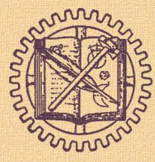
RADIO

A STUDY OF FIRST PRINCIPLES

E. E. BURNS



RADIO

A STUDY OF FIRST PRINCIPLES

For Schools, Evening Classes and Home Study

BY
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I am indebted to Mr. A. J. McMaster of G-M Laboratories, Chicago, for material on photoelectric cells. I am also using certain circuit diagrams through the courtesy of the magazines, " Radio Engineering," " Short Wave Craft " and " Radio Broadcast."

PREFACE

One of the amazing features of the universal interest in radio is the vast amount of technical knowledge that is being absorbed by boys and young men.

A few years ago a prominent electrical engineer in conversation with the writer ridiculed the idea of teaching the principle of electrical resonance in the schools, saying that this principle is one of the most difficult in the electrical engineering course. Today millions are tuning in their radio receiving sets and applying the principle of electrical resonance. Boys have learned something of this difficult engineering principle. They are adjusting inductances and capacities to obtain the desired frequency of oscillation. They are talking freely about microhenries and microfarads and using other terms that once were confined to college textbooks. They know something of the flow of electrons through grid leaks, the electric surge in a coil, and the disruptive discharge of a condenser. They have learned something of the electron theory through their eagerness to know what goes on in the tubes of their receiving sets.

It is worth noting that the popularizing of radio came at a time when physicists had just succeeded in formulating the new theory of the atom. Recent investigations had led up to the electron theory of matter. Electricity and matter had been brought together in a single generalization. New fields of research had been opened up by the discoveries in the field of atomic physics. The control of the electron had brought new developments in engineering fields such, for example, as synchronous converters being replaced by high power electron tubes. These developments will continue.

It is significant that as the need has arisen for a new generation of scientists and engineers to carry forward the work opened up by the discoveries in atomic physics, a popular application of the electron theory has brought about an unprecedented opportunity for training the scientists and engineers of the future. Indeed they are to a large extent training themselves but the schools have the opportunity of utilizing this interest. Never before in the history of science teaching has the interest of pupils been focussed so intensely on a scientific subject.

Mr. E. F. W. Alexanderson, Consulting Engineer of the General Electric Company and of the Radio Corporation of America says:

" We think of radio now as a useful system of communication and a delightful form of entertainment but its greatest significance in the future will be its educational influence. Radio will be the school of training which will educate the engineers, inventors and scientists of tomorrow, not by the thousands but by the millions."

This book is an attempt to present, simply and clearly, the fundamental principles of electricity as applied in radio. It is my belief that the educational value of radio will find increasing recognition, that radio will find a larger place in the schools and that a book giving a simple and clear explanation of fundamental principles is needed. It is my hope also that the book may be of use to radio experimenters who are looking for a simple exposition of radio theory and to those who are well along in experimental work and wish to review the fundamentals.

Such a study necessarily includes the principles of direct currents and of alternating currents of both high and low frequency. All explanations of electrical phenomena in the book are based on the electron theory. Such explanations are as readily understood as others that have been current in textbooks and they have the advantage of being in line with the accepted theory of matter and electricity and of building up in the reader's mind a conception of that theory. Only the simplest mathematical formulae are used and these follow the discussion of the theory. The effort has been to lead the student first to visualize the action that goes on in the radio circuit. When he has done this, mathematical formulae are better understood. The book consists principally of material which I have used for some years in teaching boys of sixteen to eighteen years of age.

In Q.S.T., the official organ of the American Radio Relay League, November 1923, the following statement was made:

" No piece of machinery, no matter what it is, is so complicated but that its action can be thoroughly understood by first studying the fundamental facts and theory. When the underlying principles have been observed, consider the parts one at a time in the order of their importance until the entire mechanism can be viewed with all of its parts working in perfect harmony. This is the way the whole subject of radio should be approached."

The method suggested in this quotation is the method of this text, a study of fundamental principles leading up to their application in radio circuits. I suppose no one ever fully realizes his ideal. I am sure I have not in this instance but I trust the book is sufficiently well done to find a useful place.

PREFACE TO SECOND EDITION

In revising this book I have adhered to the aim stated in the first preface. Fundamentals remain the same. Methods of application change. The superheterodyne has taken precedence of all other receiving circuits. In the screen grid, pentode and variable μ tubes almost perfect control of the electron flow has been achieved. The characteristics of short waves have been more thoroughly investigated. Photoelectric cells, the eyes of television, have been greatly improved. I have attempted to state clearly the first principles of these developments. I have also made additions to the chapter on radio measurements which I hope will increase the usefulness of this chapter.

To the Student who uses this Textbook:

This textbook represents many years of learning and experience on the part of the author. It does not treat of an ephemeral subject, but one which, since you are studying it in college, you must feel will have a use to you in your future life.

Unquestionably you will many times in later life wish to refer to specific details and facts about the subject which this book covers and which you may forget. How better could you find this information than in the textbook which you have studied from cover to cover?

Retain it for your reference library. You will use it many times in the future.

The Publishers.

SUGGESTED COURSE OF STUDY

It is well for the student to begin where his chief interest lies. The great majority of students who take up the subject of radio are interested first of all in the construction of radio receiving sets. While the purpose of this textbook is to teach the fundamentals of radio and not to serve as a handbook on construction work, nevertheless attention is given first to the construction of the basic radio circuits. The student should construct these circuits. For class work where time is limited the work may be prepared for the class by mounting the parts on baseboards. The students then simply wire the circuits according to the diagrams. As the student does this he will come to see that the same parts may be used for different circuits and that the great number of receiving circuits with long puzzling names are only modifications of a few simple, basic circuits.

The student will see the need of understanding the action of the batteries which he uses and this leads to the next step, the study of batteries. He will understand that certain magnetic effects take place in the coils of his receiving set as it operates. He should then study magnetic fields and electromagnetism. Ohm's law is fundamental in all electrical work and should be taken up at this point. The study of the theory of electric batteries and of electromagnetism and Ohm's law may be carried on at the same time that the student is constructing and operating receiving sets. The construction work outlined in Chapter I may be made the laboratory or shop work while the student is studying Chapters II, III and IV.

The student may next take up the testing of tubes as explained in Chapter V. He can construct his own testing circuits as described in this chapter. While carrying on his experiments on tubes he may study the theory of alternating currents. He can be led to see that in certain parts of his receiving circuit he is dealing with currents that do not flow constantly in one direction but surge back and forth and that it is important to know how such currents differ from direct currents. The tube tests of Chapter V may be carried on as shop or laboratory work while studying Chapter VI.

By this time the student has become fairly familiar with the electron theory and is ready for a more thorough study of the action of electron tubes as detectors and amplifiers. A more thorough study of receiving circuits is next in order. This includes the theory of receiving circuits in general and some circuits such as the superheterodyne that are more complicated than those that were studied in Chapter I. By this time the student will understand the meaning of regeneration and may take up the study of oscillators and transmitters which involve the same principle as the regenerative receiving circuit. Chapters VII, VIII and IX, then, may be studied while continuing the tube tests of Chapter V and making some of the measurements of Chapter X.

The subject of radio measurement is taken up in the last chapter. This is done for the sake of method in arranging the textbook material. It is not necessary nor best to delay the subject of measurement until all the other ground has been covered. On the other hand measurements described in the last chapter should be taken up as soon as the student is ready for them. Selections from this chapter should be made according to the needs of the student.

By following the plan outlined above the student will carry forward his construction and experimental work parallel with his study of radio theory.

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CHAPTER I

SIMPLE RECEIVING CIRCUITS

Radio receiving circuits are not difficult to construct if one begins with the circuits that are fairly simple and proceeds by easy stages to those that are more complex. There are only a few fundamental circuits. When these are once learned and the principles of their action understood it is not difficult to go on to the complex circuits for these are only modifications of the few that are fundamental. It is well to begin with the simplest possible radio receiver, that in which a crystal detector is used.

1. **The Crystal Detector.** — A radio receiver may be made of a coil, a crystal detector and a pair of head phones connected to an antenna and ground. The coil should be wound with a number of taps; that is, loops brought out at intervals along the coil. This is shown in Fig. 1.

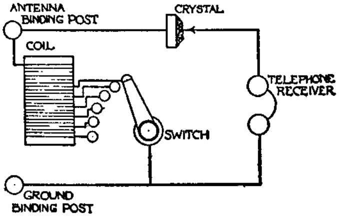


Fig. 1. — A Simple Crystal Detector Receiving Circuit

The antenna should be a copper wire which may be stranded; that is, made up of a number of fine wires twisted together. The antenna should be supported by means of insulators. The insulators may be porcelain cleats such as are used by electricians or the wire may be covered with electrical tape at points where it comes in contact with the building. Rubber covered wire or common bell wire may be used. In this case the wire is already insulated and it is only necessary to fasten the wire to supports and scrape the insulation off the end where it is connected to the receiving circuit. The antenna may be indoors, simply suspended from the ceiling or run along the molding which is usually placed near the ceiling. So far as good reception is concerned the principal advantage an outdoor antenna has over one that is indoors is that it can be placed higher and made longer. An indoor antenna sometimes has the disadvantage of being shielded by the walls. If the wall of a building is a conductor of electricity it forms a shield through which radio waves do not readily pass. On the other hand radio waves go through a non-conducting wall as readily as through air. Walls built of wood do not cut off the waves nor do brick and stone walls when dry. Metal walls cut off the waves almost completely. Brick and stone walls when wet are fairly good conductors and in this condition reduce signal intensity up to ninety percent.

The ground connection may be simply a wire which need not be insulated but must be connected with something that runs to the earth. A water pipe is a good ground connection. An iron rod may be driven into the ground far enough to come into contact with the moist earth and the ground wire or lead as it is called, connected to this rod.

The coil may be made by winding number 22 cotton covered wire on a cardboard tube three inches in diameter, winding 25 turns and bringing out a tap, then continuing the winding and bringing out a tap every five turns up to 50 turns. While number 22 wire is specified, wire of any size, say from number 18 to number 26, may be used. The cardboard tube may be more or less than three inches in diameter. If the diameter is less, more turns of wire will be needed. If more, fewer turns are necessary. These specifications and those that follow are for broadcast receivers to receive signals of 200 to 600 meters wave length.

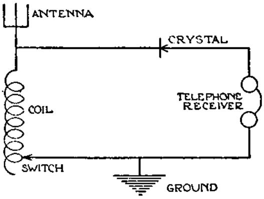


Fig. 2. — Circuit Diagram of Crystal Detector Receiving Circuit

When the coil, antenna and ground are ready, the circuit may be completed as shown in Fig. 1. This figure is a picture diagram. The corresponding circuit diagram is given in Fig. 2. To tune the circuit just described it is only necessary to change the switch from one tap to another until signals are heard.

A better crystal receiver may be made by using a tuning condenser. For a coil of 45 turns the condenser should have a capacity of 0.0005 microfarad. The meaning of the term " microfarad " will be clear when the action of condensers has been studied (Chapters VI and VII). If a tuning condenser is used the taps on the coil are not necessary. The circuit is shown in a picture diagram in Fig. 3 and the circuit diagram is given in Fig. 4.

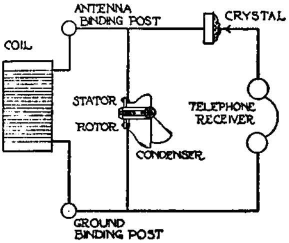


Fig. 3. — Crystal Detector Circuit with Tuning Condenser

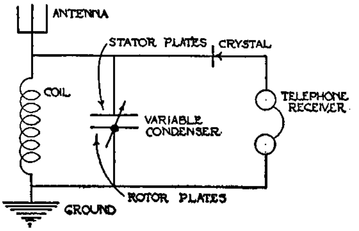


Fig. 4. — Crystal Detector with Tuning Condenser, Circuit Diagram

A further improvement can be made by using two windings, primary and secondary, the primary winding may have 15 turns and should be connected to the antenna and ground only. The secondary winding may have 45 turns and be connected to the crystal and the phones as shown in Figs. 5 and 6. The primary may be wound directly over the secondary.

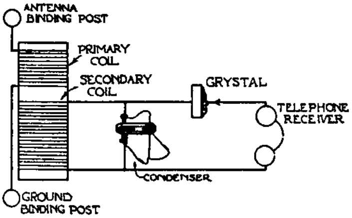


Fig. 5. — Crystal Detector Circuit with Primary and Secondary Windings

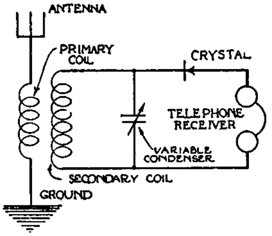


Fig. 6. — Crystal Detector with Primary and Secondary Coils, Circuit Diagram

When the primary and secondary windings are used the impulses received by the antenna are transmitted from the primary to the secondary by magnetic action.

