this thereby reduces the output of the tube. This may also cause, in the tube, heating effects that interfere with its normal operation. In order to eliminate these parasitic oscillations when tubes are operated in parallel, an inductance and resistance in parallel are connected in series with the plate of each tube.

The So-called *Push-Pull*.—Another method of using more than one tube is known as the *push-pull* operation. (See Fig. 184.) In this instance it should be observed that the output current from the two tubes flows in opposite directions through the two parts of the tapped primary of the output transformer. It should also be observed that when the input signal makes the grid of one tube negative, it at the same instant makes the other positive. As a consequence of this, the action is opposite in direction on the plates of the two respective tubes. Therefore the resulting currents in the primary of the output transformer are such as to produce a greater effect than does that of a single tube. The effect of distortion is almost completely eliminated because the increases in one tube offset the decreases in the other. The power output of the two tubes in *push-pull* is somewhat greater than it is when the tubes are operated in parallel. Radio-frequency amplifiers in both receivers and transmitters make use of the principle of *push-pull*.

The Classification of Radio-Frequency Amplifiers.—For convenience in referring to the principal methods of using tubes as amplifiers, it has become common practice to group them into several classes. In this section we shall mention only those used for radio-frequency amplification. These are Class A, Class B, and Class C. A *Class-A* amplifier is an amplifier in which the grid bias and alternating grid voltages are such that the plate current flows

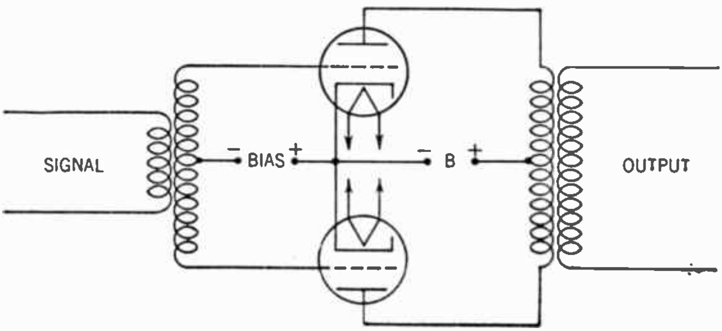


Fig. 184.

at all times. A *Class-B* amplifier is an amplifier in which the grid bias is approximately equal to the cut-off value; thus the plate current is approximately 0 when no exciting voltage is applied. In the Class-B amplifier, the plate current flows for approximately one-half of each cycle whenever an alternating grid voltage is applied. A *Class-C* amplifier is one in which the grid bias is appreciably greater than the cut-off value; thus the plate current is 0 when no alternating grid voltage is applied. In the Class-C amplifier, the plate current flows for appreciably less than half of each cycle whenever an alternating grid voltage is applied.

The Class-A Amplifier.—In a Class-A amplifier, a radio tube is used for reproducing grid voltage variations across an impedance or resistance in the plate circuit. These latter variations have almost the same form as has the input signal impressed upon the grid, but of increased amplitude. Fig. 185 shows a graphical representation of the input and the output of a triode used as a Class-A amplifier, together with the characteristic curve of the tube. It should be observed that here the output signal has the same general form, but that the amplitude is increased. This type of amplifier is therefore used wherever high-voltage amplification and exact reproduction of the wave form are demanded. Class-A amplifiers, though not producing distortion, have very low output and efficiency. Radio-frequency amplifiers in receivers that demand a large voltage gain, and in which very little power output is required, can use the Class-A amplifier very satisfactorily. In the case of transmitters, however, the power output is important; here the Class-A amplifier will be found unsatisfactory. In operating the amplifier, care must be taken that the input voltage on the grid be kept on the straight part of the characteristic curve, and that the grid voltage never become positive. Because of this, the input voltage swing must be confined between points *a* and *b* on the curve.

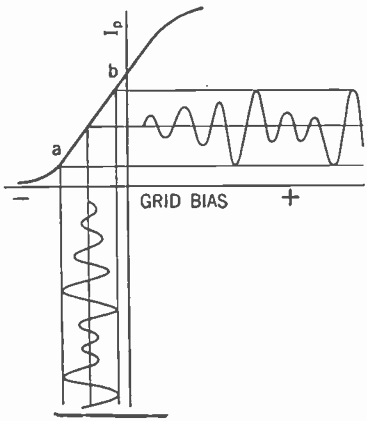


Fig. 185.

The Class-B Amplifiers.—The exciting signal amplitude of the Class-B amplifier is such that the entire linear portion of the characteristic curve of the tube must be used. Fig 186 shows a graphical representation of the input signal and of the output, together with the characteristic curve for a Class-B amplifier. As has previously been mentioned, it should be observed that the current in the plate circuit is almost 0 when no signal voltage is applied to the grid; also, that the current in the plate circuit flows only for the positive half of the alternating-current cycle impressed upon the grid. Class-B radio-frequency amplifiers are chiefly used in transmitters. This type of amplifier combines faithful reproduction with high plate efficiency and high power output. In radio transmitters, it is desirable to get the maximum power output with the smallest amount of input power. For this reason the Class-B amplifier has been found to be satisfactory for this purpose, while the Class-A amplifier is altogether unsuitable.

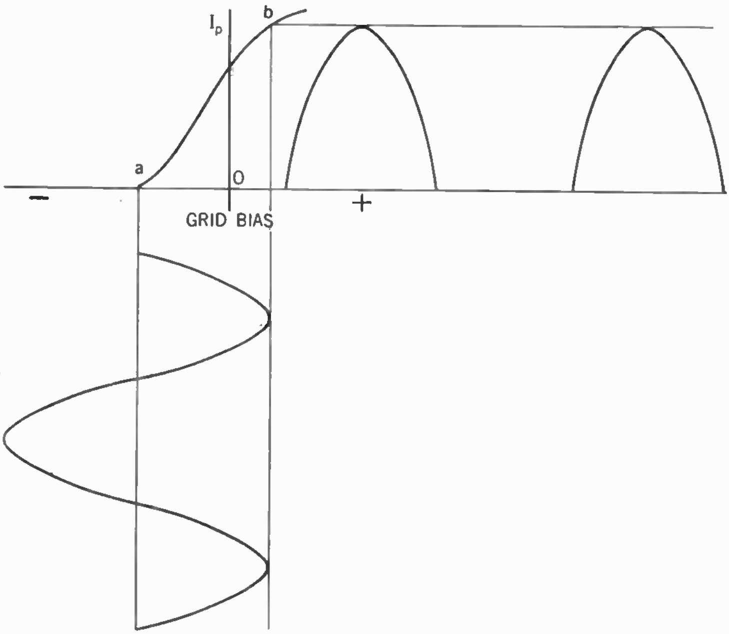


Fig. 186.

The Class-C Amplifier.—Of all classes of amplifier, the Class-C has the highest output efficiency and power. It should be recalled that in this instance the grid bias is considerably greater than the cut-off value; thus the plate current is 0 when no alternating current is impressed upon the grid, and when the plate current flows for considerably less than half of each cycle of the applied alternating-grid voltage. Fig. 187 shows a graphical representation of the operation of a Class-C amplifier. It can be seen that here the output is distorted because the input signal voltage exceeds the limits of the straight-line portion of the curve. It should also be observed that less than half of the input cycle is in this instance utilized. Because of its high power and efficiency, this class of radio-frequency amplifier is used for transmitter circuits. In both the Class-B and Class-C amplifiers, only a part of the impressed wave form is present in the output. This indicates that the alternating current in the plate circuit flows for only half a cycle in the Class-B amplifier, and for an even shorter time in the Class-C amplifier. At first it might seem that under these circumstances the circuit would not have a complete wave form. When we realize, however, that the tube merely amplifies the current in the tuned circuit, then we can understand why it is unnecessary for the amplifying tube to introduce energy

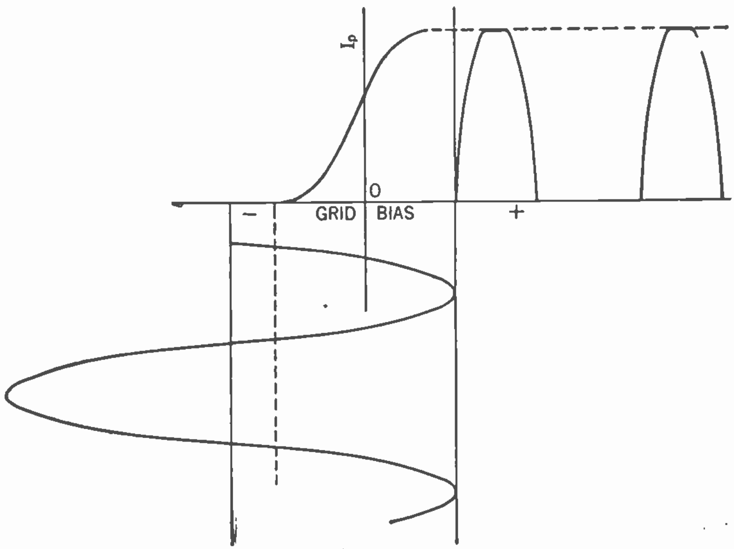


Fig. 187.

into the oscillating current throughout the entire cycle. The oscillating current, of course, has its full wave form. In case this seems difficult to understand, a simple mechanical analogy should make the matter clear. With respect to an ordinary swing, energy may be added to the swing during its entire motion. Ordinarily, however, one pushes the swing during only a part of its motion. In both instances the swing nevertheless executes its complete oscillation. In the case of a Class-B or a Class-C amplification, the oscillations in the tuned circuit resemble those of the swing; the amplifying action of the tube acts only through a part of each cycle.

The Design of Transformer Coils.—One serious drawback of a radio-frequency amplifier is the effect of the magnetic field of one transformer upon other transformers in the amplifier. Since the magnetic field extends to a considerable distance from the coil, consequently induction takes place in other coils that are in the vicinity. One solution of this problem is to place the transformers far apart. Since we usually attempt to make the whole apparatus compact, this practice is obviously impracticable. Another plan is to have the magnetic field of each coil confined as nearly as possible to the immediate vicinity of the coil. This last condition can be satisfied by making the coil long and of small diameter. The effect of the magnetic field of one coil upon another can also be greatly reduced by setting the coils at right angles to one another. By this means the field of one coil does not so readily thread the turns of the second coil; thus induction is greatly reduced.

Shielding.—The most satisfactory method of limiting the magnetic fields of a radio-frequency transformer is to surround each with a thin metal case. The magnetic field is then confined to the region inside the case. This principle is known as *shielding;* the metal case is called a *shield.* The action of the shield may be understood by studying Fig. 188. An alternating current flows in coil *A*, which has associated with it a magnetic field that varies at the same rate as does the current. This varying magnetic field would induce an e.m.f. in coil *B* if the metal shield were not placed between the two. When the shield is present, however, the varying magnetic field induces a current in the metal shield. This current, known as an *eddy current*, is shown at a given instant in the diagram. The eddy current in turn sets up a magnetic field, which, according to Lenz's law, opposes the original magnetic field. Thus coil *B* is protected from the influence of the magnetic field set up by the current in coil *A*. In a receiving set, the coils are either placed in separate metal cases, or certain parts of the circuit are shielded from those parts in which detri-

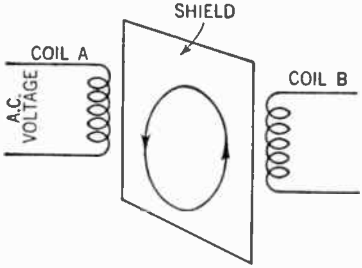


Fig. 188.

mental induction might take place. It should be kept in mind that because the metal of the shield has some resistance, energy is in consequence consumed by the eddy currents in the shield; this results in the production of heat. The energy comes from the coil that is being shielded, and so increases its resistance. This is one factor in the alternating-current resistance of the coil. At greater frequencies, the eddy currents are greater; consequently, the shielding is in these instances more complete.

The Feedback.—We have already seen how the feedback of various types may be utilized in an oscillator circuit. In radio-frequency amplifiers, the feedback produces undesirable oscillations that bring about a serious distortion of the signal. The feedback takes place in various ways. One of the most important ways by means of which the feedback occurs is through the grid-plate capacitance. Because it is impossible to eliminate this capacitance, special circuits have been devised for preventing oscillations from being set up through this capacitance. A simple method of diminishing these unwanted oscillations is by putting a large resistance in series with the grid. Though this method is quite effective for diminishing the feedback, nevertheless it also weakens the signal. Various circuits have likewise been invented for offsetting the effect of the feedback through grid-plate capacitance. This process is known as *neutralization*.

Neutralization.—The principle of neutralization is based upon taking some of the radio-frequency current from the output or input circuit of the amplifier and then impressing it upon the other circuit so that it has the effect of canceling the current that flows through the grid-plate capacitance of the tube. Because of this arrangement, it becomes impossible for the tube to supply its own excitation. Plainly, for complete neutralization, two currents must be equal in amplitude and opposite in phase. This result may be accomplished in two ways. According to the first method, the out-of-phase current is obtained by using a balanced tank circuit in the grid and by feeding it to the plate by means of a condenser known as the *neutralizing condenser*. This condenser has a capacitance approximately equal to that of the grid-plate capacitance. This circuit is known as a *grid-neutralized circuit*. According to the second method, one uses a balanced tank circuit in the plate and feeds the neutralizing voltage to the grid. The circuit is then known as a *plate-neutralized* one.

The Plate-Neutralized Circuit.—Many kinds of plate-neutralized circuit are in use. Fig. 189 shows a typical one. One may see that the voltage induced in the extension of the tank coil, L, is fed back into the grid through the neutralizing condenser, C_N, in order to balance the voltage that appears between the grid and the plate. The capacity of C_N depends upon the size of the tank coil extension. The value of C_N must increase as the coil extension becomes smaller. Neutralization is satisfactory only

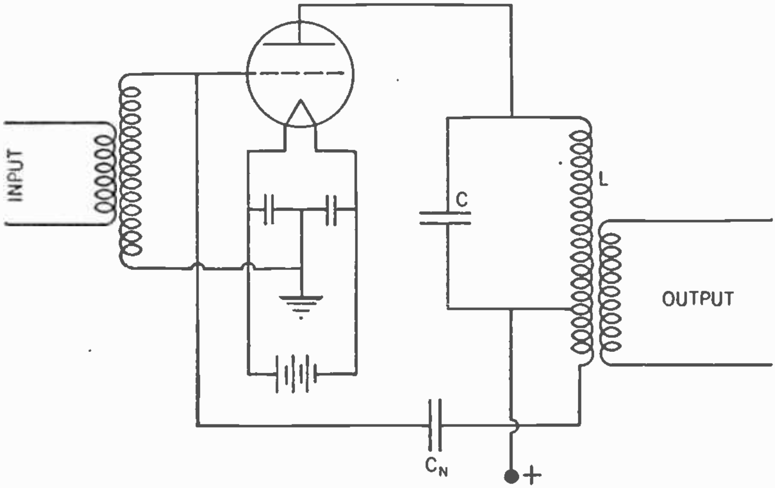


Fig. 189.

over a small range of frequencies. Many other circuits make use of plate neutralization, but most of them are merely modifications of the circuit shown in Fig. 189.

The Grid-Neutralized Circuit.—The idea of neutralization for grid-neutralization is similar to that for plate-neutralization, except that in this case the tank circuit is in the grid circuit and the neutralizing voltage is fed back to the plate by the neutralizing condenser. One example of a grid-neutralizing circuit is shown by Fig. 190. The neutralizing condenser, C_N, is used for impressing the neutralizing potential upon the plate. When tubes are used for the push-pull, two neutralizing condensers are employed. When two or more tubes are connected in parallel, then the neutralizing capacity will be proportional to the number of tubes employed.

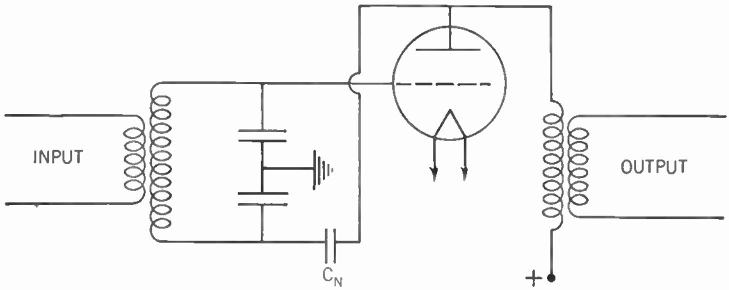


Fig. 190.

The Pentode Radio-Frequency Amplifier.—We have learned of the need of neutralization in triodes when these are used in radio-frequency circuits. The pentode, however, requires no neutralization at all because the inter-electrode capacitances are offset by the construction of the tube. It should be kept in mind that this tube consists of a cathode, a control grid, a screen grid, a suppressor grid, and a plate. If the suppressor grid is connected to the cathode, it acts as a shield between the plate and the control grid. Because of this, the suppressor grid reduces the plate-grid capacitance to such an extent that not enough energy is fed back from the plate to the grid circuit to cause oscillations. For this reason one does not need to neutralize the pentode. The screen grid of a tetrode also eliminates the grid-capacitance. Because of this, the tetrode may also be used in radio-frequency amplifiers without neutralization. The pentode, however, is more effective; pentodes are preferred to tetrodes for this purpose. Pentodes are particularly well adapted for Class-A amplifiers; they are also used in transmitters as Class-B amplifiers and as Class-C amplifiers.

QUESTIONS

1. Explain the reason for amplification in a receiver.

2. What are the two kinds of frequencies?

3. What are the limits of audio-frequency?

4. What type of coupling is most satisfactory for radio-frequency amplifier stages?

5. Explain the benefit of tuned radio-frequency with respect to sharpness of resonant curves.

6. Describe the construction of a gang condenser.

7. What method may be used for connecting a number of amplifier tubes?

8. Draw a diagram, then explain the principle of *push-pull.*

9. What are the three classes of radio amplifiers?

10. How long does the plate current flow during a cycle for a Class-A amplifier. **Ans.** For the entire cycle.

11. By means of a diagram, show the output of a Class-A amplifier.

12. How faithful is the reproduction of the wave form for a Class-A amplifier?

13. Describe the conditions of a Class-B amplifier.

14. By means of a diagram, show the distortion of the wave form for the Class-C amplifier.

15. What special advantage is gained by using a Class-C amplifier?

16. How can a Class-C radio amplifier that operates over only part of a cycle have an output that is a complete wave form?

17. What disadvantage has the feedback in a radio amplifier?

18. Explain the construction of radio transformer coils so built as to avoid stray magnetic fields.

19. What is the basis of screening?

20. Explain the methods that are employed for eliminating feedback through the grid-plate capacitance for radio-frequency amplifiers.