2. A One Tube Detector Circuit. — A simple detector circuit using an electron tube is shown in a picture diagram in Fig. 7, Fig. 8 being the corresponding circuit diagram. The parts may be mounted on a board for practice work or the rheostat, condenser and a jack for the phones may be mounted on a panel. The same coil and condenser may be used as in the crystal detector circuit. The primary winding is in the antenna circuit, connected to the antenna and ground, while the secondary winding is in the grid circuit of the tube, connected between grid and filament. The plate circuit includes the phones and the plate or " B " battery. Care must be taken to connect the " B " battery in the proper way as shown in the

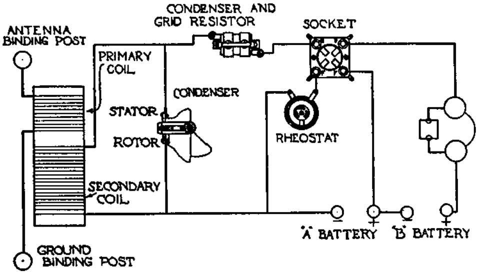


Fig. 7. — A Simple Electron Tube Detector Circuit

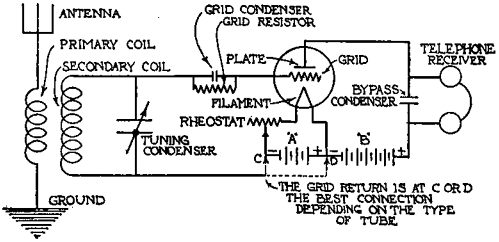


Fig. 8. — Circuit Diagram, Electron Tube Detector

diagram. A single winding could be used as in the crystal circuit of Figures 1 and 2. A single coil used in this manner and combined with a tuning condenser would make a single circuit tuner. It is much better, however, to use the primary and secondary windings because the circuit tunes more sharply.

The circuit just described may be made much more sensitive, which means that it will receive signals from a greater distance, by inserting a variable condenser between the plate and grid circuits as shown in Figs. 9 and 10. This is a regenerative circuit. The meaning of regeneration will be explained in Chapter VIII.

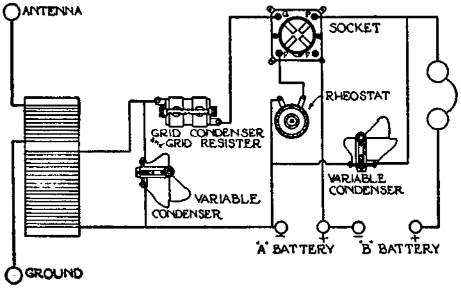


Fig. 9. — A Regenerative Circuit

3. Amplifying the Signals. — The circuits so far described can be used only with head phones. To use a loud speaker it is necessary to amplify the signals. This can be done by adding a second tube coupled in the proper way to the circuit of the

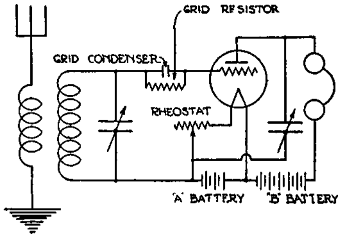


Fig. 10. — Circuit Diagram, Regenerative

first tube. A one tube amplifier is sufficient to reproduce signals from a nearby broadcasting station with sufficient volume for a loud speaker. The distance may be up to about one mile or in certain cases more depending on the power used by the broadcasting station and on atmospheric conditions. Such an amplifier is shown as a separate unit in Fig. 11. It would be well to wire the detector and amplifier units separately and then connect them together in the proper way. By this means the relation between detector and amplifier is made clear. Fig. 12 is a circuit diagram of the amplifier.

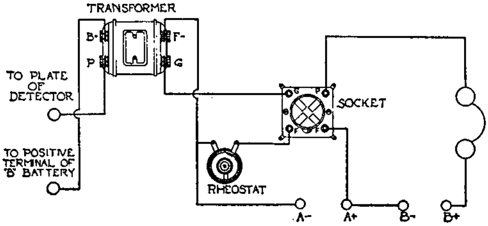


Fig. 11. — An Amplifier Unit

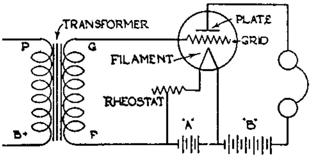


Fig. 12. — Circuit Diagram of Amplifier Unit

The amplifier shown in Figs. 11 and 12 can be connected to a crystal detector as shown in Figs. 13 and 14. It may also be connected to any form of tube detector circuit. The important point to keep in mind is that the output of the detector circuit must be connected to the grid circuit of the amplifier. If a transformer is used as shown in the diagrams the primary of the transformer is connected in the plate circuit of the detector tube, usually between the plate terminal of the tube (marked P) and the positive terminal of the " B " battery. One terminal of the secondary of the transformer is connected to the grid terminal of the amplifier tube. The other terminal of the secondary is connected to the negative terminal of the "A" battery. The rheostat of the amplifier tube is connected between the negative terminal of the "A" battery and one terminal of the filament.

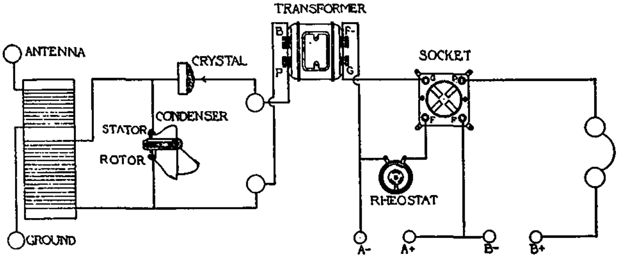


Fig. 13. — Amplifier Connected to Crystal Detector

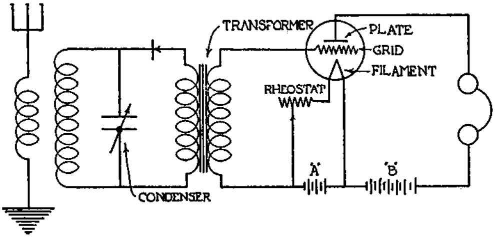


Fig. 14. — Amplifier Connected to Crystal Detector, Circuit Diagram

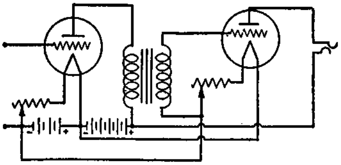


Fig. 15. — Circuit Diagram of a Two Tube Amplifier

Another amplifier tube may be added thus making a three tube circuit. The circuit diagram of a two tube amplifier is given in Fig. 15.

4. Amplifying Before Detection. — The signals may be amplified before reaching the detector tube. This is called radio frequency amplification for reasons which will be explained in a later chapter. A two tube radio frequency amplifier for wave lengths of 200 to 600 meters is shown in Figs. 16 and 17. The transformers of this amplifier may be simply coils wound on a cardboard tube three inches in diameter, the primary having 15 turns and the secondary 40 turns. Cotton covered wire may be used, either number 22 or 24. A variable condenser is connected across the secondary of each transformer. These condensers should be of 0.0005 microfarad capacity. It will be noticed that the output of the radio frequency amplifier; that is, the secondary of the third radio frequency transformer, is connected to the antenna and ground connections of the detector tube circuit. The detector tube receives the amplified signals instead of receiving them directly from the antenna. The advantage of this arrangement is that fainter signals can be detected which means that signals can be received from a greater distance.

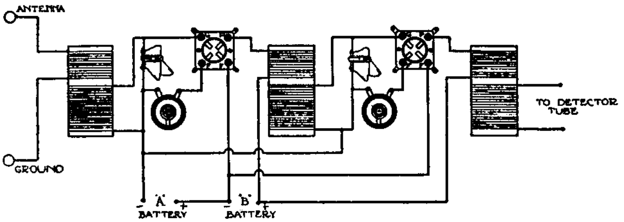


Fig. 16. — A Two Tube Radio Frequency Amplifier

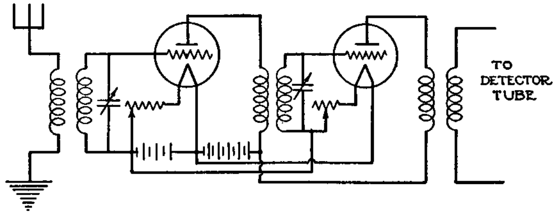


Fig. 17. — Radio Frequency Amplifier, Circuit Diagram

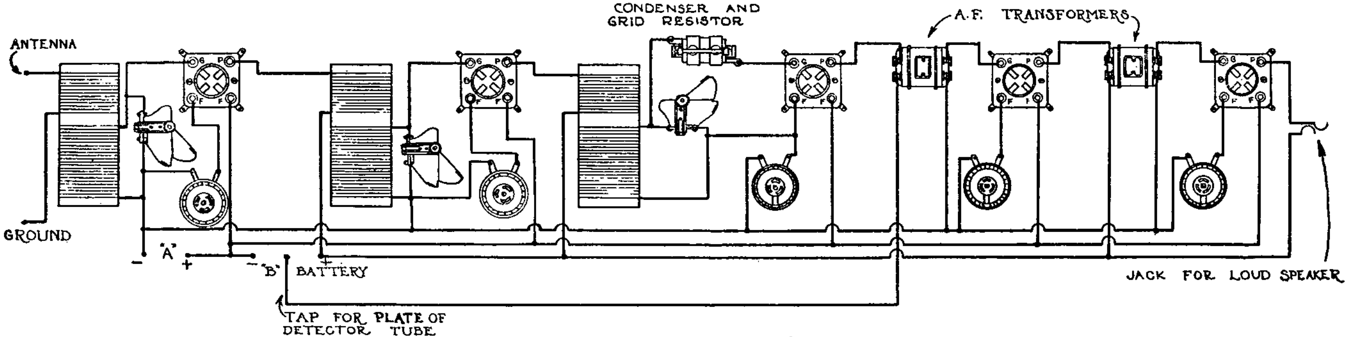


Fig. 18. — Five Tube Receiver

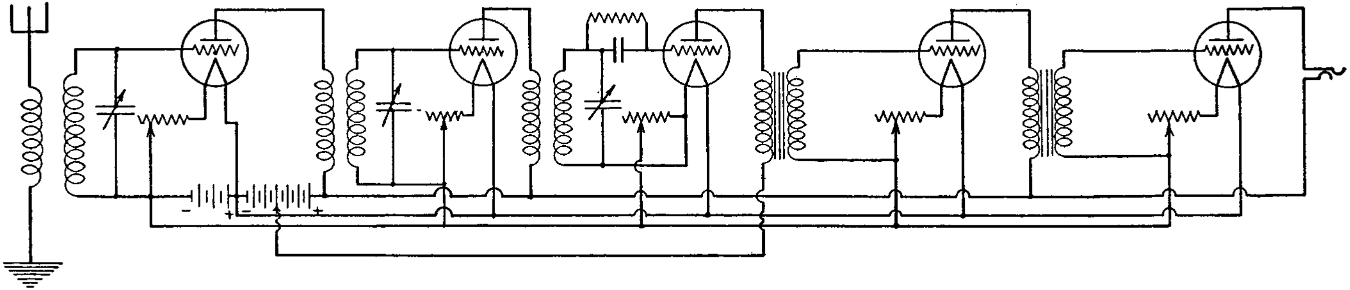


Fig. 19. — Five Tube Receiver. Circuit Diagram

5. Combining Circuits. — Any one of the circuits described may be built on a baseboard for practice work or may be put in a cabinet making a complete radio set. The radio frequency amplifier described in Section 4 may be combined with the three tube circuit described in Section 3 making a five tube receiver. This is a good practical receiver. Fig. 18 shows the complete circuit in a picture diagram and Fig. 19 gives the conventional wiring diagram.

The circuits so far described are all fundamental circuits. These fundamental circuits can be combined in various ways. For example: a radio frequency amplifier can be connected to a crystal detector and this followed by an audio frequency amplifier, making a four tube and crystal circuit.

Thus far we have had the simple crystal detector, the one tube detector both regenerative and non-regenerative, the crystal detector with audio frequency amplifier, two types of three tube circuits, a four tube and crystal circuit having both a radio frequency and an audio frequency amplifier and a five tube circuit of the type known as a tuned radio frequency circuit.

Questions

1. Draw a diagram of a simple crystal detector circuit.
2. Draw a diagram of a simple non-regenerative circuit using one tube.
3. Draw a diagram of a regenerative circuit.
4. Draw a diagram of a three tube circuit.
5. Draw a diagram of a five tube circuit using both radio frequency and audio frequency amplification.
6. What advantage has an outdoor antenna for a broadcast receiver?

CHAPTER II

ELECTRIC BATTERIES

It is important now to study the action and uses of the various elements that make up a radio receiver. A thorough mastery of the principles on which a radio receiver operates forms a good foundation for engineering and scientific work. First of all we shall study the batteries which furnish current for the radio receiver.