CHAPTER 11

AUDIO-FREQUENCY AMPLIFICATION

The Purpose of Audio-Frequency Amplification.—After the detector has changed the electrical frequency in the receiver from the radio-frequency range to the audio-frequency range, further amplification may also be desired. As has previously been explained, both radio-frequency and audio-frequency amplification are commonly employed in the same receiver. Two general types of audio-amplifiers are available. The first, which causes an increase in the voltage, is known as a *voltage amplifier*. The second, whose purpose is to increase the power, is known as a *power amplifier*. So far as concerns the power amplifier, voltage is only a secondary consideration. Voltage amplifiers, however, are primarily used for supplying an increased voltage to the grid of the tube in the next stage of the amplifier. The power amplifier is used when a large amount of power must be supplied to a loud-speaker or to any other consumer of power.

A Comparison of Radio Amplification and Audio Amplification.—The radio-frequency amplifier takes care of frequencies on the order of thousands of kilocycles per second; the audio-frequency amplifier is limited to frequencies between 30 to 20,000 cycles per second. The radio-frequency amplifier is designed to take care of only one frequency at a time, or, to take care of a narrow band of frequencies, at the most. The audio amplifier, on the contrary, must cover the entire band of audio-frequencies at one time. In radio-frequency amplification we are dealing with a resonant frequency. In audio-amplification, frequencies to be amplified are non-resonant.

Audio-Amplification and the Decibel.—Since the audio-amplification is directly concerned with the effect upon the ear, it is only reasonable to use for this purpose a unit that bears some relationship to the sensitivity of the ear. In the consideration of sound (page 120), the unit of relative sound intensity known as the *decibel* (*db*) was mentioned. It should be kept in mind that when the ratio of the intensities of two sounds is 10, they are said to differ by one *bel*. A decibel is one-tenth of a bel. The human ear is barely able to distinguish sounds that differ by one decibel. The use of the decibel in audio-amplification is very useful because it gives a truer picture of the effects of audio-amplification. The formula for decibels is

$$dbs = 10 \log \frac{I_2}{I_1},$$

where *dbs* are the decibels, I_2 is the intensity of the louder sound, and I_1 is the intensity of the other sound. The intensity of the sound produced by the loud-speaker will be directly related to the power of the oscillating current. As a consequence of this, the gain or loss of an amplifier may be thus represented in decibels:

$$\text{Gain (or loss) } dbs = 10 \log \frac{P_2}{P_1}.$$

The logarithm of 2 is approximately 0.3. If the power ratio is 2, then the power gain is 3 decibels. The importance of this will be appreciated when we consider a power ratio of 1,000,000 where the power gain in decibels is 60. If we were to increase the power delivered to a loud-speaker from 1,500 microwatts to 2,000 microwatts, it would appear to be a large increase. Upon using the above formula, however, we find that the gain is only 1.1 dbs. This gain is insignificant because, under ideal conditions, the ear can only distinguish sounds that differ by 1 decibel.

Voltage Gain and the Decibel.—So far as concerns power amplifiers, we are interested in the power gain. With respect to voltage amplifiers, however, the power gain is of little importance and consequently we want to find the voltage gain.

$$\text{Voltage Gain} = \frac{E_2}{E_1}$$

where E_2 and E_1 are the voltages. Since power is equal to

$$\frac{E^2}{R},$$

then $$dbs = 10 \log \frac{E_2^2 R_1}{E_1^2 R_2} = 20 \log \frac{E_2 \sqrt{R_1}}{E_1 \sqrt{R_2}},$$

and if the resistances are equal, we have

$$dbs = 20 \log \frac{E_2}{E_1}.$$

The Classification of Audio Amplifiers.—Audio-frequency amplifiers are classified much as are radio-frequency amplifiers. The three classes of audio amplifiers are known as Class A, Class B, and Class AB. A *Class-A* amplifier is one in which the plate current flows continuously throughout the cycle of alternating current applied to the grid. As we have noted in the case of the Class-A radio-frequency amplifier, the operation of the tube is confined to the straight line portion of the curve. The shape of the output voltage wave is a faithful reproduction of the signal voltage that is applied to the grid. A *Class-B* amplifier is one in which the plate current flows for only one-half of each cycle of the alternating voltage applied to the grid. In a *Class-AB* amplifier, the plate current flows for more than half a cycle, but for less than a complete cycle.

Class-B Push-Pull Audio-Frequency Amplifier.—It has been explained that the distinguishing operating condition in Class-B amplifiers is that the plate current is relatively low without excitation, and that the exciting signal voltage is such that the entire straight line portion of the characteristic curve is used. The plate current flows only during the positive half of the excitation voltage, and no plate current flows during the negative portion of the cycle. The wave form of the plate current is essentially the same as the positive portion of the excitation voltage. Since the plate current is driven up almost to the saturation point, it is usually necessary for the grid to be driven positive with respect to the cathode during part of the cycle. For audio-frequency amplifiers, Class-B amplification requires push-pull operation. A diagram of this circuit is shown in Fig. 191, together with the input signal, the output of each tube, and the combined output. The output is fed to a transformer whose secondary coil is divided into two equal parts. The outside terminals of the secondary coil are connected to the grids of the two tubes. The center tap is connected to the source of the grid bias. A second transformer, having a primary coil that is divided into two equal sections, has its end terminals connected to the plates of the two tubes. The positive B-voltage is connected to the center tap. When the input voltage makes positive the section of the transformer that is connected to the grid of the tube, then the plate current flows in Tube 1, but no current flows in Tube 2. When the voltage swing is such that the grid of Tube 2 is positive, then the plate current flows in Tube 2, but no current flows in Tube 1. The corresponding voltages produced in the primary coil of the second transformer are such as to induce an amplified wave form of the same nature as that of the input voltage. With push-pull operation of a Class-B amplifier, there is negligible distortion. The Class-B amplifier delivers much more power than does a Class-A amplifier for the same size tubes.

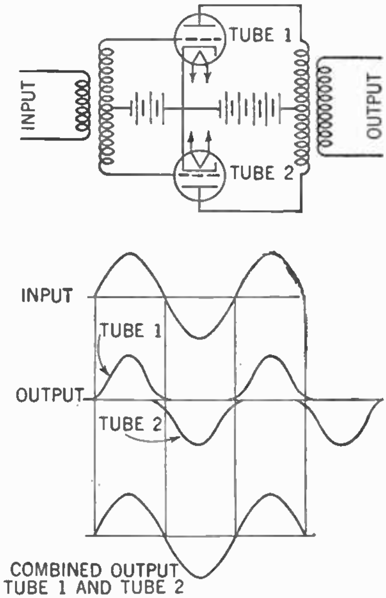


Fig. 191.

The Class-AB Amplifier.—In the Class-AB amplifier, we employ two tubes that are connected in push-pull with a higher negative grid bias than is used in the Class-A amplifier. If the bias is so adjusted that the tube draws a moderate value of plate current, the amplifier will operate Class-A at low input voltages and more nearly Class-B at higher input voltages. The advantages of this method are low distortion at moderate input voltages and higher efficiency at high input voltages; thus, relatively small tubes may be used in audio amplifiers. A further classification of AB amplifiers is sometimes made. In Class-AB_1 there is no flow of grid current. The peak input voltage is not greater than the negative grid bias voltage. The grids, therefore, not being driven to a positive potential, do not draw grid current. In Class-AB_2 amplifiers, the peak input voltage is greater than the bias; thus the grids are driven positive and current is drawn from the grid. There is a loss of power in the grid circuit of a Class-AB amplifier because of the flow of current in the grid. The input transformer used in this type of amplifier is usually a step-down transformer.

Coupling Audio-Frequency Amplifier Stages.—If several stages of audio-frequency amplification are employed, it is necessary to devise some method of coupling the successive stages. This can be done by means of any one of three general methods. These are (1) by transformer coupling, (2) by resistance coupling, (3) by impedance coupling. Each method of coupling has certain advantages and disadvantages. The transformer coupling and resistance coupling have already been described in the discussion of radio-frequency amplification. (See pages 165-166.) The resistance coupling, however, was found to be unsatisfactory for radio-frequency coupling.

Transformer Coupling for Stages of Audio-Frequency Amplification.—Although transformer coupling is in general use for coupling the last stage of an audio amplifier to the loud-

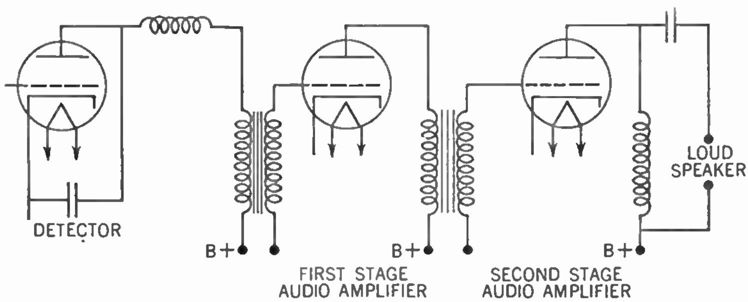


Fig. 192.

speaker, nevertheless it is also used for coupling the separate stages of the audio-amplifier. The diagram of a circuit that employs transformer coupling in the audio amplifier is shown in Fig. 192. The transformers have their primary coils and secondary coils wound on a steel core. The secondary coil usually has more turns than has the primary coil. In consequence of this fact, it steps up the voltage. As the signal voltage varies on the grid of the tube, the plate experiences a similar change. Because the plate is connected to the primary coil of the transformer, variations in the plate circuit cause the same variation in the primary coil of the transformer. These variations in the primary coil cause induced voltages in the secondary coil that have the same wave form as the voltage in the primary coil but are amplified by the step-up action of the transformer. The secondary coil of the transformer is connected to the grid of the next tube; thus the voltage is again amplified by the action of the tube. In this manner the audio-frequency can be amplified by any number of stages. Two stages of transformer coupled audio-frequency are usually found to be sufficient.

Amplification of One Stage of the Transformer Coupled Audio-Frequency Amplifier.—If E_1 is the audio-frequency signal voltage amplified to the input of one stage of an audio-amplifier, μE_1 will be the audio-frequency voltage introduced in the plate circuit of the tube. It should be recalled that μ is the amplification factor of the tube. The primary coil of the audio-transformer has a large impedance. In addition to the impedance of the primary coil, the plate resistance also opposes the flow of current through the plate circuit. The current in the plate circuit is

$$I_p = \frac{\mu E_1}{Z_p + Z},$$

where Z_p is the impedance due to the plate resistance and Z is the impedance of the primary coil of the transformer. The voltage drop across the primary coil of the transformer is IZ. If the turn ratio of the transformer is N, then E_2, the output voltage of the transformer, would be NI_pZ_p. The amplification of the single stage of the audio amplifier is

$$\frac{E_2}{E_1} = \mu \left(\frac{Z}{Z_p + Z}\right) N.$$

When the impedance of the primary coil is large in comparison with the plate resistance, then the ratio $\frac{Z}{Z_p + Z}$ approaches 1. In such a case the amplification is equal to μN. The impedance of the primary coil varies with the frequency of the plate current. The impedance is greater when the high audio-frequency voltages are received than it is when the low-frequency voltages are received. The result is that, at low frequencies, the voltage across the primary coil of the transformer is much less than it is at high frequencies. As we have seen, this results in smaller amplification of the low frequencies as compared with the high frequencies. This indicates that the primary coil of the transformer must have a large number of turns and that the permeability of the core must be very large.

Audio-Frequency Transformer Design.—We have just learned that in order to obtain a sufficiently high impedance at low frequencies for the primary coil of the transformer, the coil must contain many turns of wire. The transformer is to be used to step up the voltage. In order to accomplish this, it is necessary to have more turns on the secondary coil than on the primary coil. If the turn-ratio is N, it is necessary to have N times as many turns on the secondary coil as on the primary coil. This, of course, makes the transformer very large and expensive. The large number of turns on both primary coil and secondary coil will produce large capacities. They will act as condensers in parallel with the two coils. Since the capacitive reactance decreases with increase in frequency, a large portion of the high-frequency current will be shunted around the coils. This has the effect of reducing the amplification of the high audio-frequency voltages. It appears, then, that the amplification of the low audio-frequencies has been increased at the expense of the high audio-frequencies. In practice, a compromise is affected between primary coil inductance and turn-ratio. If the plate current is so large that the increase in the plate current due to the variation of the grid voltage is such as to cause the transformer to operate at the bend of the magnetization curve of the iron, then distortion of the wave form will result. This distortion is known as *hysteretic distortion.* In order to avoid this condition of saturation in the iron, a large amount of steel is used in the cores.

Resistance Coupling.—Another method of connecting the stages of an audio-frequency amplifier is by means of a resistance in the plate circuit. The varying current in the plate circuit produces a varying voltage across the resistance that is similar to the varying voltage impressed upon the grid of the same tube. This voltage across the resistance is then applied to the grid of the tube in the net stage of the amplifier. Fig. 193 shows in detail how this may be done. The varying plate current of the detector tube produces a potential difference across the resistance, R_p, which is on the order of 0.1 of a megohm. This voltage cannot be applied directly to the grid of the tube of the first amplifier stage because the B-voltage would put a large positive bias on the grid of the tube. This difficulty is overcome by so placing a condenser that it blocks the constant B-voltage, though the condenser does not

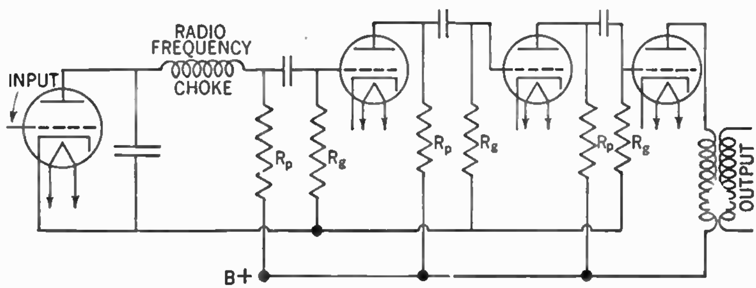


Fig. 193.

prevent variations of the alternating voltage across R_p from being transferred to the grid of the first amplifier tube. In order to provide a leakage path for the negative charges that would otherwise accumulate on the grid, a resistance, R_g, is connected between the grid and the cathode. The coupling used between the other stages is similar to that just described.

Amplification of One Stage of the Resistance-Coupled Audio Amplifier.—In the resistance-coupled amplifier, there is no transformer action to produce a step-up in voltage. Because of this, the amplification is due entirely to the amplifying action of the tube. The amplification is given by the ratio of the signal voltage on the grid of the second amplifier tube, to the signal voltage on the grid of the first amplifier tube. The amplification, or voltage, gain would be $\frac{E_2}{E_1}$, where E_2 is the signal voltage on the grid of the second tube and E_1 is the voltage on the grid of the first tube. The current in the plate circuit of the first tube is

$$I_p = \frac{\mu E_1}{r_p + R_p},$$

where r_p is the plate resistance of the tube and R_p is the resistance in the plate circuit. The voltage across R_p is I_pR_p, and the voltage gain is

$$\frac{E_2}{E_1} = \frac{\mu R_p}{r_p + R_p}.$$

When R_p is large with respect to the plate resistance r_p, then the voltage gain is equal to the μ of the tube. Because the voltage gain of a resistance-coupled stage is less than that of a transformer-coupled stage, therefore, for the same amount of amplification, it is necessary to use a larger number of resistance-coupled stages than transformer-coupled stages.

The Pentode Amplifiers.—We have already learned that the plate resistance, r_p, and the amplification factor, μ, of a pentode

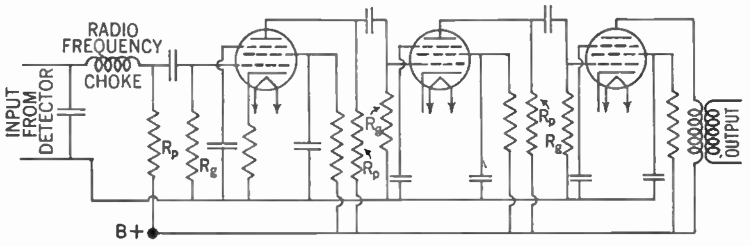


Fig. 194.

are very great. Because of this, the resistance that is placed in the plate circuit is very much smaller than r_p. A resistance-coupled audio-frequency amplifier using pentodes is shown in Fig. 194. Here the circuit is quite like that of the amplifier that uses triodes. The resistances, R_p and R_g, are the resistance in the plate circuit and the grid-leak resistance, respectively. The resistors connected to the screen grids are used for the purpose of reducing the voltage in the screen grid below the voltage on the plate. The blocking condensers are connected in the control grid circuit. In the pentode tube, the plate resistance, r_p, is very large. Because of this, the resistor used in the plate circuit must be made much smaller than r_p, instead of larger, as in the case of the triode. The amplification factor, μ, of a pentode is also very high. The amplification of one stage is

$$\text{Voltage Gain} = \frac{E_2}{E_1} = \frac{\mu R_p}{r_p + R_p},$$

where r_p is very much larger than R_p. If we assume that $r_p + R_p$ is almost equal to r_p, then the

$$\text{Voltage Gain} = \frac{\mu R_p}{r_p}.$$

We know that the mutual conductance, g_m, of the tube is equal to $\frac{\mu}{r_p}$; in consequence, the *voltage gain* $= g_m R_p$. Therefore the amplifying ability of a pentode depends upon its mutual conductance, g_m, rather than upon its amplification factor, μ.

Impedance Coupling.—The method of impedance coupling is similar to the resistance method of coupling, except that in this instance impedances instead of resistances are used. Several stages

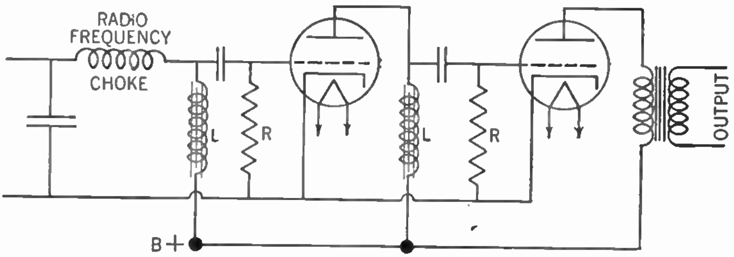


Fig. 195.

of an impedance-coupled amplifier are shown in Fig. 195. The impedances, L, consist of coils of thousands of turns of wire wound on a steel core. The resistance of the coils to direct current is comparatively small, but the impedance to currents of audio-frequency is large. Since the impedance varies with frequency, large inductances must be used in order that low audio-frequencies may be amplified. In this case, blocking condensers and grid-leak resistances perform the same function as in resistance coupling. Since in this instance there is no step-up due to transformer action, the entire amplifying action takes place in the tube, as it also does in the case of resistance coupling.

A Comparison of Coupling Methods.—Resistance- or impedance-coupled amplifiers are quite compact as compared with transformer-coupled amplifiers because the audio transformers are large and take up considerable space. In addition, good audio transformers are expensive. Resistance- or impedance-coupled amplifiers are cheaper to build. Because the entire amplification in resistance-coupled amplifiers is in the tubes, more stages of amplification are required than is true of the transformer-coupled amplifiers. Three stages of resistance coupling are needed, where otherwise only two stages of transformer coupling would be sufficient. In the case of resistance coupling, the amplification is quite uniform over a wide range of frequencies.

Overloading the Audio Amplifier.—Signal voltage applied to the grid of the first amplifying tube is amplified by the first stage of the amplifier. This increased signal voltage is then applied to the grid of the tube in the second stage, whereupon further amplification takes place. This process of increasing the voltage repeats until the last stage of amplification is reached. For every vacuum tube there is a definite operating range over which the characteristic curve is straight and in which the changes in the plate current are proportional to the changes in voltage applied to the grid. Because each stage amplifies the voltage, the amplitude of the signal voltage may become so great, when applied to the grid of the tube of the last stage of amplification, that it may force the grid potential beyond the linear portion of the characteristic curve. Doing this brings about distortion of the wave form of the signal voltage. This overloading, which may readily occur in audio amplifiers, produces considerable distortion of the signal. Overloading rarely occurs in radio-frequency amplifiers because the input voltage is usually very small. In order to take care of the overloading in the tube of the last stage of audio amplifiers, special devices, known as *power tubes,* have been designed for this purpose.

The Power Amplifiers.—The last tube of an audio amplifier is designed with special characteristics so as to supply undistorted power to the loud-speaker. Since very little power is involved in the early stages of the audio amplifier, only a small current flows in the plate circuit. In the last stage, however, where a large power is required, the current also must be rather large. In order to accomplish this, the grid voltages must be large. In order to produce these grid voltages, we must use a tube having a long straight portion to the characteristic curve. In this case, triodes that have a fairly low amplification factor, or pentodes that have a high amplification factor, are used. The pentode has a high amplification factor, but it also has a high plate-resistance. Class-A amplifiers are employed as power amplifiers by using a lower plate resistance on them than when they are employed as voltage amplifiers. When employed as a power amplifier, the highest possible plate voltage is used because power increases as plate voltage increases. In order to obtain greater power amplification, Class-AB and Class-B amplifiers are used. We have already learned that amplifiers of these latter types produce distortion when single tubes are used. Because of this fact, most power amplifiers have two tubes in push-pull.

The Maximum Power Output.—The power delivered by a power-amplifying tube may be found by multiplying the output voltage e' by the plate current i_p; that is, $P = e'i_p$. By using the amplification factor of the tube, we may find e_2 (the amplified voltage) in terms of e', the signal voltage applied to the grid for $e_2 = \mu e_1$. One must realize, however, that it is the power due to the fluctuating signal voltage that causes the motion of the moving element of the loud-speaker. A steady voltage produces no motion in the loud-speaker. The current in the plate circuit is

$$i_p = \frac{e_2}{r_p + R_p} = \frac{\mu e_1}{r_p + R_p},$$

where r_p is the plate resistance of the tube and R_p is the resistance of the resistor in the plate circuit. The e' voltage across the resistor is equal to

$$i_p R_p = \frac{(\mu e_1)\, R_p}{r_p + R_p}.$$

Hence,

$$\text{Power Output} = e'i_p = \frac{(\mu e_1)}{r_p + R_p} R_p \times \frac{\mu e_1}{r_p + R_p} = \frac{\mu^2 e_1{}^2 R_p}{(r_p + R_p)^2}.$$

When $r_p = R_p$, the power output is at a maximum. The maximum power is therefore

$$P_m = \frac{\mu^2 e_1^2}{4r_p}.$$

This is a theoretical value because considerable distortion would normally occur under these conditions. Empirical values have, however, been obtained for the maximum undistorted power of a power amplifier; these values are somewhat less than the theoretical value given above.

Distortion.—In the process of amplification, the signal voltage may have its wave form changed to a certain degree. This change of the signal wave form is known as *distortion*. Most distortion can be classified under some one of three types: (1) *frequency distortion*, (2) *nonlinear distortion*, and (3) *phase distortion*. At times the response of an amplifier over a given range of frequencies may vary for the different frequencies. This phenomenon is known as *frequency distortion*. If the relationship between input and output is given by a curved characteristic, this form of distortion is then known as *nonlinear distortion*. When signals of different frequencies have a tendency to change in phase as they pass through the amplifying system, we have what is known as *phase distortion*. This latter form of distortion has no appreciable effect upon the sound produced.

Frequency Distortion.—The inability of the amplifier to amplify all audio-frequencies equally brings about *frequency distortion*. As has already been explained, the tendency toward unequal amplification is most pronounced for the very low and very high frequencies. An amplifier that equally amplifies all frequencies over a given range is said to be *flat* over that range. Fig. 196 shows a frequency response curve for an amplifier that suffers from frequency distortion. This curve *A* is drawn by plotting gain in decibels against the logarithm of the frequency. Curve *B* shows the same relationship for an amplifier that has a flat characteristic and a minimum of frequency distortion.

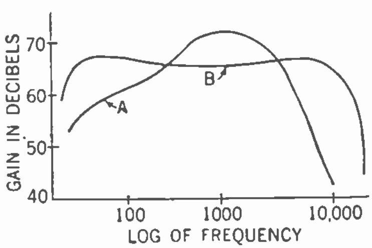


Fig. 196.

Non-Linear Distortion.—In the case of distortionless amplification, the grid bias is so selected that the tube operates over the straight portion of the characteristic curve. There are several reasons why the tube may not operate along the straight portion of the curve. If the negative grid bias applied to the tube is too great, the negative half-cycle of the signal voltage causes the grid potential to go so far negative that the tube operates on the lower bend of the characteristic curve. This causes a distortion of the negative half of the output cycle. If, on the contrary, the grid bias is too small, then the tube operates at the upper bend of the characteristic curve. Since, in the curved portion of the characteristic curve, changes in the plate current are not proportional to changes in grid potential, a distortion of the positive half of the signal voltage results. The grid bias may also be such that the positive half of the signal voltage causes the grid to be slightly positive. So soon as the grid becomes positive with respect to the cathode, it attracts some of the electrons emitted by the cathode. This develops a current in the grid circuit. This current, flowing through the resistance in the grid circuit, produces a potential drop. The potential drop modifies the voltage on the grid because of the positive portion of the signal voltage. Fig. 197 shows the resultant of the signal voltage and the potential drop in the grid circuit when the grid is driven positive. In this illustration the distorted output signal is also shown. It is important that any amplifying tube be so operated that the grid will at all times be kept negative under the usual signal conditions.

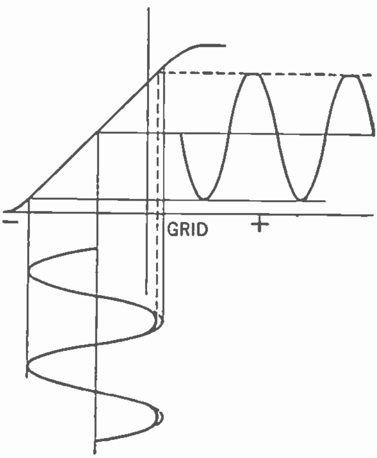


Fig. 197.

The Harmonics.—In the case of a wave of any given frequency, other waves may also be present at the same time. If these other waves have frequencies that are integral multiples of the given frequency, they are then known as *harmonics*. The given frequency is known as the *fundamental*. The presence of harmonics with musical notes is very common. If the musical note *A* (of 440 vibrations per second) is sounded on such a stringed instrument as a violin, then on a wind instrument such as a trumpet, we can readily recognize the difference, even though the fundamental note is the same in both cases. The reason for this is the presence of different harmonics in the two respective cases. The harmonics of *A* would be 880 vibrations per second, 1,320 vibrations per second, 1,760 vibrations per second, and so on.

Harmonic Distortion.—So far as concerns sound waves, we have already learned that harmonics are present in them. These harmonics affect the quality of the sound. Similarly, harmonics may exist along with electrical frequencies. In some cases these latter harmonics produce distortion. As an illustration, let us consider a pure sine wave current and its second harmonic, *i.e.*, a current having twice the frequency. Fig. 198 shows the combination of these two frequencies. Curve *A* is the fundamental. Curve *B* is the second harmonic, and Curve *C* is the resultant wave form. Distortion of this type is similar to the distorted wave output shown in Fig. 197.

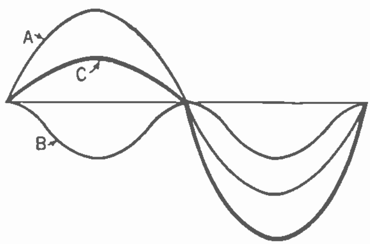


Fig. 198.

The Degenerative Feedback.—If a certain portion of the output on an amplifier is fed back to the input so that it becomes 180° out of phase with the original signal, then it is possible largely to eliminate the harmonic distortion. Because the harmonics in the input are out of phase with the same harmonics that are being fed back, they will be practically eliminated. A circuit of this type is known as a *degenerative feedback circuit*. Fig. 199 shows one of a great many commonly used degenerative feedback circuits. The relative values of R_1 and R_2 deter-

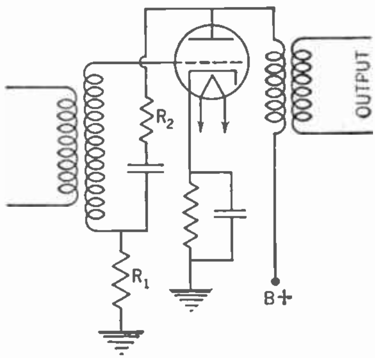


Fig. 199.

mine the amount of the feedback. Another advantage of the degenerative feedback is that it tends to give the amplifier response curve a flat characteristic. This is because those frequencies that suffer excess amplification are the ones most affected by the feedback because they are excessively amplified in the feedback current. Degenerative feedback so reduces the amount of amplification that it is necessary to employ it in a circuit having surplus amplification.

QUESTIONS

1. What is the purpose of audio amplification?

2. What is the frequency range of audio amplification?

Ans. 30 to 20,000 cycles/seconds.

3. Explain the advantage of the decibel for determining audio amplification.

4. Compare voltage amplification and power amplification.

5. What are the three classes of audio amplifiers?

6. Explain the operation of a Class-AB amplifier.

7. Draw the circuit diagram showing the push-pull operation for a Class-B amplifier. Explain the principle of its operation.

8. Name the principal methods of coupling audio-amplifier stages.

9. What advantages does resistance-coupling have over transformer-coupling?

10. What is the amplification of one stage of a transformer-coupled amplifier that uses a triode?

11. Explain the problem of amplification of low frequencies with transformer coupling.

12. What is the amplification of one stage of a resistance-coupled audio amplifier that uses a triode?

13. What is the amplification of a resistance-coupled amplifier that uses a pentode?

14. Describe distortion that is due to overloading.

15. Explain the particular characteristics of power amplifiers.

16. What is the maximum power output of a power amplifier?

17. Name the three kinds of distortion.

18. Explain the meaning of frequency distortion.

19. What is a flat response curve?

20. Explain the meaning and purpose of degenerative feedback.

CHAPTER 12

MODULATED WAVE TRANSMISSION

The Carrier Wave.—The production of radio-frequency currents in the antenna of a transmitter, and the resulting high-frequency electromagnetic wave sent out into space, have already been discussed. (See page 136.) This latter wave is known as the *carrier wave*. As concerns radio telegraphy, we have learned that by means of various methods of keying the transmitter, the dots and dashes of telegraphy can be produced by interrupting the carrier wave. In radiotelephony, the sound to be transmitted is also made to produce certain changes in the carrier wave. The process of changing the characteristics of the carrier wave by means of the sound wave is known as *modulation*.

An Explanation of Modulation.—The carrier wave can be modified in two ways. According to the first method, the amplitude of the carrier wave is affected by the sound wave. This is known as *amplitude modulation*. By means of the second method, the frequency of the carrier wave is modified. This is known as *frequency modulation*. Though the use of frequency modulation is a relatively new departure, nevertheless it has met with considerable success. Because the reception of frequency modulated waves requires special receivers, the adoption of this method of broadcasting has not as yet been widely adopted, despite its proven superiority.

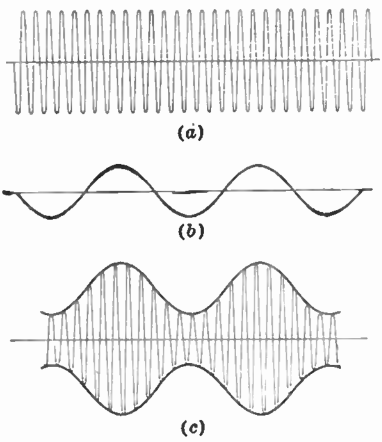


Fig. 200.

Amplitude Modulation.—The principle of amplitude modulation may be understood by examining the illustrations shown in Fig. 200, where (*a*) is the unmodulated carrier wave, (*b*) is an audio-frequency wave produced by a given sound, and (*c*) is the carrier wave modulated by the audio-frequency wave. It should be noticed that in (*a*) the frequency and amplitude of each wave are exactly the same. It will be recalled that the frequency of the carrier wave is maintained constant by means of using a crystal. In (*c*) the maximum amplitude of the modulated wave occurs at the crest of the audio-frequency wave that corresponds to the condensation of the sound wave which produces it. The minimum amplitude of the modulated wave occurs at the time when the audio-frequency wave is a trough that corresponds to the rarefaction of the sound wave.

The Percentage of Modulation.—In Fig. 200 the minimum amplitude of the modulated wave is not 0. Under these circumstances, the wave is not completely modulated. If the wave is in this condition, it is said to be *undermodulated.* The amount of modulation is figured in percentages. If the amplitude of the

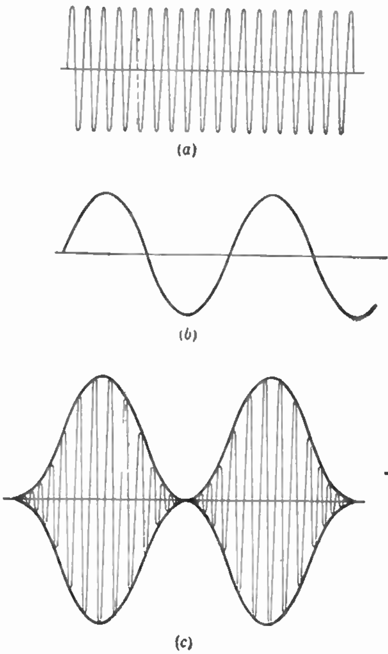


Fig. 201.

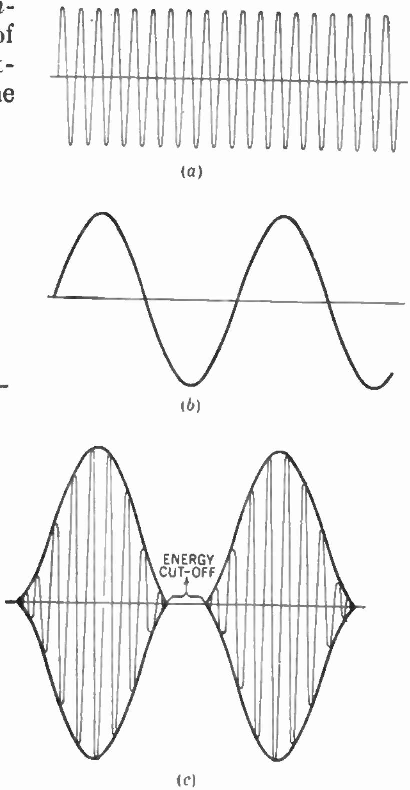


Fig. 202.

audio wave is three-quarters of the carrier wave, then the modulation is 75 per cent. Complete, or 100 per cent, modulation is shown in Fig 201. The amplitude of the audio wave is equal to that of the carrier wave. The minimum amplitude of the modulated wave is 0, and the maximum is twice the amplitude of the unmodulated wave. If the audio wave has an amplitude greater than that of the carrier wave, then the wave is *overmodulated;* that is, the percentage is greater than 100 per cent. In this latter case, there is a period during which the energy of the wave is cut off. This can be seen by examining Fig. 202, which shows an example of overmodulation. The cut-off of energy due to overmodulation naturally leads to distortion. On the contrary, undermodulation does not make use of all the available power. It is therefore evident that the ideal condition is 100 per cent modulation. For the sake of simplicity, our explanation of a modulated carrier wave was given on the basis of a single audio wave. In actual radio-telephony, however, this is not the case because in these instances there will be sounds of many frequencies and intensities. Here, however, the principle of modulation is nevertheless the same, though the modulated wave will be far more complicated. Even though 100 per cent modulation is to be desired, obviously this cannot be achieved for all the different sound intensities. The important factor is that none of the sounds that are to be transmitted should produce overmodulation, and that the most intense sounds should be 100 per cent modulated.

Power.—If the resistance of the circuit is constant, the power is proportional to the square of the current. Let us consider the case of a transmitting circuit that produces a 100 per cent modulated wave. The amplitude of the audio wave must be the same as that of the carrier wave. The peak value of the modulated wave will be twice the peak value of the unmodulated carrier wave, as may be seen in Fig. 201. Because the current is doubled, the instantaneous power for the peak value will be four times as great. The minimum value of the power, however, will be zero. Taken over a complete cycle, the average value of the power under such conditions can be shown to be 1.5 times the power in the unmodulated wave. This represents an increase of 50 per cent. The additional 50 per cent comes from the modulator. An increase of 50 per cent in power will produce an increase in the effective value of the current, which can be found by taking the square root of 1.5. This value is approximately 1.23. The increase in the effective current is therefore 23 per cent. When the carrier wave is completely modulated, the effective current in the antenna is 23 per cent greater than it is when the carrier wave is unmodulated.

Sidebands.—When two waves occur simultaneously, they combine in such fashion as to produce two new frequencies. These frequencies are known as *beat frequencies*. One of the beat frequencies is equal to the sum of the frequencies of the original waves; the other is equal to their difference. As an example, let us consider two frequencies of 1,000,000 vibrations per second and 5,000 vibrations per second, respectively. The beat frequencies will be 1,005,000 vibration seconds and 995,000 vibrations per second. These new frequencies, which appear on each side of the carrier wave, are known as *side frequencies*. Since we are dealing with a group of audio frequencies, there will be a band of side frequencies on each side of the carrier wave. These are known as *sidebands*. Hence, a modulated wave occupies a group of frequencies. Each broadcasting station therefore requires a *channel* instead of a single frequency. The carrier wave is at the center of the channel, and the width of the channel is twice the highest modulation frequency. According to the above illustration, if the 1,000,000 cycles per second were the carrier wave, and if the 5,000 vibration seconds were the maximum modulation frequency, then the center of the channel would be 1000 kilocycles, and the width of it would be 10 kilocycles. For powerful broadcasting stations, a single channel must be reserved. For weaker stations, which are several hundred miles apart, the same channel may be used.