6. Uses of Electric Batteries. — Electric batteries are commonly used for producing electric currents where a current is needed for only a short time or where a comparatively weak current is needed for a longer time or where steadiness and absence of ripple are of great importance. In a radio circuit the filament battery commonly called the " A " battery furnishes current to heat the filament in the tube. Storage batteries were used for this purpose almost exclusively until tubes were invented that required only a small current for the filament. Dry cells may now be used as filament batteries with certain tubes because the current required is small. With such tubes a dry cell battery will last a hundred hours or more. The first cost is much less than that of a storage battery and the inconvenience of charging the battery is avoided. Dry cells are especially useful in portable receiving sets. With tubes requiring stronger current dry cells are not practicable. This is true if the current for all the tubes taken together is one ampere or more. The ampere is the unit of current.

In electric bell circuits and certain burglar alarm circuits dry cells are sometimes used. In these circuits the current flows at infrequent intervals and then for only a few seconds at a time. In other alarm circuits a form of wet battery is used which is capable of giving out a small current for a very long time. Batteries may be used to furnish a weak current or to furnish a strong current for a short time. An example of a very strong current furnished by a battery for a short time is the current used in the starting motor of an automobile. For this a storage battery is used. For a few seconds while starting the engine this battery gives out from 200 to 500 amperes or more than two hundred times as much current as that which flows through the filament of an ordinary electric bulb such as is commonly used in house lighting.

For electric lighting and other circuits in which a strong current is used for a long time batteries are impractical. For such circuits a current from a dynamo is used.

7. **Materials Needed to Make a Battery.** — A simple experiment illustrates the construction of an electric battery. Place between a dime and a penny a piece of blotting paper or other porous paper which has been moistened in a solution of common salt. Now place a sensitive ear phone to the ear and touch one of the phone tips to the dime and the other to the penny. A click will be heard in the receiver. An electric current has been produced, very weak it is true, but strong enough to affect the telephone receiver. Water from the faucet may act as well as salt water for water from wells or lakes usually contains mineral substances in solution. If a radio loud speaker is at hand this experiment can be demonstrated to a class by using the tips of the cord connected to the loud speaker.

In this experiment two different metals are used. The dime consists mostly of silver and the penny mostly of copper. Together with these metals a solution is used which acts chemically on the metals and tends to dissolve the copper more rapidly than the silver. This illustrates the principle of all electric cells. A cell consists of two plates of different metals or of carbon and a metal and a solution of an acid or other compound that has a stronger chemical action on one of the plates than on the other.

8. **A Simple Voltaic Cell.** — One of the simplest electric cells is made of a rod or strip of copper and one of zinc placed in a dilute solution of sulphuric acid. A battery of such cells was made by Alexander Volta in Italy in the year 1800. This was the discovery of the first known means of producing an

electric current. Our knowledge of electric currents began with Volta's discovery and it is for this reason that a cell of this type is called a voltaic cell.

In the voltaic cell (Fig. 20) the acid attacks the zinc much more than it does the copper. When the cell is producing a current the zinc is rapidly eaten away. This chemical action is closely connected with the flow of the electric current as we shall see. If we connect the copper and zinc plates of this cell with a copper wire a current flows. Evidence of this current is seen in the bubbles that collect around the copper plate. The copper plate is said to have a positive electric charge and the zinc plate a negative charge. It is customary to think of the current as flowing from the copper to the zinc through the connecting wires and from the zinc to the copper through the solution in the cell.

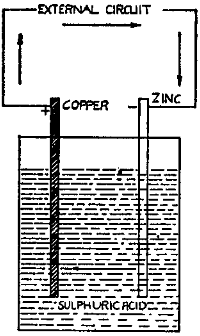


Fig. 20. — A Simple Electric Cell

Any two metals might be used for the plates of the cell or any metal could be used for one plate with carbon for the other plate. Other solutions might be used in place of sulphuric acid. The essential parts of an electric cell are two plates of different metals or of a metal and carbon and a solution of a substance that will act chemically on one plate more vigorously than on the other. Of course certain materials are better than others. For example: Carbon and zinc give a stronger current than copper and zinc through the same circuit.

If a dry cell is connected to an electric bell and a push button, as shown in Figs. 21 and 22, when the button is pressed the bell rings. Pressing the button closes the circuit. There is then a complete path or circuit along which the current can flow. The circuit in this case is made up of the plates and the solution in the cell, the coils and other conducting parts in the bell, the push button and the connecting wires. When the push button is not being pressed the circuit is open, the current cannot jump across the gap. In order to get a current from a battery there must be a closed circuit made up of materials that will act as electrical conductors.

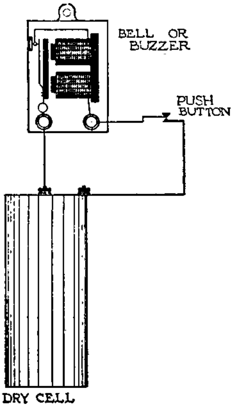


Fig. 21

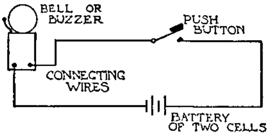


Fig. 22

9. Action Within the Cell. — When the voltaic cell is in action, bubbles may be seen collecting on the copper plate. These bubbles consist of hydrogen. The hydrogen travels through the liquid in the cell from the zinc to the copper plate in particles so small that they cannot be seen. These invisible particles are called ions. An ion is an atom or a group of atoms carrying an electric charge. When the cell is producing an electric current there is a stream of positive ions flowing to the copper plate and a stream of negative ions flowing to the zinc plate.

The chemical action of the acid on the zinc is expressed in the following equation:

$$Zn + H_2SO_4 \longrightarrow ZnSO_4 + H_2$$

Zinc + Sulphuric Acid become Zinc Sulphate + Hydrogen.

A similar action goes on in any electric cell. The substance in the solution is known as the electrolyte. The molecules of the electrolyte break up into positive and negative ions. The positive ions go to one plate and the negative ions to the other. The plate to which the negative ions go is the one that is eaten away more rapidly.

10. Theory of the Electric Current. — It is the belief of scientists that an electric current consists of a flow of extremely small negative charges of electricity called electrons. As we go on in our study of radio we shall have a great deal to say about electrons for, in order to understand radio or for that matter any other branch of electricity it is necessary to know something of their action.

Though atoms are so small that they cannot be seen even with the help of the most powerful microscope, electrons are very much smaller than atoms. An atom is composed of a number of electrons which are negative, grouped around a nucleus which is positive. The electrons are in rapid motion revolving around the nucleus. Perhaps the best picture we can get of the inside of an atom is that it is like the sun and the planets, the nucleus being in the center and the electrons revolving around the nucleus as the earth and other planets revolve around the sun.

An electron is a very small negative charge of electricity. There are also very small positive charges of electricity which are called protons. The nucleus of an atom contains more protons than electrons and is therefore positive. In every atom there are electrons revolving around the nucleus. If there are just enough electrons revolving around the nucleus to balance the positive charge of the nucleus then the atom is neutral; that is, it acts as if it did not have any electric charge. If the atom has more electrons than it needs to balance the positive charge of the nucleus it is negative. If it has fewer electrons than the nucleus requires, the atom is positive.

In an electric cell the hydrogen ions are positive because the atoms of hydrogen have given up some of their electrons.

An electric current in a wire is a flow of electrons. Some of the electrons may flow from one atom to another, some may flow between atoms, some may even flow through atoms as a comet may go through the solar system. The electron may dash in and out without attaching itself to the atom. Whatever the individual electrons may do, an electric current in a wire is a stream of electrons flowing through the wire. This is the theory held by physicists and it is the theory that enables us best to understand the various kinds of electric action with which we have to deal, whether in radio or any other branch of electricity.

When we connect the copper and zinc plates of a voltaic cell with a wire the current is said to flow along the wire from the copper to the zinc. What really happens is that a stream of electrons flows through the wire from the zinc to the copper. Before the discoveries were made that led to the electron theory physicists believed that it was the positive electricity that flowed along the wire and therefore it became the custom to say that the current flows from copper to zinc. This custom cannot well be changed so we must still speak of the current as flowing from the positive terminal of the cell to the negative but it is well to bear in mind that the thing that really flows in the wire is a stream of negative electrons from the negative to the positive terminal of the cell.

11. Electromotive Force and Current. — In an electric circuit such as a bell circuit the electric cell produces a force which keeps the electrons moving in the circuit. This force has been called by Mr. John Mills an electron-moving force. The term commonly used is electromotive force. There can be no current without an electromotive force. The abbreviation commonly used for this force is e.m.f. We shall have frequent occasion to speak of the e.m.f. of a circuit.

Electromotive force is measured in volts. The simple voltaic cell produces an e.m.f. of about one volt, the dry cell of about one and one-half volts. The terms voltage and difference of potential are sometimes used in place of electromotive force.

The strength of an electric current is measured in amperes. An ampere is a certain rate of flow of electrons. If the current is two amperes, twice as many electrons per second are flowing around the circuit as if the current were one ampere. To take a real example: A certain detector tube requires a filament current of one ampere. Another tube requires only one-fourth ampere. In the second tube only one-fourth as many electrons flow through the filament in one second as in the first tube.

The greater the electromotive force in a given circuit the greater is the current. We might state this in a different way by saying that the greater the force which causes the electrons to move the greater will be the stream of electrons flowing around the circuit.

12. The Dry Cell. — The dry cell is especially important in radio work because of its use for plate batteries and for filament batteries with tubes of low amperage. A dry cell has an e.m.f. of about one and one-half volts regardless of its size. The small dry cells used in flash-lights and in plate batteries have the same voltage as the larger dry cells. A three-volt flash-light requires two dry cells. Fifteen dry cells are required to make up a battery of 22½ volts. Fig. 23 shows the construction of a dry cell.

The larger dry cells used for door bell circuits and for filament batteries will give from twenty to thirty amperes when connected directly to an ammeter while the smaller dry cells used for flash-lights and for plate batteries will give only four or five amperes. The reason for this will be explained in Chapter IV, Sections 23 and 24.

13. Polarization. — In the dry cell hydrogen collects on the carbon plate just as in the simple voltaic cell it collects on the copper plate. When the hydrogen ions have given up their positive charges to the carbon plate they are of no further use in helping the current to flow. In fact they are an actual hindrance to the current. The effect of the hydrogen in weakening the current is called polarization. To remove the hydrogen from the carbon plate a black powdered substance known as manganese dioxide is used.

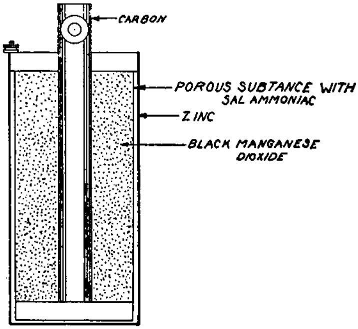


Fig. 23. — Showing the Construction of a Dry Cell

14. The Storage Cell. — The storage cell is like all other cells in this respect: It consists of two plates of different materials and a substance in solution which attacks one of the plates more than it does the other. The negative plate is lead and the positive plate is lead peroxide. The electrolyte (See Section 9) is a dilute solution of sulphuric acid. When the storage cell is discharging; that is, giving out a current, lead sulphate is formed on the negative plate. The action on the positive plate is somewhat complicated but the result of it is also the formation of lead sulphate. The net result is that as the cell discharges both plates are reduced to lead sulphate; that is, a surface layer of lead sulphate is formed on each plate. When the cell is being charged the reverse action takes place.

The chemical equation which shows the net result of the reactions when the cell is discharging is as follows:

$$\overset{\text{Negative plate}}{\mathrm{Pb}} + \overset{\text{Positive plate}}{\mathrm{PbO_2}} + \overset{\text{Electrolyte}}{2\mathrm{H_2SO_4}} \longrightarrow \overset{\text{Both plates}}{2\mathrm{PbSO_4}} + \overset{\text{Water}}{2\mathrm{H_2O}}$$

Lead + lead peroxide + sulphuric acid become lead sulphate + water.

The chemical action of the cell when being charged is as follows:

$$\overset{\text{Both plates}}{2PbSO_4} + \overset{\text{Water}}{2H_2O} \longrightarrow \overset{\text{Negative plate}}{Pb} + \overset{\text{Positive plate}}{PbO_2} + \overset{\text{Electrolyte}}{2H_2SO_4}$$

Lead sulphate + water become lead + lead peroxide + sulphuric acid.

One of these equations is exactly the reverse of the other. The storage cell differs from other cells in just this respect, that the action can be reversed. When the cell is discharged an electric current can be sent through it and the plates and electrolyte restored to their original condition. This cannot be done with any other cell.

Observing the first equation we see that the electrolyte is reduced to water as the cell discharges and that sulphuric acid is again formed as the cell is charged. Since sulphuric acid is denser than water it is possible to determine the state of charge or discharge by testing the density of the solution.