Methods of Amplitude Modulation.—The modulating signal is introduced into the radio-frequency current of the transmitter by means of any one of three general methods. According to the first method, the audio signal is applied in the plate circuit of the radio-frequency amplifier. This is known as *plate modulation*. The second method, according to which the audio frequency is applied to the control grid circuit, is known as *grid bias modulation*. By means of the third method, the audio frequency is applied to the cathode. This last method is known as *cathode modulation*. Really, it is a combination of the first two methods.

The Heising System.—An early form of plate modulation system was the constant-current, or *Heising*, system. A circuit-diagram of this form of modulation is shown in Fig. 203. The theory of this system is based upon the fact that, in comparison with the resistance of either the modulator or oscillator tube, the reactance of the audio-frequency choke is high at all audio frequencies. If the resistance of the modulator tube varies at some certain audio frequency, then the current from the B battery will not vary at this rate because of the large reactance of the choke at this frequency. Therefore, the total battery current is constant. As the resistance of the modulator tube increases, less

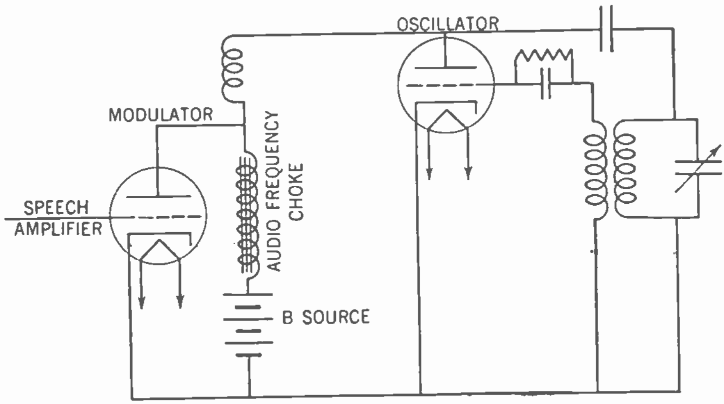


Fig. 203.

current will be taken by it, and more will flow to the oscillator tube. When the resistance of the modulator tube decreases, it will take more current; this reduces the current in the oscillator. Thus the radio-frequency current in the oscillator will be modulated by the audio-frequency changes in the modulator. One difficulty of modulating the oscillator is that the frequency generated by the oscillator is not independent of the plate voltage. This causes serious variation of the frequency that cannot be tolerated on the ordinary broadcast bands. Modulation is therefore never produced directly on the oscillator. According to the Heising system, the modulator acts as a Class-A amplifier. We have learned that the power at 100 per cent modulation is 50 per cent greater than when the carrier wave is unmodulated. This means that the modulator must supply 50 per cent of the amount of power delivered by the oscillator alone. Since a Class-A amplifier is usually less than 25 per cent efficient, the power consumed by the modulator would have to be an amount that is twice the value of the power of the unmodulated wave. The constant-current system of modulation is therefore very inefficient; it has been replaced by more satisfactory methods.

Plate Modulation with Transformer Coupling.—A widely used system of plate modulation is shown in Fig. 204. It should

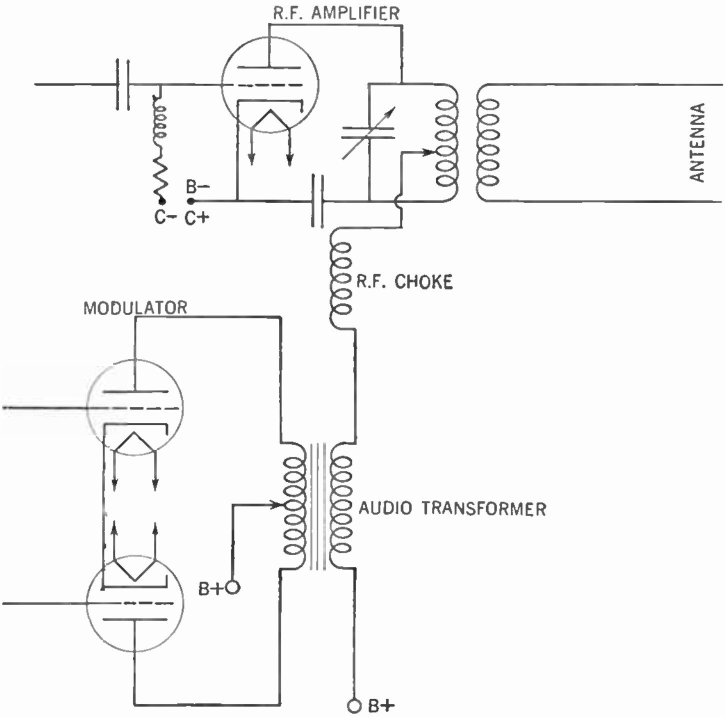


Fig. 204.

be observed that this circuit has two distinct parts. One part is the modulator which consists of the audio circuit; the other is the radio frequency amplifier. The audio circuit consists of a balanced push-pull Class-A, Class-AB, or Class-B amplifier. The audio, or modulator, circuit is transformer-coupled to the plate circuit of a Class-C radio-frequency amplifier. There is danger that the radio-frequency current will feed from the secondary of the transformer into the audio circuit. This can be avoided by using a choke coil having large impedance to radio frequencies. This coil is connected between the tank of the radio-frequency amplifier and the secondary of the modulator transformer.

Choke Coupling.—When using a single tube with Class-A amplification as a modulator, the circuit shown in Fig. 205 is

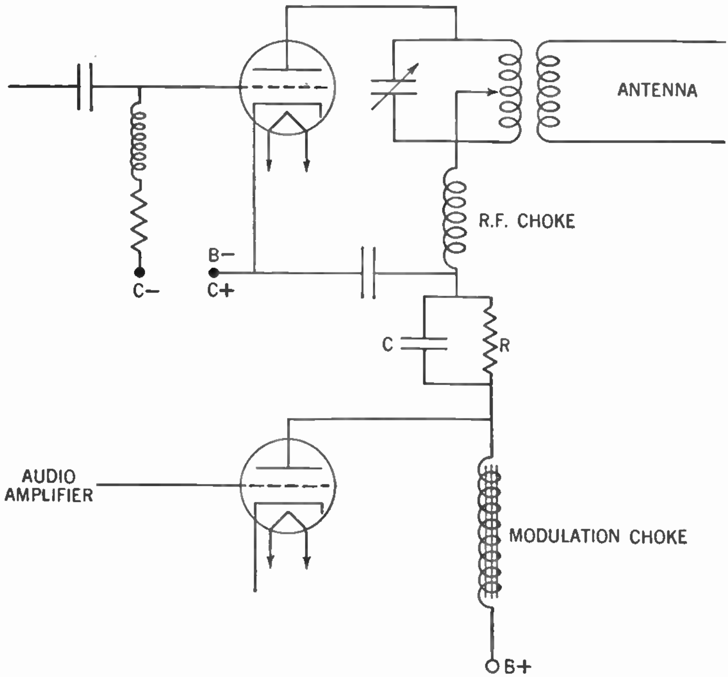


Fig. 205.

frequently employed. The plate power for both the modulator and the modulated amplifier is supplied from the same source, through a modulation choke that has a large impedance for audio frequencies. This method of modulation is known as *choke-coupled plate modulation.* The modulator superimposes its output upon the power supplied to the plate of the radio-frequency amplifier. In order to produce 100 per cent modulation, the audio-frequency voltage applied to the radio-frequency plate circuit across the modulation choke must be equal to the voltage on the modulated amplifier. This requires that the radio-frequency amplifier be operated at a direct-current plate voltage less the modulated plate voltage. The exact voltage relationship depends upon the types of tube used. The lower voltage for the amplifier tube is obtained by means of the resistance, *R*, which produces a voltage drop. The condenser, *C*, is a by-pass condenser that permits the audio-frequencies to pass. The output of a Class-A amplifier is much lower than that obtained from a push-pull arrangement operating a Class-B amplifier. For this reason the choke coupling is not used where large power is required. It is convenient, however, for portable transmitters that have a limited power output.

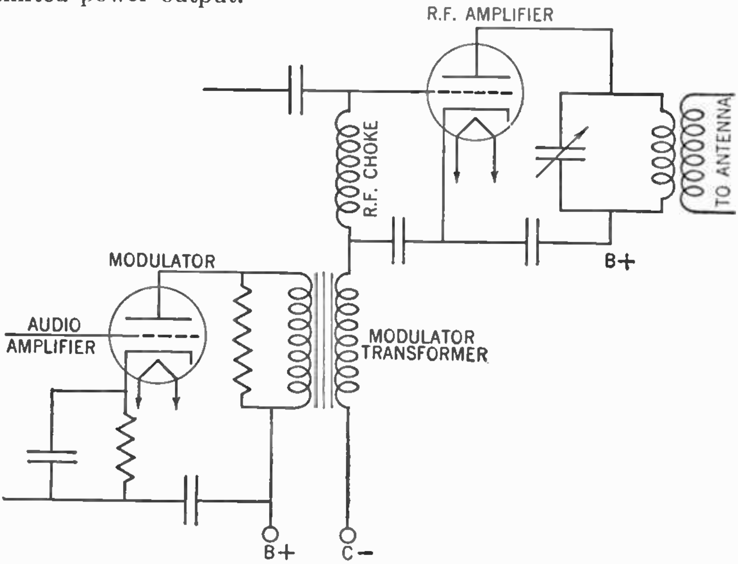


Fig. 206.

Grid-Bias Modulation.—The circuit for grid-bias modulation is illustrated by Fig. 206. It may be seen that here the primary coil of an audio transformer is connected to the plate of the modulator tube. The secondary coil of this modulator transformer is connected to the grid of the modulated amplifier. A radio-frequency choke is connected between the grid and the secondary of the transformer in order to prevent radio-frequency currents from entering the audio circuit. The audio-frequency voltage introduced into the radio-frequency circuit varies the grid bias and so controls the power output of the radio amplifier. The latter is operated as a Class-C amplifier. In grid-bias modulation, the plate voltage is constant, and the increase of power output with modulation is obtained by making the plate current and plate efficiency vary with the modulating voltage. Very little power is required in the modulator because it is only necessary to vary the grid bias of the radio-frequency amplifier. A Class-A audio-frequency amplifier is usually sufficient for the purpose. A grid-bias modulator of small power is sufficient for transmitters of large power. The change in bias voltage with modulation causes the grid current of the amplifier to vary. If the bias source has large resistance, the change in grid current will cause a change in bias in the direction opposite to that caused by the modulation. For this reason a grid bias source of low resistance should be used to reduce this bias variation to a minimum. Grid leak bias for a grid-modulated amplifier is unsatisfactory and should never be used.

The Suppressor-Grid Modulator.—A screen grid pentode may be modulated in the suppressor grid circuit. This arrange-

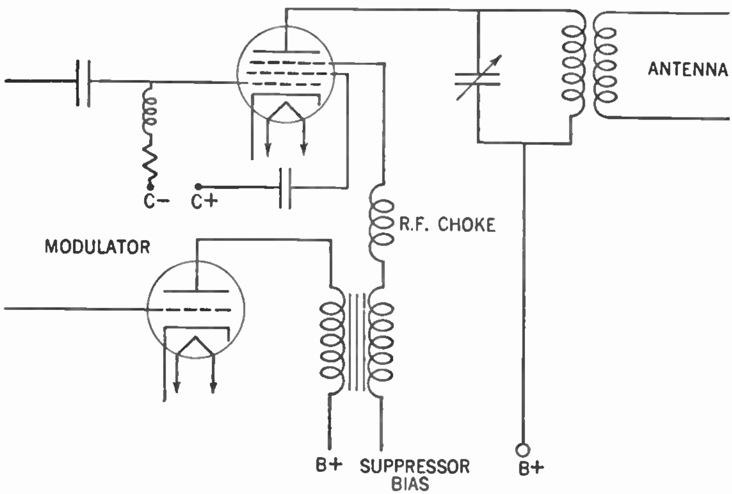


Fig. 207.

ment is shown in Fig. 207. The principles of operation are the same as those used for grid-bias modulation. The principal difference is that the radio-frequency excitation and the modulation excitation are applied to separate grids. This has a decided advantage over control-grid modulation because the best adjustment for proper excitation and modulation is obtained when the two are controlled independently.

Cathode Modulation.—A combination of plate modulation and grid-bias modulation is known as *cathode modulation*. Fig.

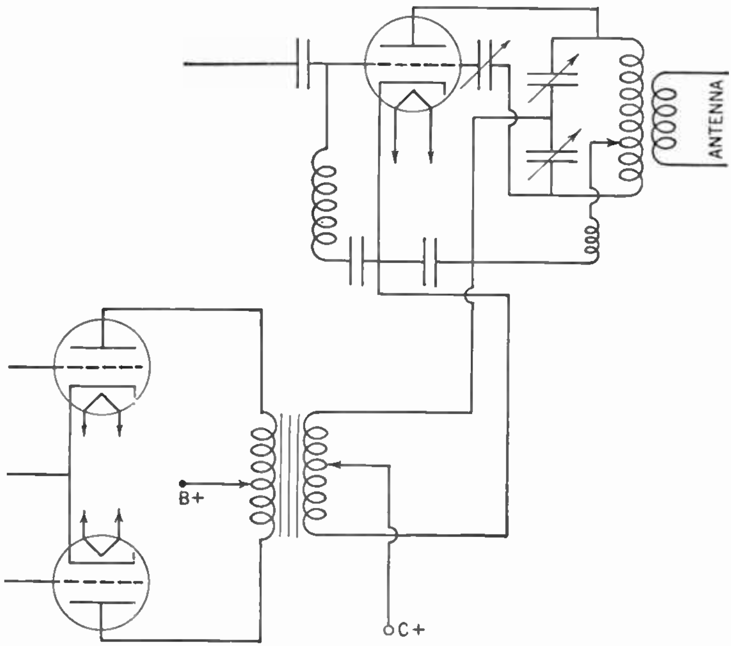


Fig. 208.

208 shows part of a cathode-modulated transmitting circuit. The audio excitation is introduced into the cathode circuit, and both grid bias and plate voltage vary during modulation. Because part of the modulation is obtained by the grid bias method, the plate efficiency of the modulated amplifier varies during modulation. The higher the percentage of plate modulation, the higher the efficiency of the modulated carrier wave.

High-Level and Low-Level Modulators.—In order to prevent the variation of frequency in the oscillator, the modulator is never coupled directly to the oscillator. The modulator may, however, be coupled to any stage of the radio-frequency amplifier. If the last stage is modulated, it is known as *high-level modulation.* When the modulator is coupled to any stage but the last, we speak of *low-level modulation.* For precise frequency, it has been found advisable to allow at least one stage of unmodulated amplification between the oscillator and the modulated amplifier. This unmodulated amplifier is known as a *buffer amplifier.* It is customary to use the last stage, or the next to the last, as the modulated amplifier.

A Complete Modulated Transmitter.—The construction of a typical modulated transmitter is made clear by means of the block diagram shown in Fig. 209. The two main sections of the

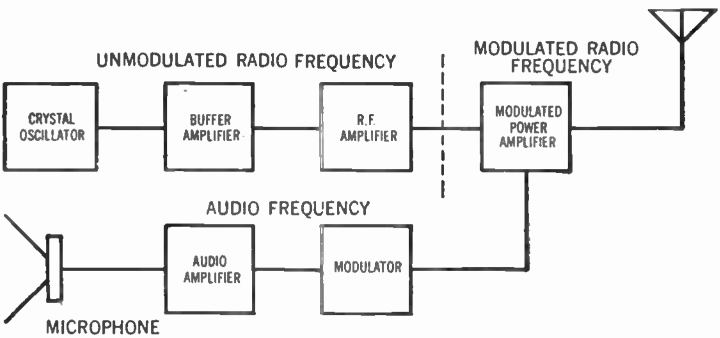
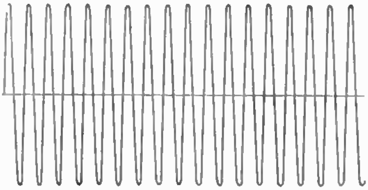


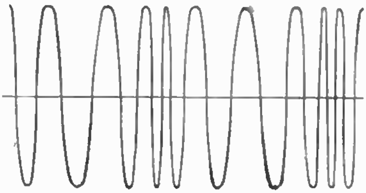
Fig. 209.

transmitter are the radio-frequency and the audio-frequency. The crystal oscillator that sets up the original carrier wave frequency, two stages of unmodulated radio-frequency amplification, and one modulated stage of amplification are in the radio-frequency portion of the circuit. The modulation is high-level modulation because the last stage is modulated. The microphone that changes the sound waves into audio-frequency electric currents, one stage of audio-amplification, are in the audio-frequency section. Though the arrangement may differ somewhat as to the number of stages of audio-frequency amplification and radio-frequency amplification, nevertheless the arrangement in Fig. 209 is a typical one.

Frequency Modulation.—Although all standard broadcasting is done by amplitude-modulated transmitters, nevertheless considerable development has taken place in frequency-modulated (FM) transmission. In this form of modulation, the frequency of the carrier wave is modified by the audio-frequency current. The amplitude of the modulated carrier wave remains constant. Fig. 210 shows the unmodulated and the frequency-modulated carrier wave. It should be observed that the amplitude of the modulated carrier wave is unchanged. Depending upon the amount of modulation, however, the frequency varies.



(*a*)



(*b*)

Fig. 210.

The Frequency-Modulated Transmitter.—Various circuits, all too complicated to be explained in a textbook such as this, are used for producing frequency modulation of the carrier wave. The fundamental principle upon which most of these circuits are based is that the audio-frequency circuit shall produce a change in the tank circuit of the radio-frequency oscillator, and by so doing bring about deviations in the carrier frequency. A simple method of accomplishing this, though an undesirable one, is to use a condenser microphone in the tank circuit. The variations of the sound wave then produce changes in the capacitance of the oscillator circuit and thus produce frequency changes that are related to the sounds that fall upon the microphone. A practical way to produce this effect is to use a reactance tube. The grid of a triode is supplied with voltage from the plate circuit after it has been given a 90° phase-shift. This causes the impedance of the plate circuit to act as a pure reactance. The grid bias is varied by the modulating audio frequency. The tube is put in parallel with the tank circuit of the radio-frequency oscillator. As a consequence of this, variations in the audio circuit produce changes in the reactance of the oscillator circuit, and thus the carrier wave suffers frequency modulation.

Advantages and Disadvantages of Frequency Modulation.—Since the amplitude of the wave does not change for a frequency-modulated transmitter, the power of the transmitter, instead of varying as it does in the case of the amplitude modulation, can be kept constant. This is a decided advantage because, where amplitude modulation is used, a large amount of power must be kept in reserve in order to take care of the peak values, even though the latter may occur very infrequently. In frequency modulation, the total power can be used at all times. Thus a frequency-modulated transmitter having considerably less power gives the same results as those given by an amplitude-modulated transmitter. Another advantage of frequency modulation is the almost complete elimination of static. Most static is only amplitude-modulated noise. Because of this fact it produces large effects when receiving amplitude-modulated waves, but produces practically no effect upon the reception of frequency-modulated waves. One serious disadvantage of frequency modulation is that it requires a wide channel for a single station. The value of this channel width is on the order of 150 kilocycles. This renders its use in ordinary broadcast channels quite impractical. At present, extremely high frequencies of megacycles are used for this type of broadcasting so as to give a sufficiently wide channel.

QUESTIONS

1. What is meant by the *carrier wave?*
2. Name the two methods of modulating the carrier wave.
3. What method of modulation is used in ordinary broadcasting?
4. Explain the meaning of *percentage modulation.*
5. What is the serious disadvantage of overmodulation?
6. What is the ideal percentage of modulation? Explain.
   Ans. 100 per cent.
7. How does the total power of 100 per cent modulation compare with the power of the unmodulated wave?
8. What is the source of the extra power in the modulated wave?
9. Assuming a single frequency for the modulating wave, how much greater is the effective current for the 100 per cent modulated wave?
   Ans. 23 per cent greater than for the unmodulated wave.

10. If there are two frequencies of 900,000 cycles per second and 1,000 cycles per second, respectively, what are the beat frequencies?
Ans. 901,000 cycles/seconds and 899,000 cycles/seconds.

11. Explain the meaning of *sidebands*.

12. Why is a channel required for each broadcasting station?

13. Name the important methods of amplitude modulation.

14. Explain the principle of the so-called Heising system.

15. What is the most important disadvantage of the Heising system?

16. Compare transformer coupling and choke coupling for a plate modulator.

17. Draw a circuit diagram for grid-bias modulation and explain how it functions.

18. State one advantage that suppressor-grid modulation with a pentode has over control-grid modulation.

19. What is the meaning of *frequency modulation?*

20. State the advantages and disadvantages of frequency modulation.

CHAPTER 13

RADIO RECEIVERS

The Purpose of a Radio Receiver.—The purpose of a radio receiver is to pick up energy from passing radio waves and convert it into such a form as to reproduce the sound effects that modulated the carrier wave. This latter process is known as *demodulation*. In general, the steps in the process of reception are: (1) induction in the antenna ground system; (2) mutual induction in the antenna coupling; (3) resonance in the tuning circuit; (4) radio amplification, detection, audio amplification, and sound reproduction by means of the loud-speaker. In various types of receiver some of these steps may be missing, the order may be somewhat changed, or additional steps may be added.

The Characteristics of a Receiver.—Any receiver must have five general characteristics: (1) sensitivity, (2) signal-to-noise ratio, (3) selectivity, (4) stability, and (5) fidelity. We are interested in a receiver's ability to pick up weak signals. This quality of a receiver is known as the *sensitivity*. This is the strength of the input signal that will produce a specified output at the loud-speaker. The sensitivity of a receiver is determined by the amount of radio amplification that precedes the detector. Though the amount of radio amplification can be increased indefinitely, nevertheless the effect of static fixes a limit to the sensitivity of any receiver. A set having a sensitivity so great as to respond to signals that are lower than the static level is useless. Of itself, every receiver generates some noise. In consequence of this, signals cannot be separated from the static, regardless of the amount of amplification. This relation between noise and a weak signal is known as the *signal-noise ratio*. The *selectivity* of a receiver is its ability to discriminate against undesired signals on channels next to the one that contains the desired signal. It has been shown that the greater the number of tuned circuits in a radio-frequency amplifier, the greater will be the selectivity. In the case of modulated waves, the selectivity can be too great; in this instance the receiver will not give uniform response over the band that is covered by the modulated wave. The *stability* of a receiver is its ability to give constant output over a period of time with a signal of constant intensity and frequency. *Fidelity* is the ability of the receiver faithfully to reproduce the sounds that modulated the carrier waves. This requires a uniform response over a band of frequencies. Other requirements for fidelity are freedom from noise and distortion.

The Types of Receiver.—Receivers are of three principal types: (1) the *regenerative receiver,* (2) the *radio-frequency* (*or RF*) *receiver,* and (3) the *superheterodyne.* Most receivers now in use are of the superheterodyne type. In addition to explaining the superheterodyne, the other two types will also be briefly explained because they have been of importance in the development of radio and because earlier ideas, once abandoned, have sometimes been revived and utilized in a new and improved form.

The Regenerative Receiver.—During the early period of the development of radio receivers, there was great demand for a

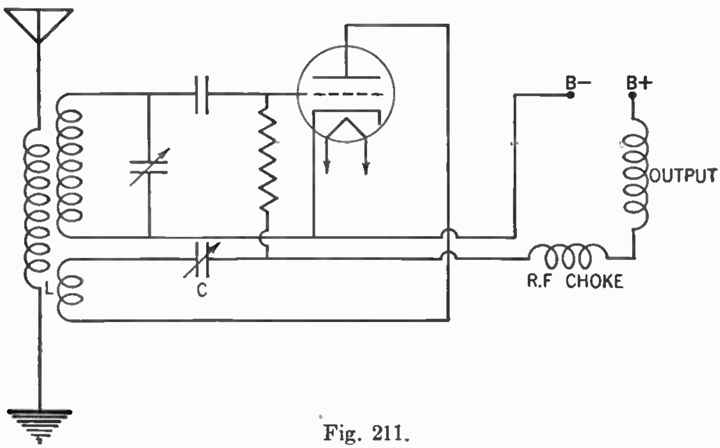


Fig. 211.

receiver that had high sensitivity. Owners of radios were eager to get stations that, because of their great distance, produced only feeble signals in the antenna ground system. Armstrong supplied the solution to this problem in the circuit shown in Fig. 211. The principal feature of the circuit is the coil, *L,* which is connected in the plate circuit of the tube. The purpose of this coil, commonly known as the *tickler*, is to feed some of the energy in the plate circuit back into the grid. Due to the tickler coil's proximity to the secondary coil of the antenna coupling, the varying current in the plate circuit causes induction in the secondary coil similar to that produced by the primary coil of the antenna circuit. This arrangement of three coils is known as a *three-circuit tuner*. By means of this feedback, or regeneration, the incoming signal can be amplified many times. By this means the sensitivity of the receiver is greatly increased. The amount of regeneration can be controlled in several ways. Most obvious of these is the removal of the tickler coil so as to increase its distance from the secondary coil. Another method is by varying the coupling. This is done by changing the angle that the tickler coil makes with the secondary coil of the antenna coupler. The method used in the circuit of Fig. 211 includes use of the variable condenser, *C*. Since some of the energy in the plate circuit is consumed in the charging of this condenser, this naturally leaves less energy to be fed back into the grid circuit. By varying the capacitance of the condenser, the amount of feedback can thus be controlled. In tuning the receiver, the control is advanced until the detector starts to hiss. The hissing indicates that the detector is oscillating. The proper adjustment for reception is just after the detector has started to oscillate.

Defects of the Regenerative Receiver.—Under ordinary circumstances, the oscillations in the tuning circuit are too weak to radiate electromagnetic waves. In the regenerative receiver, however, these oscillations may be built up to such a point that a strong radio wave is produced and thus the receiver acts as a transmitter. These undesired waves cause interference with regular reception by other receivers in the vicinity. The interference appears as undesirable sounds, such as whistles and howls. A regenerative receiver also tends to change frequency when the hand is moved toward the dial. This defect is brought about by body capacitance. Power-supply frequency hum may be present in a regenerative receiver, even though the plate supply is free from ripple. Because of these disadvantages, the regenerative receiver is no longer used.

The Radio-Frequency (RF) Receiver.—The block diagram of a radio-frequency receiver is shown in Fig. 212. The radio-frequency amplifier amplifies the signal voltage from the antenna before it passes to the detector. The first stage is tuned to resonance with the desired frequency. In the tuned radio-frequency receiver, the remaining radio-frequency stages are also tuned. The greater the number of tuned stages, the greater is the selectivity of the receiver. The radio-frequency input-signal voltage to the detector must be sufficiently high to attain a proper signal-to-noise ratio. The input voltage to the detector must not be below a certain threshold value. This is provided for by using a sufficient number of stages of radio-frequency amplification. In a receiver,

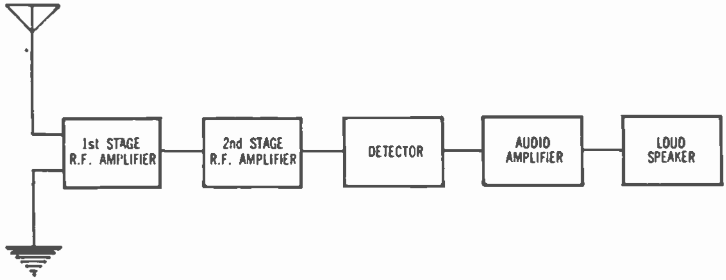


Fig. 212.

maximum sensitivity and selectivity are desired. In order to attain these with a tuned radio-frequency receiver, the tuning circuit should have a natural frequency exactly equal to the frequency of the incoming wave. The tuning circuit, however, is designed to handle *all* frequencies in the broadcasting ranges. In order to take care of this large range of radio-frequencies, a compromise must be made in the design of the radio-frequency transformer in the tuned circuit. When this compromise is made, considerable sensitivity and selectivity are lost as a result. Some attempt must then be made to overcome this difficulty so as to produce a receiver that has maximum selectivity and sensitivity.

The Heterodyne.—When two waves of different frequency are simultaneously produced, the two waves will at times reenforce each other, at other times oppose each other. This gives rise to the effect known as *beats*. Regular systematic increase and decrease of the resultant wave intensity will also occur. The frequency of the beats, which is equal to the difference between the two frequencies, is known as the *beat frequency*. The phenomenon of beats is characteristic of all kinds of waves. It is particularly noticeable when two sounds of slightly different pitch are heard at the same time. The principle of beats as applied to radio waves, known as *heterodyne,* is utilized by certain types of receivers. In order to make use of this effect, it is necessary for the receiver to produce a second radio-frequency that differs from the radio-frequency signal that is being received. In the heterodyne circuit this is produced by means of a separate oscillator, then introduced into the detector circuit. The frequency that is produced by the local oscillator is usually selected so that it differs by 500 cycles to 1,000 cycles per second. The beat frequency will also be of the same value, namely, 500 cycles to 1,000 cycles per second. This latter is the audio range of best response for ear and sound equipment. The heterodyne circuit is only used for the transmission of code. In some circuits the detector tube itself is made to produce the second radio-frequency oscillations. A detector of this type is known as an *autodyne detector.*

The Superheterodyne.—So far as concerns the heterodyne receiver, the beat frequency is that within the audio-frequency

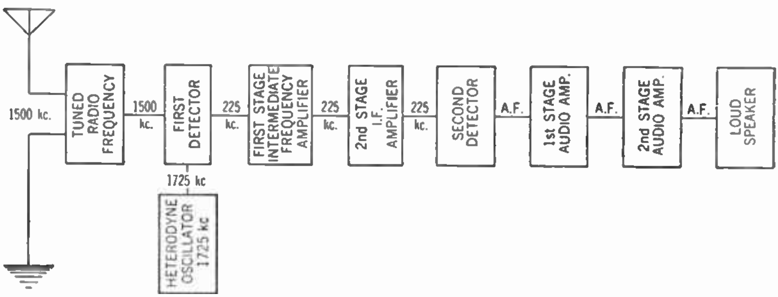


Fig. 213.

range. In the radio-frequency range the superheterodyne circuit produces a beat that is known as the *intermediate frequency.* Let us consider a radio wave of 1,500 kilocycles; the oscillator of the superheterodyne receiver produces 1,725 kilocycles. On this basis the intermediate frequency is 225 kilocycles. This intermediate frequency is then amplified by means of a radio-frequency amplifier. The block diagram of a complete superheterodyne receiver is shown in Fig. 213. The signal frequency from the antenna is amplified by means of the tuned radio-frequency circuit. The first detector is really a mixer tube in which the signal frequency that originates in the antenna is mixed with the frequency that comes from the local oscillator. The resultant beat frequency, or intermediate frequency, is then amplified by means of several stages of amplification. Up to this point, however, the signal is still within the radio-frequency range. Thereupon the second detector changes the intermediate radio-frequency into audio-frequency. Sufficient stages of audio-frequency amplification are then employed for the purpose of amplifying the audio-frequency so that it operates the loud-speaker.

The Significance of Frequency Conversion.—So far as concerns the first detector of the superheterodyne receiver, frequency conversion is there used for the purpose of changing the frequency of the radio-frequency signal to an intermediate frequency. In order to effect this change of frequency, a frequency-converting device that consists of an oscillator and a frequency mixer is used. According to this arrangement, the input radio-frequency signal, together with the radio-frequency oscillation produced by the oscillator, causes beats that represent the intermediate frequency. This may be accomplished by means of one or another of three methods. According to the first method, a triode, a tetrode, or a pentode is used as a mixer tube. The oscillator voltage and signal voltage are then applied to the same grid. By means of this method, the coupling between the oscillator and the mixer circuits may be obtained by means of inductance or capacitance. According to the second method, one uses a tube that has an oscillator and a frequency mixer that are combined within the same envelope. According to the third method, one uses a tube that has two independent control grids and is used with a separate oscillator tube.

The Inductive, or Capacitive-Coupled, Mixer.—When using the first method of frequency conversion, the local oscillator is so arranged that it at all times produces a frequency that is higher, by a fixed amount, than is the input signal. Though this difference may vary from as little as 150 kilocycles to as much as several hundred kilocycles, nevertheless it is common practice to use about 450 kilocycles for home receivers. Another problem is the introduction of the frequency of the local oscillator into the mixer tube. This may be accomplished in several ways. The two circuits may be coupled by means of inductance or capacitance.

A circuit in which the oscillator is coupled to the mixer by means of a condenser is shown in Fig. 214. Here the input signal is connected to the grid of the first detector, which here also serves as the mixer. In consequence, the oscillator produces a radio-frequency voltage whose frequency is a given amount above the signal frequency. This voltage is also applied to the grid of the mixer by using coupling condenser *C*. The two frequencies im-

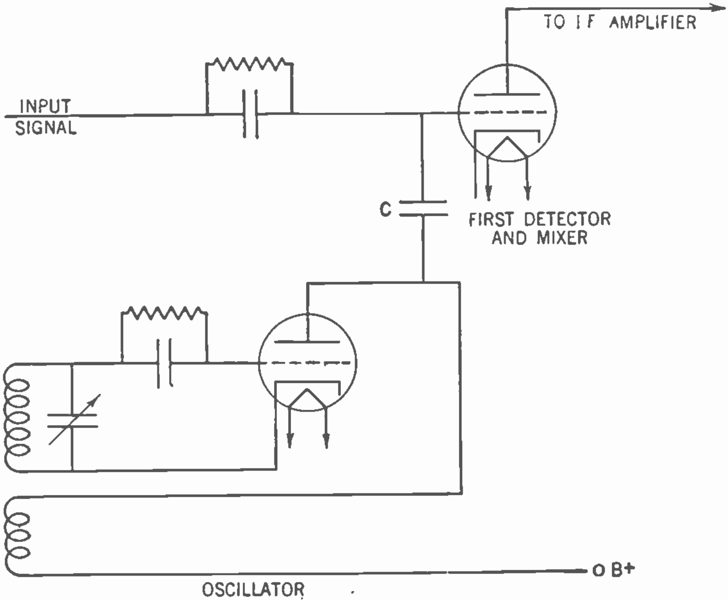


Fig. 214.

pressed upon the grid produce the beat frequency in the plate circuit of the mixer. This intermediate frequency is then amplified by means of the first stage of the intermediate frequency amplifier. In this instance the oscillator may also be coupled by means of mutual inductance. So far as concerns this arrangement, great care should be exercised to shield the oscillator from the rest of the circuit; otherwise serious cross-modulation will take place. By mounting the tuning condensers in both circuits on the same shaft, oscillator frequency can be so maintained that it is always of the same amount above the frequency of the input signal.

The Pentagrid-Converter.—The method of producing intermediate frequency that has just been described was discarded at the time when new converter tubes were built. One of these tubes is the so-called pentagrid-converter. This is a tube that has a cathode, a plate, and five separate grids. It may be used for the second method of producing the intermediate frequency; that is, where oscillator and mixer are contained within the same envelope. An arrangement in which the pentagrid-converter is used for this purpose is shown by Fig. 215. In this figure the five grids

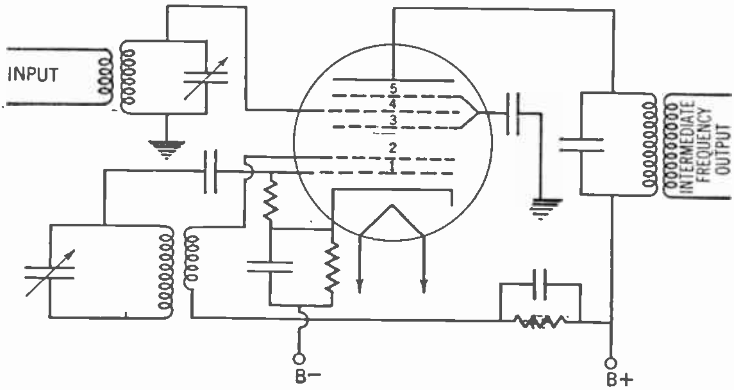


Fig. 215.

of the converter tube are numbered from 1 to 5. The grid nearest the cathode is known as No. 1. Grids No. 1 and No. 2, together with the cathode, are connected to an outside circuit so as to act as a triode oscillator. Grid No. 2 has the same function as has the plate in the ordinary triode oscillator. Grid No. 1 serves as the grid of the oscillator. These two grids, together with the cathode, supply to the rest of the tube an electron stream of the same frequency as that of the oscillator. Grid No. 4 is connected to the tuned radio-frequency of the input signal. This grid also controls the electron stream within the tube. Thus, variations in the plate current are due both to the signal frequency and to the oscillator frequency. Grids No. 3 and No. 5, connected together inside the tube, are so designed as to accelerate the electron stream and to shield Grid No. 4, electrostatically, from other electrodes in the tube. At medium frequencies, pentagrid tubes are excellent frequency converters; even so, at lower frequencies they function better than at high frequencies. At high frequencies, interaction between the oscillator portion and the signal portion of the tube causes undesirable effects. In order to overcome this difficulty in part, some pentagrid tubes are so designed that no single electrode functions as does the oscillator anode. This is brought about by having Grid No. 1 act as the oscillator grid, and by having Grid No. 2 connected to Grid No. 4 within the tube. Grids No. 2 and No. 4, combined, act as the anode of the oscillator triode and so shield Grid No. 3, which latter acts as the signal grid. Grid No. 5 serves as a suppressor. According to this arrangement, the space charge is unaffected by electrons from the signal grid or from its electrostatic field.