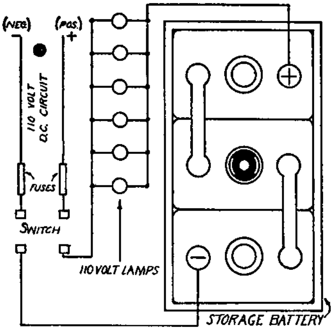


Fig. 24. — A Storage Battery Connected for Charging

In charging a storage cell the current must be sent through it in the direction opposite to that of the discharging current. This means that the positive terminal of the cell must be connected to the positive line wire and the negative terminal to the negative line wire. Figure 24 shows a storage battery connected for charging, the current in the line being direct. If the current is alternating a rectifier is needed as explained in Chapter VI, Sections 76, 77 and 78.

15. Care of a Storage Battery. — A storage battery should not be allowed to become completely discharged. If by chance it is completely discharged it should not be allowed to stand for any length of time in that condition. The reason is that both the positive and negative plates have a surface layer of lead sulphate and this substance will crystallize if allowed to stand. When the lead sulphate has crystallized the battery is practically useless.

The battery should be frequently tested with an hydrometer to determine its state of charge. The hydrometer indicates the density of the electrolyte. By means of a rubber bulb a small quantity of the liquid is drawn up in a glass tube. A small hydrometer floats in the liquid in this tube. The more dense the liquid the higher it raises the hydrometer. If the cell is completely discharged the hydrometer may sink to the bottom. A scale marked on the hydrometer indicates the density of the solution. If the cell is fully charged the line marked 1,280 will be at the surface of the liquid. This means that the density of the solution is 1.28; that is, a certain volume of the solution would weigh 1.28 times as much as the same volume of water. For a battery used for automobile ignition a density of 1,300 is safe. For a radio battery the density should not go above 1.28. It is best to recharge the battery before the density drops below 1,185.

A lead storage cell gives a current of from 200 to 500 amperes on a short circuit. A storage cell cannot be tested with a pocket ammeter such as is used for testing dry cells because the strong current would burn out the instrument. Special ammeters capable of carrying 200 amperes or more are made for testing storage cells.

The voltage of a lead storage battery on open circuit is about 2.2 volts for each cell and this voltage is approximately the same for a cell partly charged as for one fully charged so that a voltage test cannot be used to test the extent to which the battery is charged.

The chief characteristic of the storage battery required for radio use is that it should give a constant voltage when discharging because even small changes in voltage produce noises in the phones. In some storage batteries for radio use constant voltage is attained by designing the cell so that the electrolyte will circulate freely over the surface of the plates. To this must be added special care in making the plates uniform in their chemical composition. A radio storage battery may be considered fully charged when the hydrometer reading is 1,250. This is even better than 1,280 because with the lower hydrometer reading the voltage of the battery will remain more nearly constant than if the density is allowed to go higher.

If a storage battery is to be left unused for a number of weeks it should be left fully charged for if left uncharged crystals of lead sulphate will form on the plates. This reduces the voltage, increases the resistance and shortens the life of the battery.

If a battery is not to be used for a considerable period of time, say a number of months, it should be put in " wet storage." To do this the battery should first be fully charged, then put in a dry place on wood strips so that air can circulate all around the battery. Vaseline should be applied to all the exposed metal. It is advisable if possible to place the battery on trickle charge, that is connect it to a charging circuit with a resistance so that it will be charging continuously at a very low rate, say half an ampere. If this cannot be done, the battery should be charged until all the cells are gassing, about once every two months. The level of the electrolyte should be kept above the plates by adding distilled water.

16. Ampere Hours. — Storage batteries are rated in ampere-hours. For example, an eighty ampere-hour ignition battery would deliver a current of ten amperes for eight hours. Such a battery would not, however, deliver eighty amperes for one hour. If the discharge rate is too rapid the number of ampere-hours that may be obtained from the battery is reduced. An example of a rapid rate of discharge is an automobile battery when operating the starting motor. The battery is then operating practically on short circuit. According to rules adopted by the National Electrical Manufacturers Association, the ampere-hour rating of an " A " battery is based on the rate (measured in amperes) at which the battery will discharge in 100 hours down to a cut-off voltage of 1.75 volts per cell, the cell temperature being 80 degrees Fahrenheit. The rating of a storage " B " battery is based on the same conditions except that the time is 200 hours. The battery must deliver current at its rated capacity until it has been charged and discharged three times. Otherwise it is considered to be improperly rated.

Questions

1. Why is it that dry cells will give a continuous current for many hours through the filaments of certain radio tubes while such cells could not be used for continuous current in an alarm circuit?
2. What is the difference between an ion and an electron?
3. A worn out dry cell battery will sometimes work well for a short time after the circuit is closed and then stop working. Why?
4. Why can the state of charge of a lead storage cell be determined by means of a hydrometer?
5. Why should a lead storage battery not be allowed to stand completely discharged?
6. Why might a storage battery suitable for automobile ignition not be satisfactory in a radio circuit?

CHAPTER III

MAGNETIC ACTION OF AN ELECTRIC CURRENT

We have seen that an electric current consists of a stream of electrons flowing in a wire or other electrical conductor. The reader must keep this idea in mind all the way along if he is to understand what goes on in an electrical circuit.

Wherever there is an electric current there is around that current a force which we call magnetic. Electrons in motion always produce a magnetic force. We could not receive radio signals if it were not for the magnetic force of the current that flows through the telephone receivers. There could be no radio transmission, no power for electric motors if it were not for the magnetic action of an electric current.

17. Magnetic Field and Lines of Force. — If iron filings are sprinkled around a steel magnet the filings arrange themselves in definite lines around the magnet. These lines mark out the direction of the magnetic force. If a small magnetic compass is placed near the magnet it will place itself parallel to the filings.

A magnetic compass is simply a small magnet mounted on a needle point so that it can turn freely. Any suspended magnet tends to place itself in a position nearly north and south. The position it takes is not the same at all places on the earth. At some places it would point exactly north and south while at other places it would be considerably out of the north and south line. In general a suspended magnet tends to place itself so that one end points toward the north magnetic pole of the earth and the other end toward the south magnetic pole. The end which points toward the north magnetic pole is called the north-seeking pole of the magnet and opposite end the south-seeking pole. These names are commonly abbreviated and we speak of the north and south poles of the magnet. The earth acts like a great magnet and the suspended magnet tends to place itself along the magnetic lines of force of the earth.

18. Magnetic Action of a Current in a Straight Wire. — If a wire through which a current is flowing is placed in a vertical position and a number of small magnetic compasses are placed around it the compass needles will arrange themselves so that they mark out a circle. If the wire is grasped with the right hand so that the thumb points in the direction of the current the fingers point in the same direction as the north poles of the compasses. It is as if the electrons as they flow along the wire produce a whirl of force around the wire (Fig. 25). If we could arrange matters so that the magnetic force would act on only one pole of the magnet, that pole would move in a circle around the wire as long as the current continued to flow. If the current is reversed the compasses turn round and point in the opposite direction. There is still a whirl of force but it has changed direction.

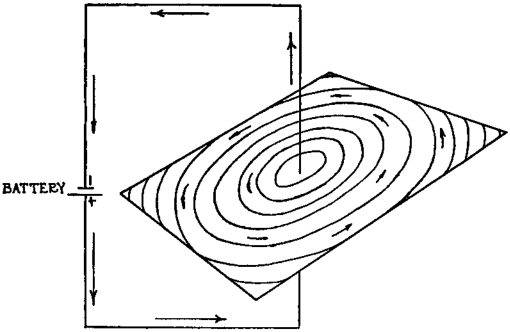


Fig. 25. — Electrons As They Flow Produce a Whirl of Force Around the Wire

19. Magnetic Action of a Current in a Coil. — If the wire is wound in a coil the lines of force around the different turns of wire unite and form straight lines within the coil. Outside the coil these lines curve around from one end of the coil to the other (Fig. 26). The coil acts as if it were a bar magnet, one end being a north pole and the other end a south pole. The north pole of the coil will attract the south pole of a compass needle and the south pole will attract the north pole of a compass needle.

If the coil is grasped with the right hand, the fingers pointing in the direction of the current, the thumb will point in the direction of the north magnetic pole of the coil.

If a bar of iron is placed in the coil when a current is flowing, the iron becomes magnetized. This forms an electromagnet. The magnetic strength of a coil with an iron core is very much greater than that of the coil alone.

According to the molecular theory of magnetism each molecule of iron is a magnet having a north pole and a south pole. When the iron is magnetized the molecules are so arranged that the greater number of them have their north poles pointing in one direction. When practically all the molecules are lined up with their north poles in one direction the magnet is said to be saturated. Its magnetic force cannot be made any greater.

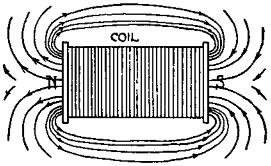


Fig. 26. — Magnetic Force Around a Current Carrying Coil

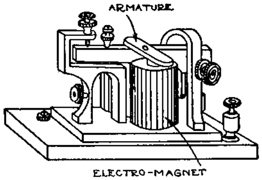


FIG. 27. — Whenever a current is passed through a telegraph sounder, the coil and its iron core become magnetized drawing down the iron armature. The armature makes the familiar click when it strikes its stop.

Different forms of iron differ greatly in the ease with which their magnetization can be changed. Tempered steel retains its magnetization for a long time if carefully handled while annealed silicon steel easily loses its magnetization.

The property of a magnetic substance by which its magnetization is changed by a magnetic force is called permeability. Soft iron has greater permeability than hard steel.

If a bar of iron is placed in a coil in which a current is flowing, the magnetic force produced by the current causes the molecules of the iron to try to turn so that their north poles all point in one direction. This could be illustrated by placing a number of small magnetic compasses in the coil. The compasses all point toward one end of the coil when a current is flowing. If the current is reversed the compasses all turn round and point in the opposite direction showing that the poles of the coil have changed. Likewise if there is a bar of iron in the coil its molecules try to turn around when the current changes direction.

The magnetic action of a coil is a matter of very great importance in radio work. In the coils of a receiving set and in the transformers there are currents that rapidly change direction and the magnetic effects of these currents are very important. These effects will be discussed more fully in later chapters.

20. Power Lost in Magnetizing and Demagnetizing Iron. — Suppose we have an electromagnet as shown in Fig. 28, with a current flowing in the direction shown by the solid arrows.

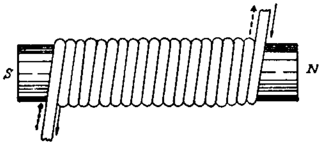


Fig. 28. — An Electromagnet

Then the end N is a north pole and S a south pole. As the current increases in strength the magnetic strength of the iron increases up to a certain limit. If we gradually decrease the current the iron loses some of its magnetic force but when the current is reduced to zero the iron still has some magnetic force. If the current is reversed so that it flows in the direction of the dotted arrows, when the current reaches a certain strength the magnetic force of the iron is zero. When the iron is magnetized by a magnetic force in one direction it requires a force in the opposite direction to demagnetize it. If the current continues to flow in the direction of the dotted arrows the iron becomes magnetized again but its poles have changed. If we reduce this current to zero the iron still retains magnetic force and we must again reverse the current to demagnetize it. The magnetic force of the iron lags behind the current. The molecules of the iron do not easily change their position. It requires a certain force to change them. Some of the energy of the electric current is used in changing the magnetism of the iron.

Soft iron and annealed silicon steel offer less opposition to changing magnetism than tempered steel and less than harder forms of iron. Soft iron and silicon steel, therefore, consume less of the energy of the current than other forms of iron. This is a matter of importance in making transformers, particularly those used in radio work.

The lagging of the magnetic force of the iron is called hysteresis (pronounced hy̆steresis). The electrical energy used up in changing the magnetization of the iron is known as

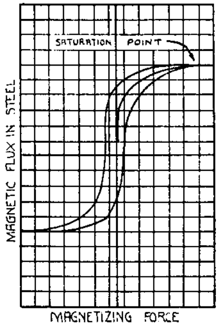


Fig. 29. — Hysteresis Curve for Annealed Silicon Steel

the hysteresis loss. This is only one of the ways in which electrical energy is lost in transformers, motors and generators.

A hysteresis curve for annealed steel is shown in Fig. 29.

In this graph the abscissas (values of X) represent the strength of the current and the ordinates (values of Y) represent the magnetic force of the iron. In other words the abscissas represent the magnetizing force acting on the iron since in any given coil this force is proportional to the current and the ordinates represent the flow of magnetic force in the iron itself. Fig. 30 is a hysteresis curve for hard steel. This curve shows that for hard steel it requires a much stronger reversed current to reduce the magnetism of the steel to zero than it does in the case of annealed steel. This means that more energy is lost in the case of the hard steel than in the case of the annealed steel. This is shown by the greater area between the two parts of the curve in the case of the hard steel.

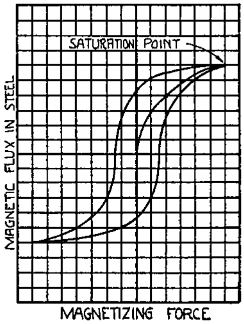


Fig. 30. — Hysteresis Curve for Hard Steel

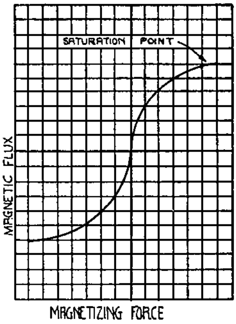


Fig. 31. — Ideal Hysteresis Curve

An ideal hysteresis curve is shown in Fig. 31. This is the curve that would be obtained if it were possible to have a kind of steel or iron for which there would be no hysteresis loss. In this case if the magnetizing current were reduced to zero the magnetic strength of the iron would drop to zero and no force would be needed to demagnetize the iron.

Questions

1. What is meant by magnetic lines of force? What is meant by the magnetic field?
2. What is the form of the lines of force around a straight wire through which a current is flowing?
3. What is the form of the lines of force around a coil through which a current is flowing?
4. What is an electromagnet?
5. How is power lost in an electromagnet?
6. What is meant by hysteresis?
7. Is hysteresis a desirable quality in the iron cores of transformers used in a radio circuit?

CHAPTER IV

ELECTRIC CIRCUITS AND OHM'S LAW

The student cannot go far in his study of radio without a knowledge of the measurements that are to be made in testing electric circuits. In a radio circuit as well as in any other electric circuit there are several quantities to be measured. There are two ways of making and operating a radio receiver or transmitter. One is by merely trying different coils, condensers and so forth until something is found that works fairly well and the other is knowing what one is using, knowing the values by one's own measurements or reliable measurements made by others. The first is a haphazard, cut-and-try method which might be compared to a surveyor stepping off the distances instead of measuring them in laying out city blocks or farms. No one would buy land laid out in such a careless fashion. The second is an accurate scientific method like that of the surveyor who gets his directions with a compass, lays his lines with a cross-staff, measures his distances with a chain and computes the areas from a base line. It is accurate work only that gives the thing permanent value.

In this chapter we shall take up only such measurements as can be applied to a direct current such as a current from a battery. Measurements for the high frequency currents of radio circuits will be given in a later chapter. These cannot be understood until direct current measurements are mastered.

21. Units of Electromotive Force, Current and Resistance. — The unit of electromotive force is the volt which is about the electromotive force of a simple voltaic cell. The electromotive force of a dry cell is about 1.5 volts and of a lead storage cell about 2.2 volts.

The unit of current is the ampere. One ampere is a certain rate of flow of electricity. If water is flowing through a pipe at the rate of one gallon per second then one gallon per second is the strength of the current of water. The gallon is the unit of quantity and one gallon per second is the unit of current. In a similar way one ampere is the flow of a certain quantity of electricity per second. The unit of quantity of electricity is named a coulomb and an ampere is a flow of one coulomb per second. The coulomb is not used so frequently as the ampere in electrical calculations. The rate of flow is the important thing.

We have seen that an electric current is a stream of electrons. An ampere, therefore, is a unit for measuring a stream of electrons. It is well to keep the idea of electrons constantly in mind because of its importance in understanding radio circuits. Electrons are very small, much smaller than atoms. So small are they that, if we have lighted the filament of a tube which takes a current of one ampere, electrons are flowing through the filament at the rate of about six billion billion per second. In figures the number would be 6,000,000,000,000,000,000. How were they counted? We cannot take space to explain that here. We can only say that the amount of electric charge that constitutes one electron has been measured and it would take six billion billion such charges to make the same quantity of electric charge as that which flows in one second when the current is one ampere.

Resistance in an electric circuit is that which opposes the flow of current. It is measured in ohms. One ohm is the resistance of a conductor through which an e.m.f. of one volt will cause a current of one ampere to flow. A number 18 copper wire 156 feet in length has resistance of approximately one ohm.

22. **Conductors and Insulators.** — In electric circuits use is made of certain materials to conduct the current. Such materials are called electrical conductors. Other materials are used to prevent the electricity escaping from a wire or other conductor. Such materials are called insulators. Copper wire is a familiar example of a conductor and the rubber covering on the wire used in house wiring is a familiar example of an insulator. There is no material that is a perfect conductor and no material that is a perfect insulator. Some materials, however, allow such a small quantity of electricity to escape or leak

through them that for practical purposes they may be considered perfect insulators. All metals are good conductors as compared with most other materials but some metals are better conductors than others. Silver is the best conductor but for obvious reasons it cannot be used in practical work. A table of some common materials in order of conductance, is given below. Silver, which has the highest conductance, is placed first. The table shows the conductance of the other materials as compared to silver. For example, the conductance of copper is $\frac{92}{100}$ that of silver.

Silver	100
Copper	92
Gold	67
Aluminum	56
Brass (copper and zinc)	28–41
Zinc	27
Nickel	21
Tin	14
Platinum	13
Soft steel	12
Lead	7
Mercury	7
Nickel steel	5
German silver (copper, zinc and nickel)	3.5–7.5
Manganin (copper, manganese and nickel)	3.5

23. Ohm's Law. — To make the filament in the tube in a radio circuit glow more brightly the rheostat must be turned so as to reduce the resistance in the circuit. To dim the filament the rheostat must be turned so as to put more resistance in the circuit. This illustrates one way of varying the strength of the current. Increasing the resistance reduces the current. Reducing the resistance increases the current. The current is reduced in proportion as the resistance is increased.

Another way of changing the strength of the current is to change the electromotive force. For example, if we connect more cells in series in a circuit the current will be increased.

This fact is sometimes learned by beginners in radio work in a very expensive way. The plate battery of 90 volts or more is by mistake connected across the filament terminals of a tube which is intended to operate on an e.m.f. of from four to six volts. The result is a current so strong that it quickly burns out the filament of the tube.

If the resistance of a circuit remains the same and the electromotive force is doubled the current is doubled. If the e.m.f. is reduced one-half the current is reduced one-half.

We may illustrate this law by comparing an electric current with a current of water. If water is flowing through a pipe there is pressure which causes the water to flow and resistance or opposition to flow. If the pressure is made greater the rate of flow is greater as when a fire engine applies extra pressure to force a stronger current through the hose. On the other hand if the opposition is greater the flow is less as when the nozzle of the hose is nearly closed.

$$\text{Rate of flow} = \frac{\text{Pressure}}{\text{Opposition}}.$$

It is the same in an electric circuit. Current or rate of flow is greater if electrical pressure or voltage is greater and less if opposition or resistance is greater.

Expressed in words:

$$\text{Current} = \frac{\text{Voltage}}{\text{Resistance}} \qquad \text{or} \qquad \text{Amperes} = \frac{\text{Volts}}{\text{Ohms}}.$$

Expressed in symbols:

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

It is clear from the above equation that if we know the e.m.f. and the resistance of a circuit we can compute the current that will flow. We can find also the e.m.f. required to cause a given current to flow through a given resistance or we can measure the current and e.m.f. of a circuit and compute the resistance. In fact Ohm's law is one of the most useful principles in radio as well as in all other electrical work.

24. Some Examples of Ohm's Law. — Let us consider the filament circuit of a single tube in a radio receiver. The circuit includes filament, battery, rheostat and connecting wires as shown in Fig. 32. Suppose we find that the voltage across the

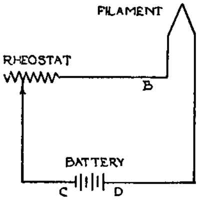


Fig. 32. — Filament Circuit

filament from D to B is 5 volts and the current is one ampere. Then the resistance of the filament is 5 divided by 1 or 5 ohms. If the voltage across the filament and rheostat taken together is 6 volts and the current 1 ampere, the resistance of filament and rheostat taken together is 6 ohms. In this case we have one ohm of resistance in the rheostat. Now suppose we have a tube which takes $\frac{1}{4}$ ampere of current when the voltage across the filament terminals is 5 volts and the rheostat has been adjusted to give the proper filament voltage, then the filament resistance is 5 divided by $\frac{1}{4}$ or 20 ohms. If there is a voltage drop of 6 volts across filament and rheostat taken together, which would be the case if we were using a six volt battery, then the resistance of filament and rheostat is 6 divided by $\frac{1}{4}$ or 24 ohms. Then we have 4 ohms of resistance in the rheostat. It is clear from this example that the tube which takes $\frac{1}{4}$ ampere requires a higher resistance in the rheostat than the tube which takes one ampere.

It will be noticed that in finding the resistance of the filament in the above example we took the voltage across the filament only and the current through the filament. In finding the combined resistance of filament and rheostat we took the voltage across both together. This illustrates an important rule to be observed in applying Ohm's law. If we are applying Ohm's law to part of a circuit we must take voltage, current and resistance for that part of the circuit only. If we are applying Ohm's law to an entire circuit we must take the voltage, current and resistance for the entire circuit.

Ohm's law may be applied to an electric cell as well as to any other electric conductor. Suppose we wish to find the internal resistance of a dry cell. The voltage must first be measured with a voltmeter. Suppose this is 1.5 volts. Then an ammeter capable of carrying a current of 25 amperes or more must be connected directly across the terminals of the cell. Let us suppose the ammeter gives a reading of 20 amperes. The ammeter forms practically a short circuit across the cell. In other words the external resistance is practically zero and the resistance of the cell itself is practically the entire resistance of the circuit. The resistance of the cell is by Ohm's law $\frac{1.5}{20} = 0.075$ ohm. If a similar test is made with a small flash-light cell it will be found that the current on short circuit is only four or five amperes while the voltage is the same as that of the large dry cell. Therefore the smaller dry cell has the greater resistance.

25. Unit of Power. — We may compare electric power with water power. Suppose the water of a water-fall is driving a water wheel or turbine. The power developed depends on the pressure of the water; that is, the height of the water-fall and the rate of flow of the water. The hydro-electric plant at Keokuk, Iowa, operates on comparatively low pressure, the water falling only about thirty feet, but it develops very great power on acount of the great quantity of water per second that flows through the turbines. In contrast with the Keokuk plant is a plant in Norway operated by a water-fall with a very small flow of water but which develops great power because of the great height, about nine hundred feet, over which the water falls. In a similar way great electric power can be developed in either of two ways, by means of great electrical pressure or by means of a strong current. In other words, the power may be increased either by increasing the voltage or by increasing the amperage.

Electric power is measured in watts or in kilowatts. If an e.m.f. of one volt causes a current of one ampere to flow through a conductor the power is one watt. The number of watts of power in an electric circuit is found by multiplying volts by amperes.

$$\text{Watts} = \text{volts} \times \text{amperes}$$

or, letting P stand for power,

$$P = EI.$$

A kilowatt is one thousand watts. " Kilo " always means one thousand. In lighting and power circuits where the watt is too small a unit to be used conveniently the kilowatt is used.

There are two other forms of the power equation that are sometimes convenient to use. From Ohm's law we have,

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

and

$$E = IR.$$

Substituting for I in the power equation already given, we have

$$\begin{aligned} P &= EI \\ &= E \cdot \frac{E}{R} \\ &= \frac{E^2}{R}. \end{aligned}$$

Substituting for E in the first power equation, we have

$$P = I^2R.$$

From the last equation it is clear that in a circuit in which the resistance remains constant the power consumed is proportional to the square of the current. If the power is all consumed in producing heat, as in an electric heater, the heat produced is proportional to the square of the current.

26. Series Circuits. — In the filament circuit of a receiving set of one tube (Fig. 32) we have a battery, rheostat, the filament of the tube and the connecting wires all connected in series. There is only one path for the electric current. Such a circuit is called a series circuit.

Each part of the circuit offers a certain resistance to the current. The resistance of the entire circuit is the sum of the separate resistances. Suppose, for example, the filament has a resistance when hot of 5 ohms, the battery a resistance of 0.05 ohm, the connecting wires a resistance of 0.1 ohm and that the rheostat is set so that it has a resistance of 2.5 ohms. Then the resistance of the entire circuit is the sum of all these resistances or

$$5 + 0.05 + 0.1 + 2.5 = 7.65 \text{ ohms.}$$

Another important fact regarding the series circuit is that the current is the same in every part of the circuit. If three ammeters were connected in the circuit at the points marked D, B, and C (Fig. 32) they would indicate the same current.