The Pentagrid Mixer.—The third method of producing an intermediate frequency is primarily designed for use with short-wave receivers. A special tube, known as a *pentagrid mixer*, is here used in conjunction with a separate oscillator tube. The pentagrid mixer has two independent control grids. The radio-frequency signal voltage is applied to one of the control grids, the oscillator voltage to the other. In this instance the construction is similar to that of the pentagrid-converter. Here there are one cathode, one plate, and five grids. Control grids are No. 1 and No. 3. The oscillator voltage is connected to the No. 3 grid, the signal voltage to the No. 1 grid. Grids No. 2 and No. 4 are connected inside the tube. Grid No. 5, which is connected to the cathode within the tube, acts as a suppressor.

The Intermediate-Frequency Amplifier.—When the intermediate-frequency current comes from the plate circuit of the mixer tube, it is then amplified. Though the intermediate frequency is in the radio-frequency range, nevertheless it is at a much lower frequency than is the radio-frequency signal. Because of this, the intermediate-frequency transformer may have a greater number of turns than has the ordinary radio-frequency transformer. As has previously been explained, the intermediate frequency of any given receiver is always the same for all signal frequencies. Because of this, a variable condenser is unnecessary. In place of a variable condenser, one uses a fixed condenser whose capacitance may be changed slightly by means of a mechanical adjustment. This device, whose purpose is to allow of small adjustments so as to align the various stages of the intermediate-frequency amplifier, is known as a *trimmer condenser*.

The Selectivity of a Superheterodyne.—The intermediate frequency of any given superheterodyne receiver is always a fixed quantity. Therefore the intermediate-frequency amplifier always amplifies the same frequency. The design of an amplifier that amplifies a fixed frequency is such as to produce a high selectivity, as compared with an amplifier that must amplify many different frequencies. This is one reason why the superheterodyne receiver has a much greater selectivity than has a radio-frequency receiver. Another reason for the high selectivity of the superheterodyne may be perceived by examining the percentage difference of the frequencies of two given input signals. For illustration, let us consider two incoming signals of 1,000 kilocycles and 1,020 kilocycles, respectively. When the circuit is tuned to 1,000 kilocycles, the percentage difference of the radio-frequency receiver is 20×100 per cent, or 2 per cent of the desired signal. In the superheterodyne receiver, on the contrary, assuming that when receiving the 1,000 kilocycles the intermediate frequency is 400 kilocycles, then the intermediate frequency of the 1,020 kilocycles will be 420 kilocycles. This gives a percentage difference of $\frac{20}{400} \times 100$ per cent, or 5 per cent. The greater the percentage difference between the desired and the undesired signal, the greater is the selectivity. Upon this basis alone, the selectivity of the superheterodyne is much greater than that of the radio-frequency receiver.

The Band-Pass Filter.—When we discussed the modulated carrier wave (page 194), it was there emphasized that the wave does not have a single frequency; rather, that it consists of two bands of frequencies, one of which is on either side of the unmodulated carrier frequency. These two bands are known as *sidebands*. Because the selectivity of a superheterodyne is as great as it is, a serious problem consequently arises. If the selectivity is sufficiently great, then a part of the sidebands may fall below the level of audibility. This condition is known as the *cutting of the sidebands*. Broadcasting stations are obligated so to transmit on each side of the unmodulated carrier wave that the sideband be no greater than 5 kilocycles. A high selectivity also causes a sharply peaked resonance curve, in which the peak of the curve is at the carrier frequency, and in which it also falls off sharply on either side. Thus the response over the 10-kilocycle band, not being uniform, seriously affects the fidelity of the receiver. The ideal condition, of course, is to have a uniform response over the 10-kilocycle range of the modulated wave, then sharply to cut off response for all frequencies that are above and below this range. A device of this type is known as a *band-pass filter*. Though the exact conditions outlined above cannot always be completely achieved, nevertheless a fairly close approach to this may be made in practice. Curve *A* in Fig. 216 shows the response curve for a superheterodyne receiver having a high degree of selectivity. The carrier-wave frequency is shown, as also the limits of the sidebands. It should be noted that the extreme upper and lower regions of the frequency range of the modulated wave are below the lower limit of audibility. Even the response of frequencies above the level of audibility is in many cases only a small proportion of the maximum response for the unmodulated carrier wave. The fidelity of any such receiver is quite unsatisfactory. This difficulty may be overcome by adjusting the trimmer condensers so that the stages are slightly out of tune. Curve *B* of Fig. 216 shows the response curve when two stages are thus adjusted. Actually the curve has two peaks, each of which is located at one of the limits of the modulated carrier wave. Though the response is not perfectly flat, nevertheless the variation is slight and the fidelity of the receiver is thereby greatly improved. There is some reduction in selectivity, to be sure, but even so this is not serious because it is possible to build superheterodynes that have greater selectivity than is usually demanded. From all this we may learn that the superheterodyne receiver combines all the principal virtues of any good receiver; these are: (1) sensitivity, (2) selectivity, and (3) fidelity.

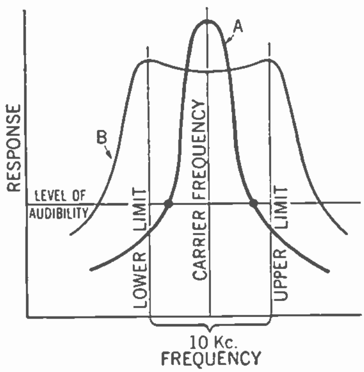


Fig. 216.

The Image Frequencies.—In an earlier part of this chapter, a superheterodyne circuit having an intermediate frequency of 225 kilocycles was described as though receiving a signal of 1,500 kilocycles. In that case the oscillator produced a frequency of 1,725 kilocycles. It should be apparent that a signal frequency of 1,950 kilocycles will also produce beats of 225 kilocycles. This undesired frequency is known as the *image* of the desired frequency. Whenever the receiver is tuned to the desired signal frequency, then the intermediate frequency output is measured for a given voltage of a desired frequency. This is then compared with the intermediate frequency output of the image having the same voltage. The resulting ratio is known as the *signal-to-image ratio.* If the signal-to-image ratio is not sufficiently large, then a tuned radio-frequency stage is introduced before the mixer tube of the superheterodyne circuit. In this latter case, the desired signal is so tuned by the radio-frequency circuit that the desired frequency has a much greater response than has its image. This stage of tuned radio-frequency also reduces the effect that powerful stations have upon adjacent frequencies. A radio-frequency amplifier used before a mixer is known as a *pre-selector.*

The Automatic Volume Control.—The principal reason for having an automatic volume control (*avc*) in a receiver is to prevent fluctuations in loud-speaker volume when the signal voltage on the antenna changes because of fading. If the receiver be set with its volume control arranged for the reception of a weak signal, and if the signal then suddenly increases in strength, the loud-speaker is likely to let out a disagreeable blast. In order to avoid or eliminate this defect, an automatic volume control so regulates the receiver's gain that the amplification is less for a strong signal than for a weak one. The *avc* works upon this principle: the strong signal increases the negative bias on the radio-frequency and on the intermediate frequency stages. By this means the output to the loud-speaker is reduced for the strong signals. Fig. 217 shows a simple *avc* circuit that makes use of a diode. When the plate is positive, the diode allows current to pass on each positive half-cycle of the signal voltage. This action produces a voltage drop in the resistance, *R;* then, through a filter, the negative bias is applied to the grids of the intermediate frequency stages. In consequence of this, when the signal voltage at the antenna increases, then the voltage on the diode also increases and so

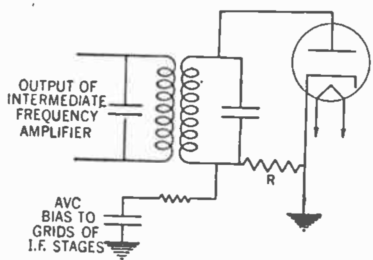


Fig. 217.

causes a large current through resistance R on the positive cycle. This produces a large voltage drop, and consequently a large negative bias on the grids of the intermediate frequency amplifier. This reduces the gain of the amplifier and so prevents the loud-speaker from blasting on strong signals. Whenever the signal weakens, the large negative bias is not produced on the grids of the amplifier; thus the gain is restored to its original value. In this manner *avc* prevents change in loud-speaker volume. If the *avc* circuit is so arranged that no bias is applied until the signal strength exceeds a certain value, it is then known as *delayed avc*. The purpose of delayed *avc* is to obtain a maximum gain for weak signals.

The Tone Control.—Many receivers have a control for the tone of the loud-speaker. If a rheostat connected in series with a condenser is also connected in parallel with a part of the audio amplifier, then the higher audio tones are shunted out. Changing the resistance by means of a rheostat, the amount of shunting is also changed, and in consequence the tone is varied. In place of this manual tone control, so-called automatic tone controls (*atc*) have recently been devised, though they have not yet been universally made a part of the receiver.

QUESTIONS

1. What are the chief characteristics of any good receiver?

2. Explain the difference between *sensitivity* and *selectivity*.

3. What is the significance of the signal-noise ratio?

4. Name the three important types of receiver.

5. Describe the disadvantages of a regenerative receiver.

6. Explain how the regenerative receiver controls the amount of regeneration.

7. Draw a block diagram of a radio-frequency (*RF*) receiver.

8. How is selectivity increased by the radio-frequency receiver?

9. What is meant by the word *heterodyne?*

10. How may the beat frequency be determined?

11. What is the difference between the heterodyne circuit and the superheterodyne circuit?

12. If the intermediate frequency in a superheterodyne circuit is 455 kilocycles, what should the oscillator frequency be when the receiver is tuned to a signal having a frequency of 1,000 kilocycles?

Ans. 1,455 kilocycles.

13. Draw a block diagram of a superheterodyne receiver.

14. Explain the principle of capacitive coupling of the local oscillator and the first detector tube.

15. Draw a diagram of a pentagrid-converter. Describe the device.

16. How does the intermediate-frequency amplifier differ from the ordinary radio-frequency amplifier?

17. Explain why a superheterodyne receiver has high selectivity.

18. Explain how the fidelity of the receiver is improved by the band-pass filter.

19. What is the reason for pre-selection?

20. Explain the meaning and principle of *avc*.

CHAPTER 14

THE PROPAGATION OF RADIO WAVES

The Nature of Radio Waves.—A radio wave is an electromagnetic wave that consists of two components. One of these is a varying electric field; the other is a varying magnetic field. The two components are at right angles to each other, and in a plane that is at right angles to the direction of propagation of the wave. Since the vibrations are at right angles to the direction of propagation, the wave is known as a *transverse wave*. A radio wave is of the same nature as a light wave and travels with the same speed; *i.e.*, 3×10^{10} centimeters/second or 186,000 miles/second, in a vacuum. Since the radio wave is of the same nature as a light wave, it can also be reflected, refracted, diffracted, and polarized.

Reflection.—Radio waves are reflected at any sharply defined interface between media. Any conductor that has dimensions at least of the order of the wave length of the wave will act as a reflector.

Refraction.—When passing from one medium into another in which the speed is different, a radio wave is bent out of its path. This bending of the wave from its original path, due to a change of speed, is known as *refraction*.

Diffraction.—The bending of the wave around the edge of an obstacle is known as *diffraction*. Though the result is somewhat similar to refraction, in that the wave is bent out of its path, nevertheless diffraction does not require a change of medium, as does refraction.

Polarization.—Because a radio wave is a transverse wave, it can be polarized. *Polarization* is the confining of the vibration of each component to a single plane. If the electrostatic vibration is perpendicular to the earth, then the wave is said to be *vertically polarized*. If the vibration is parallel to the earth, the wave is said to be *horizontally* polarized.

The Ground Wave and the Sky Wave.—When the radio wave leaves the antenna, it travels outward in all directions. One part of it, known as the *ground wave*, travels along the surface of the earth. The other part, which travels out into the sky, is called the *sky wave*.

Propagation of the Ground Wave.—Due to the curvature of the earth, the ground wave must be propagated by diffraction. The ground wave dies out fairly rapidly because it causes induction in passing over the earth. Because the earth has a large resistivity, this takes the energy away from the wave fairly rapidly. In those areas of the earth where the resistivity is smaller, over large bodies of water, for example, the energy absorbed is also much smaller and in consequence here the range of the ground wave is correspondingly greater. Since higher-frequency waves cause a greater induction, their range is considerably less for the ground wave. The lower-frequency ground waves may have a range of as much as 1,000 miles, though the higher frequencies may have a range of only a few miles.

The Ionosphere.—In order to explain *fading* and *skip distance*, Kennelly and Heaviside independently proposed the existence of a layer of ionized air above the surface of the earth at a distance that varies from 50 miles to 150 miles. This ionized layer, formerly known as the Heaviside layer, is now called the *ionosphere*. Actually, it is several layers of ionized air that extends from 50 miles to 250 miles above the earth's surface. It should be borne in mind that ions are charged electrical particles. They may be either electrons or atoms that have lost one or more electrons. The electrons have a negative charge; the atoms that have lost electrons are positively charged. In order to understand the reason for the existence of the ionosphere, and why its ion density varies at different heights, we must first investigate the phenomenon of ionization. The production of ions is brought about in various ways. In the case of a gas, ionization can be caused by the impact of an ion against an un-ionized atom. This process is known as *ionization by impact*. Ionization may also take place when a gas absorbs certain radiations. With respect to ionization by impact, the ion that causes the impact must be traveling at a high velocity if it is to knock off electrons from the neutral atoms. At the surface of the earth, where the atoms of the air are crowded together, the ion collides with an atom before it has sufficient velocity to cause ionization. The greater the altitude, the lower the density of the atmosphere and the greater the distance between the atoms. At first this favors ionization by impact. If the air becomes too rare, however, the probability of impact is greatly reduced. Ultra-violet light and cosmic rays are also a source of ions. Since these radiations originate at a great distance from the earth, they first affect the upper limits of the atmosphere. Because their energy is absorbed as they pass through the atmosphere, there is naturally less energy left for causing further ionization. Only a small amount of the radiant energy reaches the earth's surface. Another reason for the small amount of ionization at the earth's surface is *recombination,* that is, the combining of electrons with positive ions. This, of course, also reduces the total amount of ionization. Since the atoms are closer together at the earth's surface than at higher altitudes, recombination is greater at the earth's surface. Climatic conditions, the time of day, and the time of year also cause marked changes in the ionosphere. Because of this, the effect of the ionosphere upon radio waves is not constant.

The Sky Wave and the Ionosphere.—If the ionosphere were not present, almost all the energy of the sky wave would be radiated off into the space beyond the earth and would therefore be useless for purposes of radio communication. The ionosphere, however, causes a large part of the energy to be returned to the earth. Fig. 218 shows a simplified diagram of the ionosphere. The dotted lines indicate the ionization of the ionosphere. The density of ionization is indicated by the spacing of the lines. The effect of the ionosphere on the sky wave sent out from a transmitter located at *T* is illustrated by means of the two rays, *A* and *B*. In the direction of *A*, the radio wave is refracted upon entering the ionosphere. As the ion density becomes greater, the wave is refracted still more. In the case of ray *A*, the wave finally passes out into space through the upper limit of the ionosphere. In the case of ray *B*, the wave is refracted to such a degree that no further refraction is possible and in consequence the wave is totally reflected back to earth. If ray *B* is the first at which total reflection takes place, it is known as the *critical ray.* The angle made by the critical ray and the vertical is called the *critical angle* ϕ. Any ray, such as *C*, whose angle is greater than the critical angle, will also be totally reflected; any ray, such as *A*, whose angle is less than the critical angle, will pass through the ionosphere into outside space. Since the sky wave goes out from the transmitter in all directions, one might better say that all rays within a cone whose axis is vertically upward, and whose vertex angle is 2ϕ, will pass through the ionosphere into the outside space, and that all rays outside this cone will be reflected back to the earth.

The explanation just given is really too simplified completely to describe the actual effect of the ionosphere. Variation of ion density, in conjunction with other changing conditions, renders the ionosphere very complex in nature. The essentials of any more detailed explanation, however, would be identical with what has already been set out in simpler terms.

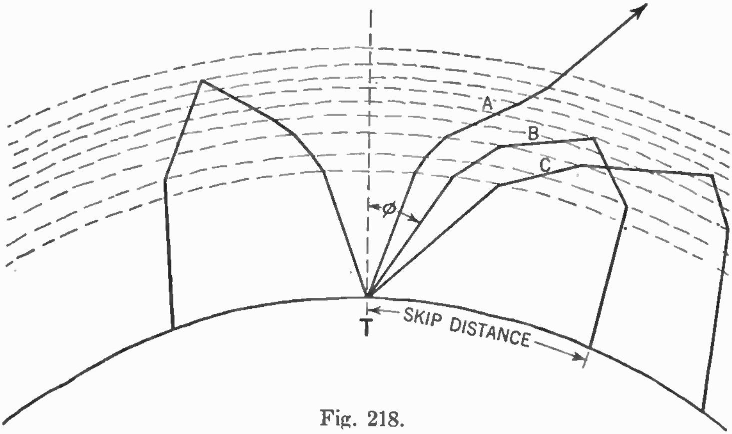


Fig. 218.

Skip Distance.—Upon examining Fig. 218 it will be discovered that none of the sky wave reaches the earth in the distance that intervenes between the transmitter and the point where the critical ray meets the earth. This intervening distance is known as the *skip distance*. All the region that lies within the skip distance is known as the *skip zone*. This explains why a signal may be heard at a great distance from the transmitter, yet not be heard at some point near by. The skip distance, which varies for waves of different frequency, is greater for waves of greater frequency. Its extent also depends upon the state of the ionosphere, which latter is constantly changing. After its first reflection from the ionosphere, the wave may be reflected by the earth, and then once again reflected by the ionosphere. This gives a second skip distance. Furthermore, this process may even be repeated several times. Thus it is that sky waves (which must travel great distances) follow the curvature of the earth.