The voltages across the different parts of a series circuit depend on their resistances. If we connect a voltmeter to the terminals of the battery (DC Fig. 32) it will indicate the terminal voltage of the battery. If two other voltmeters are connected, one across the terminals DB to give the filament voltage and the other across BC to give the voltage drop across the rheostat, the sum of the readings of these two voltmeters will equal the reading of the first. The filament does not get the full voltage of the battery but the voltage across the filament plus the voltage across the rheostat equals the voltage across the terminals of the battery. This illustrates one law of voltage in a series circuit. The entire voltage across the circuit is equal to the sum of the voltages of the conductors taken separately.

Another important fact is that if a current is put through a small resistance and a large resistance in series, there will be a much larger voltage across the high resistance than across the low one. If the high resistance, for example, is 1000 ohms and the low resistance is 5 ohms, then with a current of one ampere the voltages will be 1000 volts and 5 volts respectively. In Fig. 32 if the filament has a resistance of 5 ohms and the rheostat a resistance of 2.5 ohms, the voltage across the filament will be twice the voltage across the rheostat. If the entire voltage across filament and rheostat is 6 volts, the voltage across the filament will be 4 volts and that across the rheostat 2 volts. Suppose we turn the rheostat knob until the rheostat has a resistance of 5 ohms, then, since the resistance of the filament and rheostat are equal the voltage will be equally divided between them and each will have a voltage of three volts.

We may sum up the laws of series circuits as follows:

1. The resistance of the entire circuit is the sum of the separate resistances.
2. The current is the same in all parts of a series circuit.
3. The voltage across a series circuit is the sum of the voltages across the parts of the circuit.
4. The voltages across the high resistances in a series circuit are greater than across the low resistances and in the same proportion as the resistances.

27. Parallel Circuits. — In a radio receiving set the filaments of the vacuum tubes are usually connected in parallel. Let us take, for example, a circuit having a detector tube and two amplifying tubes as shown in Fig. 33. If the filament of each tube takes one-fourth ampere of current, the entire current delivered by the battery is three-fourths ampere. The total current in a parallel circuit is the sum of the currents in the separate parts.

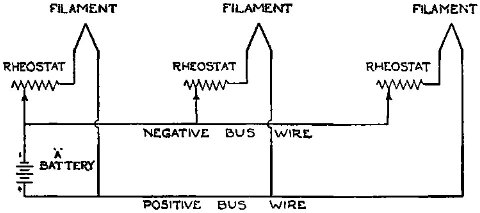


Fig. 33. — Filaments Connected in Parallel

One wire from the positive terminal of the battery leads to one terminal of each filament. We call this the positive bus wire. Another wire leads from the negative terminal of the battery to the rheostat, the rheostat being connected between this wire and the other filament terminal. This is the negative bus wire. The voltage on the bus wire is practically the same for all the filaments and is the same as the voltage at the battery terminals. This is true if the bus wires have very low resistance. The voltage is the same for any number of tubes as for one tube.

Ohm's law may be applied to each of the filaments. The current flowing through each filament equals the voltage across the bus wires divided by the resistance of the filament and its rheostat. Having the separate rheostats makes it easy to control the current in each filament independently of the others.

The laws of parallel circuits may be stated as follows:

1. The total current is the sum of the currents through the parts of the circuit.
2. The voltages are equal across all parts of a parallel circuit.
3. The combined resistance is less than the resistance of any part of the circuit.

For a more complete discussion of resistances in parallel circuits see appendix.

28. **Ammeters.** — In the ammeters commonly used for measuring direct current, the coil is mounted on a shaft which is supported on jeweled bearings like the bearings of a watch. The coil, therefore, moves with very little friction. A spring like a watch spring is attached to the coil and the mounting at each end. The coil is set at an oblique angle with relation to the lines of force of the magnet. When a current flows through the coil the coil tries to turn so as to place its lines of force parallel to those of the magnet but the springs tend to hold it back. The stronger the current flowing through the coil the farther it can turn against the action of the springs. A pointer attached to the coil moves over a scale marked to indicate the current strength. To make the magnetic field uniform a soft iron cylinder is supported within the coil. The iron cylinder remains stationary and the coil moves in the small space between the cylinder and the pole pieces of the magnet.

Since the coil of the ammeter is of very fine wire and can carry only a small current, a shunt must be used to enable the instrument to measure a large current. When a shunt is connected across the coil the greater part of the current goes through the shunt and only a small part through the coil. Suppose the shunt has $\frac{1}{9}$ as great resistance as the coil. Then the shunt will have nine times as strong a current as the coil. In other words the shunt will take nine-tenths of the total current and the coil one-tenth. Since the coil and shunt are in parallel the laws of parallel circuits apply.

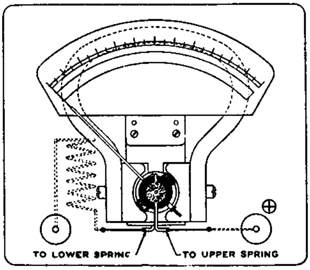


Fig. 34. — Showing Construction of a Milliammeter

Ammeter shunts are usually inside the instrument though with some instruments external shunts are provided. The scale of the instrument is usually marked to indicate the total current which is the current through coil and shunt together.

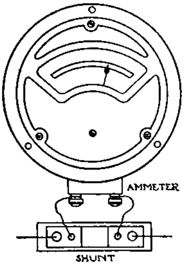


Fig. 35. — Ammeter with Shunt

A galvanometer is a specialized relative of the ammeter made extremely sensitive, usually to measure millionths of an ampere or microamperes. A milliammeter measures thousandths of an ampere. A milliammeter can be used as an ammeter by providing it with suitable shunts.

Since an ammeter is used to measure current it must be connected in the circuit whose current is to be measured so that the entire current will flow through it. Always connect an ammeter in one side of the line, never across the line.

29. Hot Wire and Thermocouple Ammeters. — A form of ammeter frequently used in radio work operates by means of the heating effect of an electric current. The essential part of the instrument is a wire of platinum through which the current flows. The current heats the wire and the wire expands. As it expands it allows a pointer to be moved over a scale by a spring. The stronger the current the more the wire expands and the farther the pointer moves.

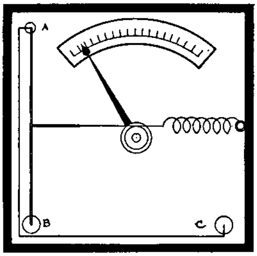


Fig. 36. — Showing the Principle of a Hot Wire Ammeter
AB is the Platinum wire, B and C are the external connections

In a thermocouple ammeter the sensitive element is a junction of two unlike metals. The principle of the thermo-couple can be illustrated by twisting together one end of an iron wire and one end of a copper wire. The other ends of the two wires are connected to a milliammeter and the twisted joint heated over a flame. The milliammeter needle will move, showing that a current is produced by heating the junction of the two metals. It is also true that when a current flows across the junction of two different metals heat is produced. With certain metails this effect is noticeable with very weak currents.

The current flowing in the antenna circuit when strong signals are being received can be measured with an electron tube and milliammeter (Sec. 169).

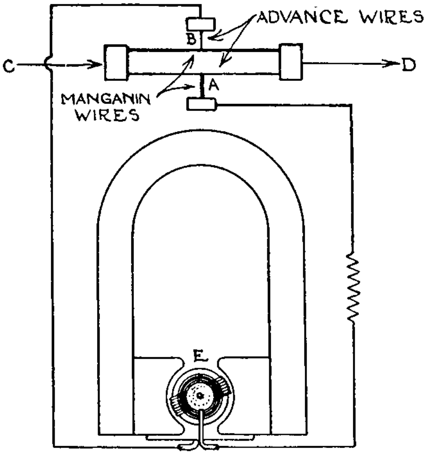


Fig. 37. — Showing the Principle of a Thermocouple Ammeter

A and B represent two thermocouples. Current flowing from C to D heats the parallel wires A and B. This heating causes a current to flow through the two junctions. This current flows through the milliammeter.

30. Voltmeters. — A voltmeter is used to measure the difference of electric pressure between two points in an electric

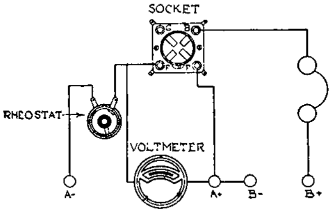


Fig. 38. — Voltmeter Connected for Testing Filament Voltage

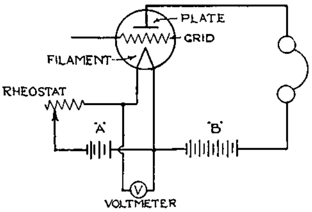


Fig. 39. — Circuit for Testing Filament Voltage

circuit. The difference of potential is commonly called voltage. The term " voltage drop " is also frequently used. In a radio set it is important to test both the filament voltage and the plate voltage. To test the filament voltage the voltmeter must be connected across the filament terminals of the socket. See Figs. 38 and 39. To test the plate voltage the voltmeter must be connected to the plate terminal of the socket and the negative filament terminal. See Figs. 40 and 41.

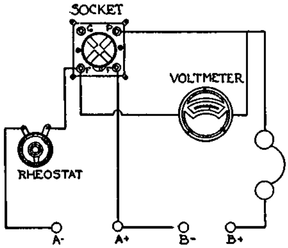


Fig. 40.—Voltmeter Connected for Testing Plate Voltage

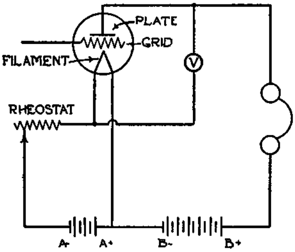


Fig. 41.—Circuit for Testing Plate Voltage

The rule for conecting a voltmeter is: Always connect a voltmeter across the line if the voltage of the entire line is wanted or across the terminals of the part of the circuit for which the voltage drop is to be measured.

If a milliammeter were connected across the line the current through the meter would be so strong that it would instantly burn out the meter coil. To prevent this a high resistance is placed in series with the coil. The milliammeter with its resistance can then be connected across the line and used to measure voltage. A voltmeter is simply a milliammeter having a high resistance in series with it and its scale graduated in volts.

Suppose the coil of the milliammeter is able to carry only one-hundredth of an ampere and the instrument is to be built to measure any voltage up to 120 volts. Enough resistance must be placed in series with the coil so that when the voltage across the terminals is 120 not more than one-hundredth of an ampere will flow. By Ohm's law

$$E = IR$$

$$120 = 0.01\ R$$

$$R = \frac{120}{.01} = 12{,}000 \text{ ohms.}$$

The high resistance is usually placed inside the voltmeter and connected in series with the coil. The scale of the instrument is graduated so that as the pointer turns it indicates the voltage across coil and resistance together, in other words the voltage across the terminals of the instrument.

Some voltmeters are provided with an external resistance called a multiplier. With an additional resistance connected in series a higher voltage is required to turn the pointer one division on the scale and therefore the instrument will measure a higher voltage. For example, suppose a voltmeter is so designed that 120 volts across its terminals will cause the pointer to move across the scale. If a resistance is added so that the total resistance is ten times as great as at first, it will require ten times as great a voltage or 1200 volts to move the pointer across the scale. With this additional resistance or multiplier the instrument will measure any voltage up to 1200.

Some current, of course, flows through the voltmeter but since its resistance is high this is a very small fraction of the main current, so small that the electric bulb or other device that is being tested is not affected.

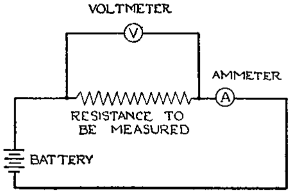


Fig. 42. — Circuit for Measuring Resistance, Voltmeter Ammeter Method

31. Measuring Resistance. Voltmeter Ammeter Method. — The simplest method of measuring the resistance of a conductor is by means of a voltmeter and an ammeter. If the voltage across the conductor and the current flowing through the conductor are measured it requires only a very simple application of Ohm's law to find its resistance. For example, suppose we find that a current of 0.25 ampere is flowing through the filament of a certain tube when the voltage across the filament is 5 volts. Then we have by Ohm's law,

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

$$R = \frac{5}{.25} = 20 \text{ ohms}$$

32. Measuring Resistance. Wheatstone Bridge Method. — The method described in Section 31 is a rough and ready method useful where great precision is not required. Where precision is important the Wheatstone bridge is used. Most resistance measurements in radio work are made with a special form of Wheatstone bridge which will be described in Chapter X.

The ordinary Wheatstone bridge consists of four resistances connected as shown in Fig. 43. The current from the battery divides at A, one part flowing along the path ABD, the other along the path ACD, the two branches uniting at D and flowing back to the battery. If the points B and C are at the same potential; that is, the same electric pressure, then, when the key is closed, no current will flow through the milliameter.

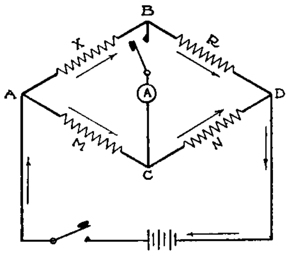


Fig. 43. — Diagram of Wheatstone Bridge

Let I_1 be the current through the path ABD and I_2 the current through ACD. By Ohm's law the voltage drop in any part of a circuit equals the current times the resistance of that part of the circuit. The voltage from A to B, therefore, equals I_1X, voltage from B to D equals I_1R, voltage from A to C equals I_2M, and voltage from C to D equals I_2N. Now since voltage from A to B equals voltage from A to C, we have the equation,

$$I_1X = I_2M.$$

For a similar reason we have

$$I_1R = I_2N.$$

Now dividing the first equation by the second, we have

$$\frac{I_1X}{I_1R} = \frac{I_2M}{I_2N}$$

Cancelling I_1 and I_2 we have

$$\frac{X}{R} = \frac{M}{N}$$

From this we get

$$X = R \cdot \frac{M}{N}.$$

This is the Wheatstone bridge equation. X is the unknown resistance which is to be measured, R is a known resistance and M and N are two resistances whose ratio is known. M and N are called the ratio arms of the bridge.

33. Resistance Boxes and Special Forms of Wheatstone Bridge. — A resistance box is commonly used for the known resistance in Wheatstone bridge measurements. It consists of a number of different coils of wire each having a known resistance. The coils are connected to brass bars on the top of the box. The bars may be connected by round tapering plugs which can be easily removed. Each plug when in place between two bars short circuits the coil. Removing the plug throws the coil into the circuit. The resistance can be adjusted to whatever value is desired by removing different plugs.

The simplest form of Wheatstone bridge is the slide wire bridge (Fig. 44). The point C is a sliding contact which is moved along the resistance wire ACD until a point is found for which there is no deflection of the milliammeter. The ratio

M/N is, then, the ratio of the lengths of the two parts of the resistance wire.

A form of Wheatstone bridge which has the advantages of accuracy and rapid work is the dial bridge. The two ratio arms are controlled by one dial. Turning this dial corresponds to moving the sliding contact in a slide wire bridge. The ratios in a common form of dial bridge are 1:1, 1:10, 1:100, 1:1000, 10:1, 100:1, 1000:1. The known resistance, R, is adjusted by means of four dials. If R is one ohm, X may be as small as 0.001 ohm. R may be as high as 1111 ohms and X may be 1000 times R. With this bridge, then, any resistance from 0.001 ohm to 1,111,000 ohms may be measured.

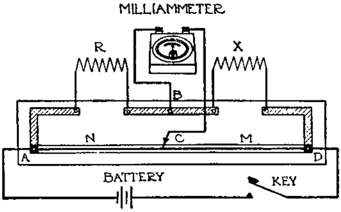


Fig. 44. — Wheatstone Bridge. Slide Wire Form

Questions

1. The filament of a certain tube takes 0.06 ampere when connected to two dry cells in series. What is the resistance of the filament?
2. If three dry cells in series are used with this tube what resistance is needed in the rheostat?
3. What is the internal resistance of a plate battery of 45 volts which delivers 5 amperes on short circuit?
4. How many watts of power does the radio tube of questions 1 and 2 consume?
5. What is the resistance of the entire circuit in question 2?
6. If three such tubes as that of question 1 are connected in series what voltage is needed for the filament? What voltage if the tubes are in parallel?
7. How must an ammeter always be connected?
8. How must a voltmeter always be connected?
9. State the principle of the hot wire ammeter and of the thermocouple ammeter.
10. Explain the principle of the Wheatstone bridge.

CHAPTER V

ELECTRON TUBES

We have seen that an electric current is a stream of electrons flowing in an electric conductor. A stream of electrons may also flow through free space if there are no molecules or very few to block the way. In other words electrons can flow readily through a vacuum. Since electrons are negative they will flow in a vacuum from a negative to a positive electrode. It is on this fact that the action of an electron tube depends.

34. Electrons from a Heated Filament. — An electric current is a stream of electrons. When an electric current is flowing in a wire, electrons are rushing along striking atoms and knocking off other electrons or dodging between atoms or even going through them. An electron is very much smaller than an atom. The smallest known atom, that of hydrogen, has a weight about 1800 times as great as that of an electron. An electron is the smallest charge of electricity that has been found to exist. Atoms are made up of positive and negative charges, the nucleus of the atom being positive and having electrons or negative charges revolving around it. Atoms are always in motion but when there is a stream of electrons in the wire it makes the atoms move faster. If a wire is connected to the terminals of a battery, the electrons that happen to be free so that they can move start rushing toward the positive terminal of the battery. As they rush along through the wire they collide with some of the atoms, giving up some of their energy to the atoms and increasing their vibration. This increased vibration of the atoms is heat. The heating of a wire when connected to a battery is due to the action of electrons. The energy the electrons lose in moving through the wire is transformed into heat energy. The greater the stream of electrons the greater is the resulting vibration of the atoms. In other words, the stronger the current the greater is the heating effect. This leads us to the next step in understanding the action of a vacuum tube.

When a wire is heated, whether by an electric current or by any other means, the atoms are set in more rapid vibration and this vibration causes some of the electrons to escape from the wire. The number of electrons escaping from the wire is small until the wire becomes red hot. If there is air or any kind of gas around the wire, the escaping electrons cannot go very far. Most of them are quickly forced back into the wire.

In one kind of electric light bulb, the common " Mazda," a tungsten filament is heated by the current. The space within the bulb is a nearly perfect vacuum. There is practically no gas to prevent the electrons escaping from the wire, therefore the electrons continue to escape until the bulb contains all the electrons it can hold for the temperature of the filament. When this condition is reached, electrons continue to escape from the wire but just as many go back into the wire so that the number of electrons in the tube remains practically constant. The space within the tube may then be said to be " saturated." If the filament is made hotter more electrons escape from the wire than return to it until the space is again saturated for the higher temperature. The accumulation of electrons around the filament is called in radio the " space charge." So far as the escape of electrons from the filament is concerned, it does not matter by what means the filament is heated but, of course, the only practical means of heating the filament in a vacuum tube is an electric current.

35. The Two-electrode Tube. — Suppose we have in the tube, in addition to the heated filament, a plate of metal connected to a wire which passes through the glass and is sealed into it. If we connect this plate to the positive terminal of a battery and connect the negative terminal of the battery to the filament as shown in Fig. 45, then the electrons in the tube are attracted to the plate because the plate is positive and the electrons are negative. What happens now is that the electrons that escape from the filament, instead of scattering throughout the tube, move to the plate. There is also a flow of electrons through the wire from the plate to the positive terminal of the battery, through the battery in the manner explained in Chapter II and from the negative terminal of the battery to the filament. In other words there is an electric current and the stream of electrons from the filament to the plate within the tube is part of the current. This is called the plate current. The circuit through which this current flows consists of the battery, the wire connecting the battery to the filament, the filament, the space in the tube between filament and plate, the plate and the wire connecting plate to battery. This circuit is known as the plate circuit.

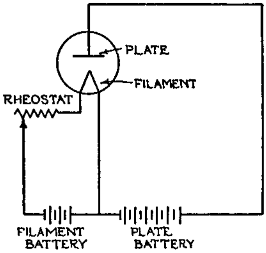


Fig. 45. — Circuit for Two-electrode Tube

Since the plate is at a low temperature, practically no electrons are given off from it so that if we reverse the battery connections making the plate negative and the filament positive, no current will flow in the plate circuit. The circuit is then open because electrons cannot go from the plate to the filament.

Since a two-electrode tube will allow current to flow in one direction only, it can be used to rectify alternating current. How this is done will be explained in Chapter VI.

36. The Three-electrode Tube. — In the vacuum tubes used in radio transmitting and receiving circuits there is a third electrode known as the grid. This is a lattice work or sometimes a loose coil of fine wire placed between the filament and plate. If the grid is made positive it attracts electrons from the filament as the plate does. Suppose we have a circuit as shown in Fig. 46. We have now three batteries. The filament battery serves only to heat the filament. The battery in the plate circuit makes the plate positive so that a stream of electrons will flow from the filament to the plate. If now we connect a battery in the grid circuit as shown in Fig. 46, so as to make the grid positive, then the grid will attract more electrons from the filament. Since the grid is nearer to the filament than the plate is, its attraction for the electrons counts for more than that of the plate. The stream of electrons is greatly increased. Only a few of these electrons are caught by the grid. Since the grid is open the greater number of them rush on through to the plate. Thus the plate current is increased by making the grid positive.

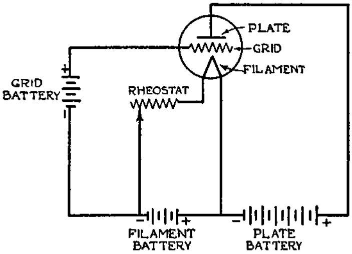


Fig. 46. — Circuit for Three-electrode Tube, Grid Positive

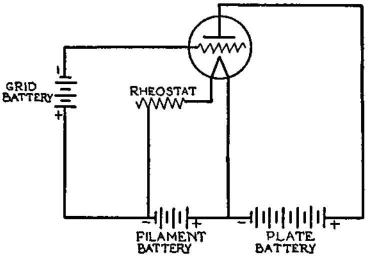


Fig. 47. — Circuit for Three-electrode Tube, Grid Negative

Suppose now we reverse the connections of the battery in the grid circuit so that the grid is negative (Fig. 47). The grid now repels the electrons and tends to drive them back to the filament. Therefore the plate current is made weaker. If the grid has sufficient negative potential it will reduce the plate current to zero. In other words, if the grid is sufficiently negative it will drive all the escaping electrons back to the filament. A negative grid cannot, however, reverse the plate current for, as we have seen, the plate current can flow only in one direction.

If we connect a sensitive telephone receiver in the plate circuit as shown in Fig. 48, the plate current flows through the receiver. If we reverse the connections of the grid battery the resulting change in the plate current causes a click in the receiver. Changing the potential of the grid from positive to negative or the reverse causes a change in the plate current which produces a sound in the receiver. A sound may also be produced in the receiver by making and breaking the connections of the grid battery thus changing the potential of the grid from zero to a certain positive value and back again to zero.

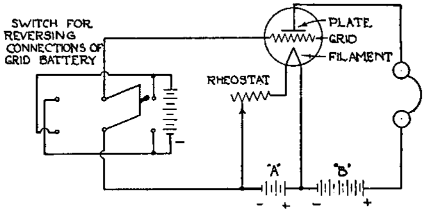


Fig. 48. — Circuit for Reversing Connections of Grid Battery

37. Plate Voltage and Plate Current. — We have seen that if the plate is made positive it attracts the electrons that are being shot out from the filament. The higher the potential of the plate the more it attracts the electrons and the stronger is the plate current. This can be shown by a simple experiment. If the reader will make this test and the others that follow, he will have a better understanding of the working of an electron tube in a radio receiving circuit than he can get in any other way.

A circuit is arranged as shown in Fig. 49. The filament battery must, of course, be of the right voltage for the tube used. The grid is left unconnected. The plate battery may be made up of the small dry cells that are used in flash-lights. These cells should be connected in series by soldering short wires to the terminals, the zinc of one cell to the carbon of the next throughout the series. It is well to have enough cells in the series to make it possible to go up to 90 volts. A radio B battery of 45 volts in series with another of 22½ volts and 15 flash-light cells will make it possible to get all the different voltages desired. The arrow point shown at E in the figure is a movable connection. This may be a small battery clip soldered to a wire. The clip can be attached to any of the battery terminals along the series of dry cells so that the plate voltage can be increased in steps of 1½ volts. A is a milliammeter. The plate current will probably not go much above 10 milliamperes. V_1 is a voltmeter for indicating plate voltage.

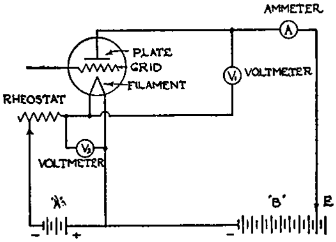


Fig. 49. — Circuit for Testing Plate Voltage and Plate Current

It will be noted that the circuit used in this test is part of a radio receiving circuit. We are using simply the filament and plate circuits with a milliammeter and voltmeter for measuring plate current and voltage and a simple arrangement for varying the plate voltage. The filament rheostat is now adjusted so that the filament current is of the same value that would be used if the tube were in a receiving circuit, or better, so that the voltage at the filament terminals, V_2, is that which is recommended by the manufacturers for the particular tube that is being tested. When this adjustment is made, readings of the milliammeter and voltmeter in the plate circuit are taken, first with the clip connected to make the plate voltage 1½ volts and then increasing in steps of 1½ volts. Care should be taken not to go much above the upper limit of plate voltage recommended for the tube under test. From these results a graph should be plotted as in Fig. 50.