Fading.—A receiver may pick up both the ground wave and the sky wave. If the two waves are in phase when received, the signal is strengthened; if the waves are out of phase, however, the signal is thereby weakened. Interference may also take place between two sky waves that have been reflected from the ionosphere and are out of phase. The difference in phase may be due to the fact that the original sky wave was reflected from two different parts of the ionosphere; or, one wave may have been once reflected by the ionosphere, the other reflected more than once. All these effects cause fading of the signal. Violent disturbance in the ionosphere set up by outside influences may also cause serious fading that may continue for a considerable period. Fading in a receiver can be corrected by means of *avc*, which has been described in the previous chapter.

Static.—Electromagnetic waves are often set up by natural phenomena that take place in the atmosphere. These phenomena may be due to the discharge of electricity from one cloud to another, at a different potential, or to the discharge of electricity from a cloud to the ground. This type of static is known as *natural static*. On the antenna it induces potentials that produce noises which may drown out, or seriously interfere with, the reception of the station signal. Similar effects may also be produced by the action of electrical devices. These latter are known as *man-made static*. Some common causes of man-made static are ignition systems, arcing wires, poor brush contact on electric motors or generator commutators, and diathermy machines. So far as concerns this latter kind of static, it should be eliminated at the source. This can usually be accomplished by placing a condenser across any arcing device, or by using filters designed to prevent disturbances from being transmitted to the power lines. The elimination of natural static is a much more difficult task. Since conditions that cause the static vary greatly and are never exactly the same, it is impossible to select any one device that will completely eliminate the effect of all natural static. Nevertheless natural static can be greatly reduced by means of a selective tuner, a directional antenna, or by means of some form of automatic volume control. This latter device makes the receiver inoperative during that instant when the static is sufficient to affect the operation of the set. Ultra-high frequencies are not affected by natural static. Because of this fact it is advantageous to use them in television communication.

Antenna.—For transmitting any given radio wave, it is highly important that a suitable antenna be used. An antenna that produces satisfactory results at one frequency may be entirely unsatisfactory at another. The important properties of an antenna are (1) its polarization, (2) its angle of radiation, (3) its impedance, and (4) its directivity. The *polarization* of an antenna is the direction of the antenna so as to produce a wave that has a given direction of polarization. An antenna that produces horizontally polarized waves is horizontally polarized; a vertically polarized antenna produces vertically polarized waves. It should be recalled that the polarization of a wave is the direction of its electrical field component. The *angle of radiation* is the vertical angle that the radiated wave makes with the tangent to the earth at the transmitting point. The *directivity* of an antenna is the direction of the antenna in which it radiates maximum power.

Half-Wave, or Hertz, Antenna.—One of the simplest forms of antenna is a straight line, as is shown by Fig. 219. Here the

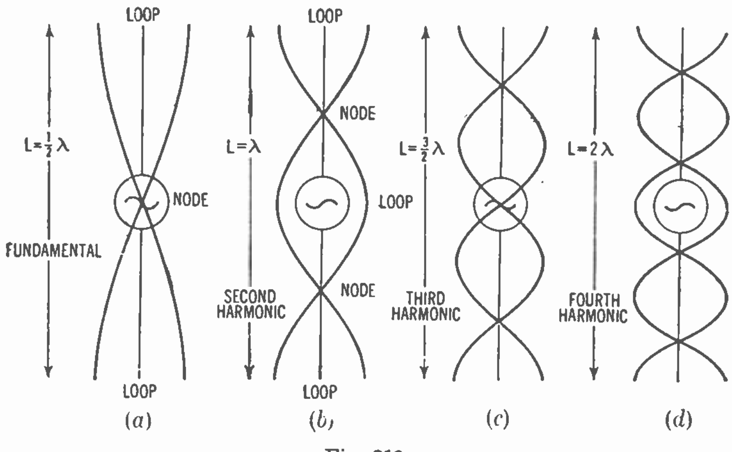


Fig. 219.

power is connected at the antenna's midpoint. The voltage wave that travels along the wire is reflected back at both ends. The reflected waves combine with the incident waves in such manner that the waves are reënforced at the ends and interfered with at the center. Points of complete interference are called *nodes;* points of complete reënforcement are known as *loops.* If the total length of the antenna is equal to one-half the length of the wave to be transmitted, then a voltage node exists at the center of the antenna and a voltage loop at each end. There will be only one node, and the wave is the fundamental of the antenna. The condition on the antenna as just described is referred to as a *standing wave.* In the half-wave antenna, the voltage is zero at the center

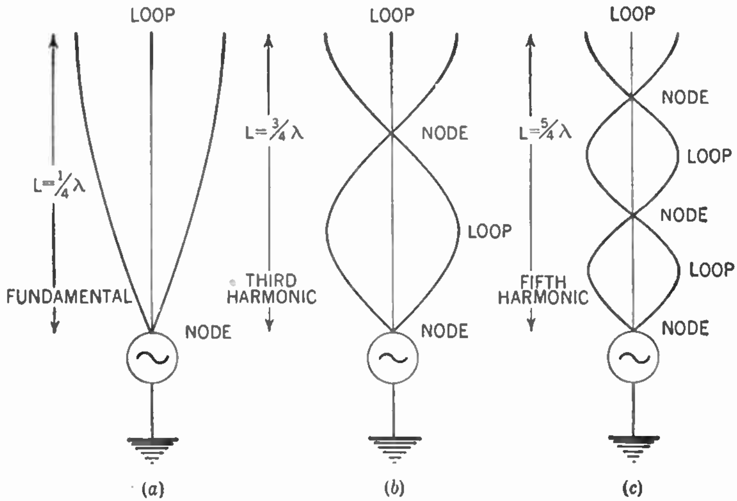


Fig. 220.

and a maximum at the ends; the current is zero at the ends and a maximum at the center. Harmonics of the wave can also be produced on the same antenna. As Fig. 219 shows, (*b*) is the same antenna as (*a*), but with the second harmonic. The third and fourth harmonics are shown in (*c*) and (*d*).

Length of the Half-Wave Antenna.—The length of the fundamental wave of a half-wave antenna can be calculated when one keeps in mind the fact that the length of the antenna is one-half the length of the fundamental wave. Since $v = f\lambda$, and since $v = 186{,}000$ miles/second, and since $\lambda = \frac{1}{2} L$, the length of the antenna is

$$L \text{ (in feet)} = \frac{v}{2f} = \frac{186{,}000 \times 5{,}280}{2f} = \frac{492{,}000}{f \text{ (in kilocycles)}}.$$

A slight correction that amounts to about 5 per cent for broadcasting frequencies must be made for end effects.

The Quarter-Wave, or Marconi, Antenna.—Another form of antenna, first used by Marconi, is shown in Fig. 220. One end of the antenna is grounded. When the antenna is in resonance, the length of the antenna is one-fourth the length of the fundamental resonant wave. Since a node must be at the grounded end of the antenna, and since a loop must be at the other end, even harmonics cannot exist. A quarter-wave antenna can produce only the odd harmonics. The third and fifth harmonics are shown by (*b*) and (*c*) of Fig. 220. More complicated antenna systems are used for handling special transmission problems.

Transmission Lines.—In order to transfer power from the transmitter to the antenna, considerable distance may have to be covered. Wires used for transferring power are known as *transmission wires*. Since the transmission wires carry radio-frequency currents, a large amount of energy is likely to be radiated out from the transmission wires before the energy reaches the antenna. Transmission lines must be specially designed if radiation is to be minimized and transmission loss reduced. These ends can be achieved by means of the *resonant transmission line*. The resonant transmission line may readily be understood if one regards it as an antenna that is folded back upon itself. The length of such a transmission line may be any integral multiple of a quarter of a wave length. Fig. 221 shows a transmission line of $\frac{3}{4}\lambda$ feeding into a half-wave antenna. Since the line is in resonance, the impedance is at a minimum. Also, there is no radiated field. Thus transmission loss from transmitter to antenna is greatly reduced.

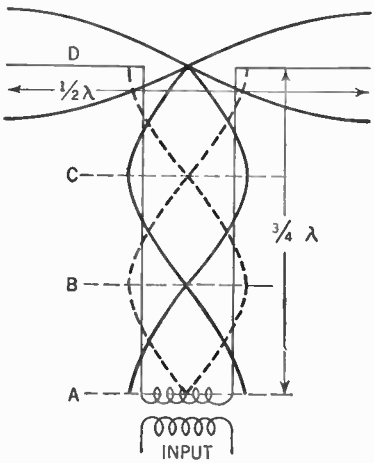


Fig. 221.

The Lecher System.—In Fig. 221 the standing voltage wave on the transmission lines is indicated by a solid line. The standing current wave is indicated by dotted lines. The current nodes are at *A* and *C*, the current loops at *B* and *D*. If the terminals of a flashlight bulb are soldered to two bare wires, then placed across the transmission wires of Fig. 221, the bulb will glow brightly at Band *D*, the current loops, and go out at *A* and *C*, the current nodes. A two-wire system so used for determining wave length is known as a *Lecher system*. If the distance between *B* and *D* is measured, then multiplied by 2, this gives the value of the wave length of the current in the Lecher wires.

QUESTIONS

1. What are some of the characteristics of radio waves?
2. What is the difference between refraction and diffraction?
3. Describe a vertically polarized radio wave.
4. Why is the range of the ground wave limited?
5. Explain the nature of the ionosphere.
6. What causes differences of ion density in the layers of the ionosphere?
7. Explain the refraction of the sky wave in passing through the ionosphere.
8. What is meant by the critical angle?
9. Define skip distance.
10. Draw a diagram that illustrates multiple skip distances.
11. Over long distances, how does the sky wave follow the curvature of the earth?
12. What are two causes of fading?
13. What are the two kinds of static?
14. Explain the difference between the Hertz and the Marconi antenna.
15. What harmonics can be produced on a quarter-wave antenna?
16. How long should a half-wave antenna be for a transmitting frequency of 1,500 kilocycles? **Ans.** 105 meters, or 345 feet.
17. How can losses in the antenna transmission line be reduced ?
18. What should be the length of a resonant transmission line?
19. At what points on the Lecher wire system will the bulb glow brightly?
20. Explain what measurements must be taken in order to determine the wave length in a Lecher system.

CHAPTER 15

TELEVISION

The Cathode-Ray Oscilloscope.—The characteristics of electrical oscillations may readily be analyzed by means of the cathode-ray oscilloscope. A diagram of the cathode-ray tube is shown in Fig. 222. The tube is a highly evacuated envelope that is supplied with electrons from a heater cathode, C; the electrons are accelerated by a positively charged electrode, G_2. By means of repulsive force, a grid, G_1, which is negatively charged, prevents the electrons from leaving the electron stream. A specially

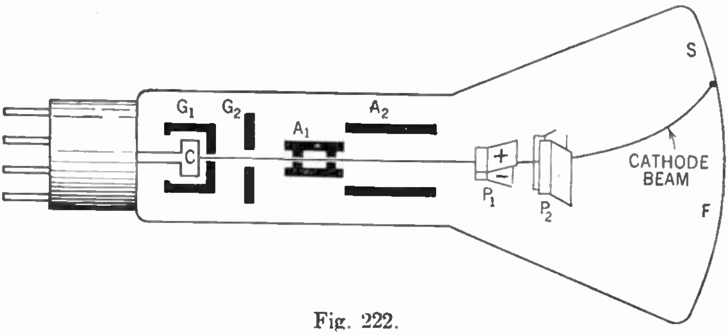


Fig. 222.

constructed anode, A_1, causes the beam to come to a focus. A high-voltage anode, A_2, causes further acceleration of the electrons. That portion of the cathode-ray tube thus far described is known as the *electron gun*. The focused electron stream, or cathode ray, strikes the end of the tube, F, which is coated with a fluorescent substance. By striking the fluorescent screen, the cathode ray causes it to give out light and so forms a bright spot, S, on the screen. Ordinarily the cathode ray travels on a perfectly straight line and so strikes the center of the screen. In this diagram, however, the beam is bent upward by charges on the deflector plates, P_1. By varying the voltage on plates P_1, the bright spot can be made to move in a vertical line over the entire screen. The horizontal deflector plates, P_2, can move the spot along a horizontal line. This method of deflection is known as *electrostatic deflection* because the force that causes the deflection of the cathode ray is electrical. Similar deflections can also be produced by means of two electromagnets that are located outside the tube near its narrow end.

Wave Analysis with the Cathode-Ray Oscilloscope.—The cathode-ray oscilloscope offers many methods for analyzing and measuring electrical oscillations. A simple method of examining the wave form of an alternating voltage is by connecting the terminals of the alternating voltage source to the vertical deflector plates, P_1. The horizontal deflector plates, P_2, are connected to a sweep frequency circuit. A *sweep frequency* is a cyclic change in voltage, though it does not follow a sine-wave relationship. Instead, the voltage increases from zero to maximum along a straight line, then suddenly drops to zero, at which point, after a very short pause, the voltage again increases to a maximum as it did in the first cycle. This operation is repeated several times per second. The cathode ray is now deflected horizontally by the sweep frequency, and vertically by the sine-wave voltage. This causes the cathode ray to describe on the screen a sine wave that is similar to the sine-wave alternating voltage. By comparing this with the pattern produced by an alternating voltage of known characteristics, the various constants of the voltage wave can be determined.

The Photoelectric Effect.—When light falls on any one of a number of substances, electrons are thereupon emitted by that substance. Production of electrons by this means is known as the *photoelectric effect*. The speed of the electrons given off by the substance depends upon the frequency of the light, but not at all on its intensity. The number of electrons emitted is determined by the intensity of the light.

Television.—The transmission and reception of transient visual images by means of electricity is known as *television*. The form of television that is of most interest today is the transmission of visual images by means of radio waves. Problems of television are far more complex than are the problems of sound transmission by means of radio waves. Before we investigate the actual mechanism at present used for television, let us first examine the general approach to the problem of transmitting an image or picture. The picture must first be broken up into sections; next, an electrical impulse that is representative of the light intensity of each section must be sent out. These electrical impulses must be sent to the receiver, and there, in some manner, produce an exact reproduction of the picture. All this must be so rapidly done that the entire picture is reproduced in a time so short that the observer is unable to detect that the picture has not been simultaneously produced. Due to the persistence of vision, if at least fifteen images are presented to the eye each second, they merge into a single image. In order to obtain an image that has a reasonable amount of detail, the picture must be broken up into a large number of parts. By the methods of modern television, the picture is broken up into thousands of parts. Since each part must produce an electrical impulse that is distinct from all the others, and since this must be accomplished in less than one-fifteenth of a second, the difficulty of the task would seem to be almost insurmountable. The process of analyzing the picture into its component parts is known as *scanning*. This was at first accomplished by mechanical means; today, however, the problem is solved according to electronic principles. In addition to accomplishing the foregoing, we must at the receiver also be able to produce exactly and almost simultaneously the light impulses that form an exact image of the picture that is being transmitted. Another problem to be overcome is that of transmitting so many different frequencies. Of course the modulation of a carrier wave can be accomplished for a great many frequencies as well as for a few. The problem here, however, has to do with the width of the sidebands. The total channel required for one television transmitter is 6 megacycles (*i.e.*, 6×10^6 cycles per second). Upon this basis, a single television transmitter would take up all the channels of the present broadcast band. All the problems that have just been mentioned are only a few of the complex and intricate ones that had to be solved before television could be satisfactorily produced. Fortunately, as a result of the exhaustive and marvelous work of radio engineers, all these problems have been satisfactorily solved. In achieving their solution, the electron gun, the cathode-ray oscilloscope, the photoelectric cell, and many other modern devices were all put to some use or other. Any account of the exact details of all these problems lies far beyond the scope of this book. Nevertheless, since the general principles are easy to understand, they will now be explained.

The Iconoscope.—The device in a television transmitter that corresponds to the microphone in a speech transmitter is known as an *iconoscope.* This word literally means *image-viewer.* Fig. 223 shows the general features of an inconoscope. The chief ones are a cathode-ray tube, an electron gun, a photoelectric mosaic, and a lens system. The photoelectric mosaic consists of a screen that is made up of a great number of microscopic photoelectric elements. By means of the lens, the subject (or picture) is focused upon the surface of the mosaic. Light falling upon the minute photoelectric cells causes electrons to be emitted by the photoelectric effect. Since the light over the mosaic varies according to the light that comes from different parts of the subject, the number of electrons emitted by a given photoelectric element is representative of the intensity of the light upon a particular part of the subject. Scanning of the image is accomplished by the electron beam that comes from the electron gun. Starting at the upper left-hand corner, the beam travels horizontally across the mosaic, being guided by means of magnetic or electrostatic deflectors. When the beam finishes the first line, the vertical deflector moves it down a given distance, and there it again travels from left to right across the mosaic. In most modern iconoscopes the beam traces approximately five hundred such lines. As the beam traces its path, it supplies electrons to the photoelectric units in proportion to their loss of electrons due to the photoelectric effect. The amount of electrons taken at any time from the electron beam is measured by a condenser directly behind the mosaic. These pulses are then amplified and conducted to the transmitter, and there they modulate the carrier wave.

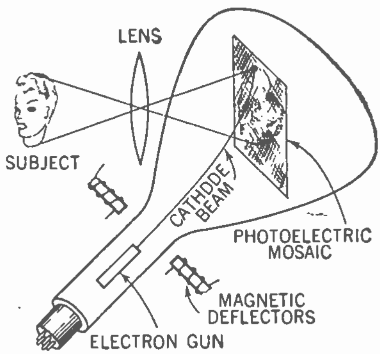


Fig. 223.

The Kinescope.—The television receiver has a device known as the *kinescope* in place of the loud-speaker that is used in sound transmission. The kinescope produces the transmitted visual image. A simple diagram of the principle of this device is shown by Fig. 224. Plainly, this is similar in construction to the cathode-ray oscilloscope. The received impulses that originate in the iconoscope cause the intensity of the cathode beam to vary. Deflectors cause the beam to move across the fluorescent screen in synchronism with the scanning that is being done by the beam in the iconoscope. It must be realized, however, that all this must be done in such manner that the formation of the complete image on the screen of the kinescope shall not require more than one-fifteenth of a second. Modern television apparatus produces the complete image in one twenty-fourth of a second; to do this requires about 5×10^6 impulses per second.

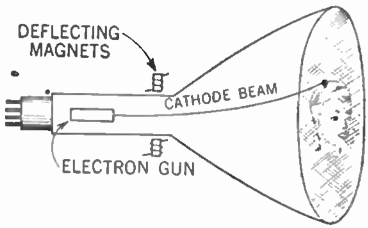


Fig. 224.

The Complete Television System.—The radio transmission of television is similar to that used for sound transmission, though

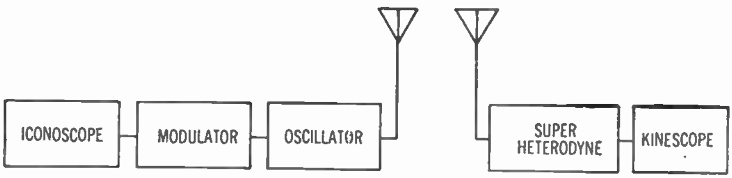


Fig. 225.

more complex. A block diagram of the general idea of a *video* transmitter and receiver is shown in Fig. 225. Variations produced in the iconoscope are fed to a modulator that modulates the carrier wave produced by the oscillator circuit. The receiver is the superheterodyne circuit. Three signals are usually employed. One is used for intensity variations; the other two for controlling the horizontal and vertical deflections, respectively. Since sound commonly accompanies the television, a separate sound transmitter is usually included with a television transmitter. At present, television broadcasting is carried on at ultra-high frequencies. The present channels reserved for television are between 44 megacycles and 108 megacycles. At these high frequencies the transmission is almost direct line transmission. Because of this, the range is necessarily limited to a short distance. Transmitting antennas must be very high. In New York City a television antenna is located on the tower of the Empire State Building. Presumably, within a few years, television will be as commonplace as ordinary radio transmission is today.

QUESTIONS

1. Explain the principle of the electron gun.
2. How does the cathode ray cause the screen to give out light?
3. What causes the cathode ray to be deflected?
4. Explain how the cathode-ray oscilloscope can be used for measuring alternating currents.
5. What is meant by the *photoelectric effect?*
6. What is the function of the iconoscope?
7. Describe the structure of the photoelectric mosaic.
8. Why is it necessary to scan the image on the mosaic?
9. Explain the meaning of persistence of vision.
10. Describe the kinescope.
11. Why is it impossible for television transmitters to operate within the limits of the ordinary broadcast range?
12. About what is the width of the channel of a television broadcast? **Ans.** 6 megacycles.
13. How many signals are used by a television transmitter? **Ans.** Three signals, exclusive of any for the sound.
14. Why must the antenna of a television transmitter be very high?
15. Does static affect television broadcasts?
16. About how many scanning lines are used in the iconoscope? **Ans.** Approximately 500.
17. What determines the number of electrons that are given off by the photoelectric surface?
18. What is the sweep frequency of the cathode-ray oscilloscope?
19. What is the least number of complete pictures that must be produced on the kinescope in one second? **Ans.** 15 images per second.
20. What is the approximate number of pictures actually produced on the kinescope? **Ans.** At the present time, 24 images per second.

CHAPTER 16

SOME APPLICATIONS OF RADIO

Some Other Aspects of Radio.—So accustomed are we to thinking of radio in terms of its entertainment or communication value that we often lose sight of its many other important uses. The number of these applications is steadily increasing; some day they may overshadow the original purpose of the device. Some few simpler adaptations of radio to practical affairs are described below.

Directional Properties of the Loop Antenna.—In the early days of radio communication, it was discovered that a horizontal antenna functions best for a given station when it points in a specific direction. This direction is along a line that passes through the particular transmitting station. Further experimentation with antennas showed that this effect can be made even more pronounced if an antenna in the shape of a rectangular loop is used. The loop, which is in a vertical plane, is rotated about a vertical axis that passes through the center of the loop. Whenever the plane of the loop is along the line to the transmitting station, the reception is best. When the loop is rotated through 90°, so that its plane is perpendicular to the line to the transmitter, no reception at all takes places. This is known as the *null point*. This latter position is the one that is employed when determining direction because it gives more precise results. This is because it is easier to detect small differences in sound intensity for low intensities than it is for high intensities.

Triangulation by Means of Loop Antennas.—It must be borne in mind that although the loop antenna determines the line to the transmitter, nevertheless it indicates neither direction nor the distance from the transmitter. The bearings of a ship at sea can be determined by two direction-finding stations located along the coast. The ship that wants bearings sends out a radio signal that is picked up by the two shore stations. By means of its direction-finding antenna, each station then determines the line to the ship. The distance between the land stations being known, the direction lines from the ship to each of the two stations are drawn on a chart. The ship's position is the point of intersection of the two lines. The position is then read from the chart and radioed to the ship. This method is known as *triangulation* because a triangle is drawn for determining the position of the ship.

The Radio Compass.—If a galvanometer is connected to a loop antenna, the entire device may be used as a *radio compass.* The loop antenna is so mounted that it is perpendicular to the longitudinal axis of the airplane. So long as the airplane is on its course, there is no induction in the antenna; *i.e.*, it is in the null position. This is indicated by the fact that no current flows in the galvanometer; the pointer remains at 0, which is in the center of the scale. If the airplane deviates to the right of the course, the antenna is no longer in the null position and induction takes place. As current flows through the galvanometer, the pointer deflects. The device is so arranged that the pointer deflects to the right when the airplane is off to the right of the course, and to the left when it is off to the left of the course. Thus the aviator is able to keep on the course by correcting his direction whenever the galvanometer deviates from the 0 position. This arrangement is sometimes called a *homing device.*

Radio Beacons.—Where airplanes are flying an established course, radio beacons are employed to keep them on the course. These beacons consist of two transmitting antennas that are located some distance apart. Signals are sent out alternately from the two antennas. The letter *A*, which is a dot and a dash in the International code, is sent out from one antenna. The letter *N*, a dash and a dot, is sent out from the other antenna. If the airplane is on its course, both signals appear equally strong and the sound resembles a single signal. If the plane gets off its course, one or the other signal becomes stronger so that it no longer resembles a single signal. The airplane is then turned back until both signals are again of equal intensity. As soon as the airplane passes one beacon, it picks up another. The beacons are generally about one hundred fifty miles apart.

The Direction Finder.—Although an ordinary loop antenna gives the angular direction of the line along which the transmitter is located, it does not tell the *sense; i.e.*, it does not indicate the direction along the given line. When the antenna is in the null position, the transmitter is along a line that is perpendicular to the plane of the antenna. It is, however, impossible to tell whether the transmitter is in one direction along the line or in the opposite direction. Because of other information that may be available, it is in some instances clear as to where the transmitting station is located. In those cases where it is impossible to make this determination, however, a so-called *sense antenna* is used. This consists of a straight vertical conductor that is coupled to the loop by mutual inductance. This unbalances the loop in such manner that it receives better in one direction than in the other. This gives a method by means of which the sense of the incoming signal may be determined. In order to operate the *direction finder*, the loop, whose sense antenna is disconnected, is rotated until it is in the null position. This determines the line of direction. The loop antenna, with its sense antenna now connected, is swung until it is also along this line. The strength of the signal in this position is then noted. The antenna is then turned through 180 degrees and the signal again noted. From whichever direction the signal is loudest will be the true sense of the incoming wave. A pointer is usually attached to the loop antenna in such manner as to indicate the direction from which the wave is coming. Direction finders are subject to a number of errors. One of these is caused by the antenna's becoming unbalanced with the ground. This can be corrected by using a compensating condenser which produces a balanced condition when the antenna is in the null position. The presence of conductors in the vicinity of the antenna may also cause trouble. If they cannot be removed, then some compensating factor must be brought into play. The ignition of airplane motors may also be a source of interference. This can be eliminated, of course, by means of magnetic shielding. Another serious cause of error is due to the sky wave. It should be borne in mind that the ground wave travels along the surface of the earth, and that the sky wave is reflected back to the earth by the ionosphere. Since the ground wave is traveling horizontally, or parallel to the surface of the earth, it therefore produces induction only in the vertical arms of the loop antenna. Since the reflected sky wave is not traveling in an entirely horizontal direction, some induction takes place in the horizontal portions of the loop antenna. This disturbs the functioning of the direction finder. The effect is worse when the reflected waves are nearly vertical. This occurs when the reflection of the sky wave takes place at high altitudes, usually at night because the ionosphere rises from a distance of about 50 miles in the daytime to about 250 miles at night. This type of error is known as the *night error*.

Radar.—Methods of detecting the presence of hostile airplanes and ships, and of revealing their location, known as *radar*, are carefully guarded military secrets of the United Nations. The efficacy of these methods, however, is no longer a secret. When the time comes for evaluating the causes that enabled Great Britain and the United States to wrest air supremacy from the Axis, radar will certainly stand out as one of the primary factors. Well rewarded are the efforts of those who had the foresight and wisdom to investigate the possibilities of using radio for tracking down enemy aircraft before we had actually entered the war. These early methods have been greatly improved, to be sure, and are now much more extensively applied. It is now possible not only to detect and locate the invisible target, but at the same time to train guns on the objective, both automatically and with a surprisingly high degree of accuracy. Though the Axis nations have developed similar methods of airplane detection, nevertheless those have been found to be highly inferior to our radar. It is gratifying to contemplate the peacetime possibilities of this war-born invention. Just as it has helped to give us supremacy in air combat, so will it also give us safety and security in peacetime aviation. It will remove the remaining hazards of flying. No longer will airplanes of necessity become lost in the fog. Radar will also eliminate human error by substituting ground determination of the location of the airplane for the pilot's judgment which in the past has been the cause of many air tragedies.

Sound Analysis.—Many uses of the cathode-ray oscilloscope have already been explained. Another application of this valuable instrument to radio is its use in the control-room of broadcasting stations. The principle of this device can be understood if we imagine a microphone circuit connected to the vertical deflector plates of the oscilloscope, and a suitable sweep frequency on the horizontal deflector plates. The sound waves striking the microphone cause fluctuations in the microphone circuit. These fluctuations cause vertical deflections of the cathode beam and thus show the characteristics of the sound that falls on the microphone. Before the oscilloscope began to be used for this purpose, the control operator listened with a headset and regulated the output of the modulating circuit so as to give uniform response. This was a purely subjective method. By using the oscilloscope, the control operator has an objective method of controlling the modulator. In this manner, if a speaker varies the loudness of his speech or changes his position with respect to the microphone, the change in the amplitude of the modulation current is detected by the oscilloscope and adequate adjustment can be made so that the modulated carrier wave goes out unaffected and the listener notes no change in the speaker's voice.

The Radio Robot.—Practically everyone recalls early tests in which automobiles were driven without a driver. Operation of the car was controlled by means of radio signals sent out from another car that followed the driverless car. The principle was then applied to ships and finally to airplanes. Development of the radio robot has progressed greatly since those earlier days. Radio-controlled apparatus is today used for a large variety of purposes, from that of turning on and tuning a radio from an armchair on the other side of the room to controlling the path of a torpedo. In the future we may well see many other applications of remote control by means of the use of radio.

Transmission of Power by Means of Radio.—Although transmission line losses have been greatly reduced by the use of high voltages, nevertheless there is still a significant loss of power in long-distance transmission. Wire transmission also involves a large outlay for expensive pole and wire installation. Extensive territory must be acquired for rights of way. Large staffs must be employed for maintaining high-tension lines. Serious interruption of service may occur, due to failure brought about by lightning or other causes. Though the problem of satisfactory transmission of power by means of radio has not as yet been solved, nevertheless it does not seem farther beyond the realm of possibility than did at one time many other scientific theories that have been brought to pass. The solution of this problem would really bring into existence the ideal of superpower. Power developments could be located at sources of energy such as waterfalls, large rivers, and coal mines. The electrical energy could then be sent by radio to local distributing stations.

The Future of Radio.—There can be no doubt that radio will undergo a tremendous development during the next decade. The ideas that have just been advanced may some day be commonplace. In addition, applications which we do not even dream of today may become a reality.

QUESTIONS

1. Name three applications of radio.

2. In what direction does a loop antenna give maximum reception?

3. What is meant by the *null position?*

4. Why is the null position used for determining direction with a loop antenna?

5. Why doesn't the loop antenna determine the sense of the direction?

6. Draw a diagram that shows how a ship at sea may be located by means of two transmitters that are located on the shore.

7. Explain the principle of the *homing device.*

8. Describe the construction of a radio beacon.

9. Why are two signals sent out by a radio beacon?

10. How does the aviator know when he is on the radio beam?

11. Describe the construction of the direction finder.

12. What is the function of the sense antenna?

13. What are the steps to be taken when using a direction finder?

14. Name some of the errors likely to affect the reliability of a direction finder.

15. What is meant by the *night error?*

16. Why does the sky wave produce less effect upon the direction finder during the daytime?

17. What noteworthy achievements have been made possible by radar?

18. Explain how the control operator is assisted by the cathode-ray oscilloscope in determining the loudness of the sound that falls upon the microphone.

19. Describe some uses of the radio robot.

20. Discuss the future of radio.

APPENDIX

LIST OF DEMONSTRATIONS *

1. An introduction to the course may be a demonstration of reception of radiotelephone transmission from loop-modulated (or other type modulated) oscillator in the same or near-by room. No antenna is to be connected to the oscillator.

2. Show the effect on reception of disconnecting the receiving antenna.

3. Show the need for tuning, by detuning transmitter and receiver.

4. Laws of electrostatic attraction and repulsion.

5. Permanent and temporary magnets.

6. Magnetic attraction and repulsion.

7. Properties of electromagnets.

8. Construction and use of demonstration galvanometer.

9. Construction and use of demonstration voltmeter and ammeter.

10. Types of resistors—wire and carbon.

11. Different kinds of series and parallel circuits.

12. Production of alternating current by magneto, using neon bulb to indicate nature of current.

13. Elementary use of oscilloscope (if available).

14. (*a*) Effect of an iron-core coil on flow of direct current through a series-connected lamp. (*b*) Effect of an iron-core coil on flow of alternating current through a series-connected lamp. (*c*) Show effect of removing iron core in demonstration (*b*).

15. Charging and discharging— (*a*) Leyden jar. (*b*) Paper condenser of two or more microfarads.

16. Construction of different kinds of condensers—air, paper, electrolytic, mica.

17. Effect of capacitance on flow of alternating current through a series-connected lamp.

18. Demonstration of resonance of sound.

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* As given in P. I. T. Manual 201, U. S. War Department.

19. Demonstration of resonance tuning receiver to different broadcast stations.

20. Demonstration of resonance by flashlight lamp connected to tuned circuit and coupled to an oscillator.

21. Construction and use of different types of diode.

22. Construction and use of typical tube.

23. Construction of different types of multigrid tube.

24. Audio amplifiers connected to microphone and phonograph pick-ups.

25. Use of oscilloscope (available) to show effect of grid bias on output wave form.

26. Demonstration of effect on reception of lengthening receiving aerial.

27. Demonstration of directional effect of rotating a table model receiver with built-in loop antenna.

28. Operation of different types of receiver.

29. Study of voltage distribution from input to output of an a.c. transformer type-B power supply.

30. Demonstration of wave form of input and output of the above power supply when connected to an oscilloscope.

31. Operation of oscilloscope as outlined.

LIST OF LABORATORY EXERCISES

The following list of exercises has been made specifically for laboratory use. They may be used as demonstration experiments under the following conditions:

(a) To provide, by repetition, more thorough understanding of principles.

(b) To replace laboratory work when apparatus is lacking.

In general, the time allotted to each exercise is 1 period, unless otherwise stated. The instructor may modify this schedule to meet the needs of individual pupils.

1. Wire splicing and soldering: (*a*) methods of joining conductors, (*b*) heating, and (*c*) use of flux.

2. Use of low- and high-scale ohmmeters.

3. Study of low-frequency power transformers.

4. Study of Ohm's law in a.c. circuits involving inductive reactance and resistance.

5. Study of electrical characteristics of several types of condenser.

6. Study of Ohm's law in a.c. circuits involving capacitive reactance and resistance.

7. Resonance at low frequencies, using paper condensers and a choke (2 periods).

8. Construct and test acceptor and rejector wave traps.

9. Construct and calibrate absorption-type wavemeter with flashlight indicator.

10. Determine the relation between plate voltage and plate current of a diode tube with the filament voltage kept constant (2 periods).

11. Determine the relation between filament voltage and plate current of a diode tube (2 periods).

12. Study the relation between plate voltage and plate current of triode tube with grid voltage kept constant (2 periods).

13. Study the relation between grid voltage and plate current of triode tube with plate voltage kept constant (2 periods).

14. Tetrode and pentode tubes: study grid-voltage and plate-current static characteristics (2 periods).

15. Study elementary class A, B, and C audio amplifiers (2 periods).

16. Study transformer-coupled audio-frequency amplifier.

17. Study resistance-coupled audio-frequency amplifier.

CAUTION: *Oscillators are not to be coupled to radiating antennas.*

18. Transformer-coupled audio-frequency oscillator.

19. Hartley radio frequency oscillator (2 periods).

20. Tuned grid, tuned plate, or crystal oscillator.

21. Construct and adjust a transmitter, using an oscillator and screen grid power amplifier coupled to an electric bulb as an output load (2 periods).

22. Construct and operate a loop-modulated oscillator.

23. Construct and operate a radiotelephone transmitter using Heising modulation (3 periods).

24. Construct and operate a crystal detector.

25. Construct and operate a diode detector.

26. Construct and operate a plate detector.

27. Construct and operate a grid-leak detector.

28. Construct and operate a regenerative detector (2 periods).

29. Construct and operate a plate detector with two stages of audio-frequency amplification (resistance or transformer coupled) (2 periods).

30. Construct and test an a.c.-d.c. type of power supply (2 periods).

ABBREVIATIONS AND LETTER SYMBOLS

Alternating current	a.c.
Ampere	a
Antenna	ant.
Audio frequency	a.f.
Automatic frequency control	afc
Automatic tone control	atc
Automatic volume control	avc
Centimeter	cm
Continuous wave	cw
Cycle per second	~
Decibel	db
Direct current	d.c.
Electric field intensity	e.f.i.
Electromotive force	e.m.f.
Frequency	f
Ground	gnd
Henry	h
Intermediate frequency	i.f.
Interrupted continuous waves	icw
Kilocycle (per second)	kc
Kilowatt	kw
Low-frequency	l-f
Magnetic field intensity	H
Megacycle	Mc
Megohm	M Ω
Meter	m
Microfarad (mfd)	μf
Microhenry	μh
Micromicrofarad (mmfd)	$\mu\mu$f
Microvolt	μv
Microvolt per meter	μv/m
Microwatt	μw
Milliampere	ma
Millihenry	mh
Millivolt	mv
Millivolt per meter	mv/m
Milliwatt	mw
Modulated continuous waves	m.c.w.
Ohm	Ω
Power	P
Power factor	p.f.
Radio frequency	r.f.
Revolutions per minute	r.p.m.
Root mean square	r.m.s.
Ultra-high frequency	u.h.f.
Volt	v
Watt	w

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