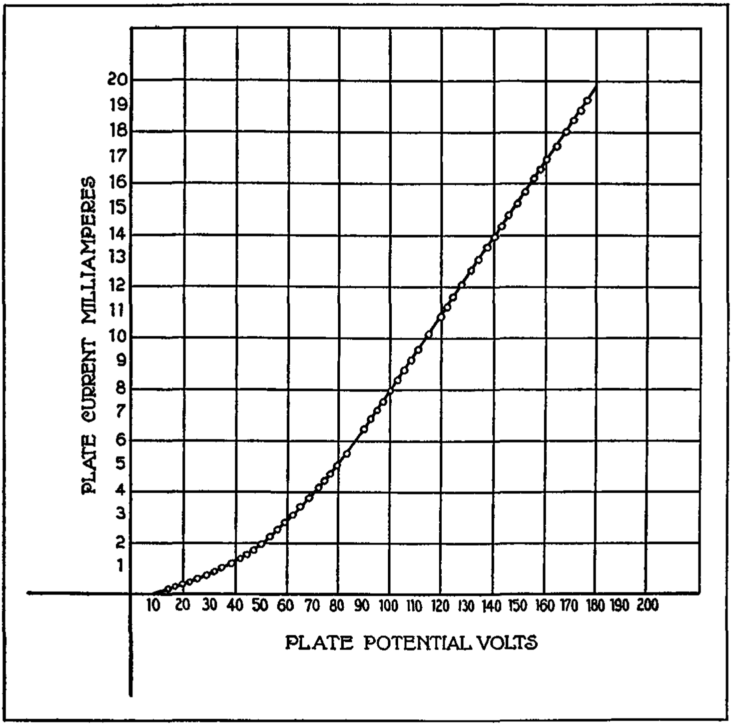


Fig. 50. — Plate Voltage, Plate Current Graph

It will be found that a limit is reached such that increasing the plate voltage beyond this limit makes no further increase in plate current. To reach this limit it may be necessary to go above the voltage limit recommended for the tube. If this is done the tube should be kept at the high voltage only long enough to make the test. The fact that the current reaches a limit means that for a certain voltage the plate attracts to itself practically all the electrons that are emitted from the filament. At the lower voltages the plate is able to attract to itself only a part of these electrons. If the test is made with a lower filament voltage; that is, with the contact arm of the filament rheostat turned so as to dim the filament, it will be found that the plate current reaches its limit at a lower plate voltage than before. This is because, when the filament is at a lower temperature fewer electrons are given off and the plate is, therefore, able to attract all the electrons with a lower voltage than before.

38. Grid Voltage and Plate Current. — We are now going more deeply into the study of the electron tube. We have seen that a change in the grid voltage causes a change in the plate current. The action of a tube in a receiving circuit depends on the relation between grid voltage and plate current. It is important, therefore, to make a thorough study of this relation.

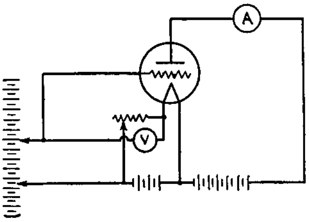


Fig. 51. — Circuit for Testing Grid Voltage and Plate Current

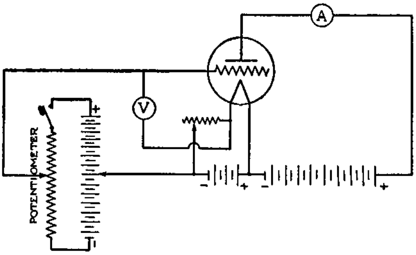


Fig. 52. — Circuit for Testing Grid Voltage and Plate Current Using Potentiometer

Figs. 51 and 52 show two circuits for testing the grid-voltage plate-current relation. In Fig. 51 a number of dry cells in series are used to vary the grid voltage. Flash-light cells may be used as in the plate-voltage plate-current test. In Fig. 52 a potentiometer is used for this purpose. Good results can be obtained by either method. The key in the potentiometer circuit is for the purpose of avoiding overheating the potentiometer when using the high voltages. The voltage of the plate battery is fixed at a value which would be used if the tube were in a receiving circuit and allowed to remain at that value during the test. The grid voltage is varied from zero down to a negative value that reduces the plate current to zero and up to as high a positive value as is practical. Readings of the plate current are taken for different values of grid voltage. It is possible, if the apparatus at hand will permit, to reach a value of grid voltage that will bring the plate current up to a limit so that a further increase in grid voltage causes practically no increase in plate current.

A graph should be plotted showing the relation between grid voltage and plate current for the tube that is being tested. (See Fig. 53.) This graph is called the characteristic of the tube. The plate voltage may be changed and another series of readings of grid voltage and plate current taken and another graph drawn. If similar tests are made for a number of different values of plate voltage and the graphs drawn, as in Fig. 53, a great deal may be learned about the action of the tube. Graphs of different tubes drawn on the same axes show in a very striking way the differences between the tubes. The characteristics of detector and amplifier tubes will be discussed in Chapter VII but we may say in a general way that for a good amplifier tube the straight line portion of the graph should be steep and that the sharper the bend at the lower portion of the graph the better the tube will work as a detector.

39. Amplification Factor. — We have seen that a certain voltage applied to the grid causes a much greater change in plate current than does the same voltage change on the plate. It requires a number of volts on the plate to produce the same effect as one volt on the grid. The ratio of the change in plate voltage to the change in grid voltage that will produce the

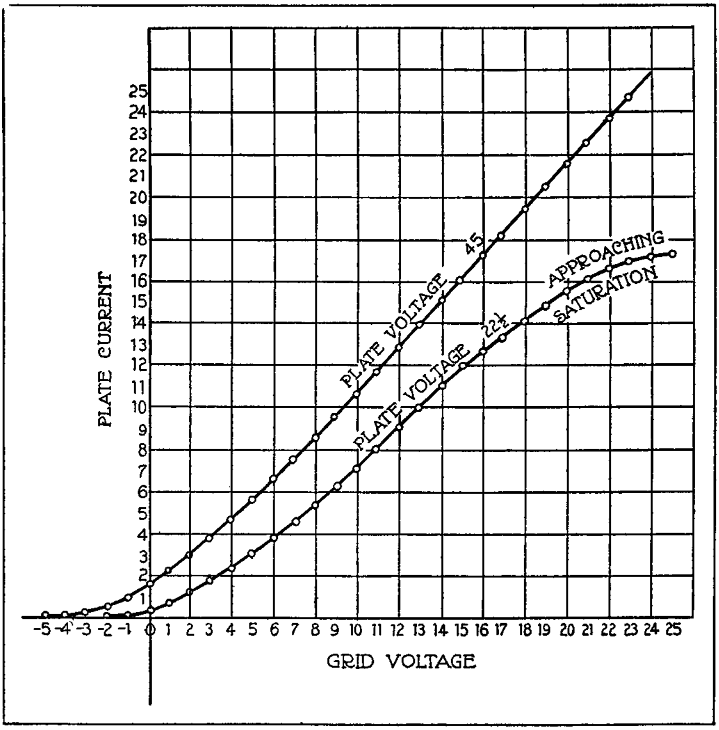


Fig. 53. — Grid Voltage, Plate Current Graphs

same effect on the plate current is called the amplification factor of the tube. For example: If it requires an increase of six volts on the plate to change the plate current as much as one volt on the grid, the amplification factor is six.

The circuit required to measure the amplification factor of a tube is shown in Figs. 54 and 55. In Fig. 54 cells are used as described in Section 37. In Fig. 55 a potentiometer is used for the purpose of varying the grid voltage. The potentiometer method of adjusting voltage is frequently used in radio work. There are two voltmeters in the circuit, V_1 and V_2, to measure plate voltage and grid voltage. There is also a milliammeter to measure plate current. The plate battery may be made up of small dry cells as in preceding tests or a commercial plate battery may be used. The grid voltage may be made zero for the first test. The plate voltage should be such that the plate current will be a little below the maximum so that the test will

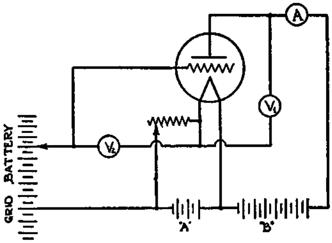


Fig. 54. — Circuit for Finding the Amplification Factor of a Tube

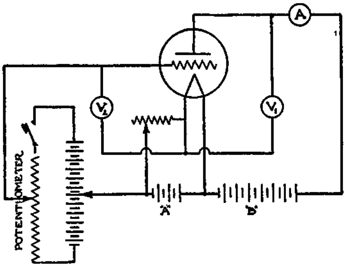


Fig. 55. — Circuit for Finding the Amplification Factor of a Tube Using a Potentiometer

be made on the straight line portion of the characteristic curve. Now the reading of the milliammeter in the plate circuit is taken. Next the plate voltage is reduced by a certain amount, say twelve volts, and the milliammeter reading again taken. It is found that the plate current is reduced by a certain number of milliamperes. Now, holding the plate voltage as it is, the plate current can be increased up to its first value by increasing the grid voltage. This will require only a comparatively small change in grid voltage. This small change in grid voltage has produced as great a change in plate current as was produced by the larger change in plate voltage. The amplification factor can now be found by dividing the change in plate voltage by the change in grid voltage. It is very interesting to compare the amplification factors of different tubes.

40. Plate Circuit Resistance. — The resistance within a tube between filament and plate is an important factor in determining the working qualities of the tube. In measuring this resistance the same circuit is used as for plate voltage and plate current (Fig. 49). The grid is kept at zero voltage. A certain voltage, say that of three dry cells, 4.5 volts, is applied to the plate and the value of the plate current noted. For example, suppose that 4.5 volts on the plate produces a current of 0.45 milliampere or 0.00045 ampere. Then we have by Ohm's law,

$$R = \frac{E}{I} = \frac{4.5}{0.00045} = 10{,}000 \text{ ohms.}$$

This is the direct current resistance within the tube between plate and filament. The plate circuit resistance is not the same for all values of plate voltage. The resistance should be measured for different plate voltages, increasing the voltage say in steps of 3 volts and continuing the tests up to 45 volts for a detector tube and 90 volts or more for an amplifier tube. It is worth while also to compare the resistances of different tubes.

After finding the resistance of a tube for different values of plate voltage a graph may be plotted letting abscissas represent plate voltage and ordinates plate circuit resistance (See Fig. 56). This graph shows that, as the voltage increases, the resistance decreases to a certain limit. We should expect this to be true for we have found in plotting the curve for plate volt-

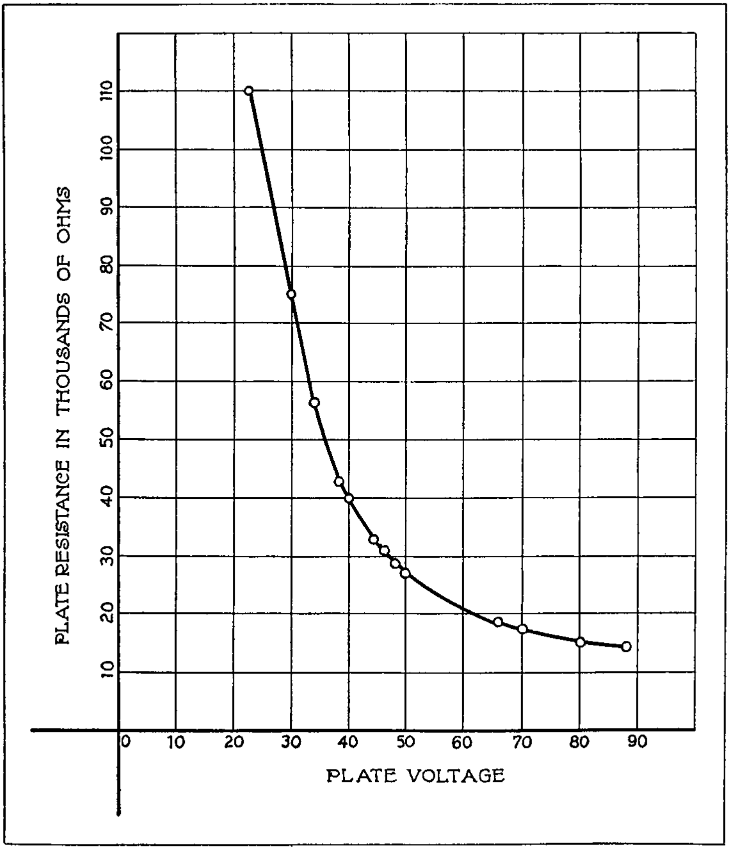


Fig. 56. — Plate Voltage, Plate Resistance Graph

age and plate current that, as the plate voltage is increased beginning at zero, the plate current increases rather slowly at first and then more rapidly. In other words a higher voltage gives a greater current in proportion to its value than a lower voltage. For example, 20 volts on the plate give more than twice as much current as 10 volts. From this it follows by Ohm's law that the resistance is less for 20 volts on the plate than for 10 volts.

To measure the alternating current resistance of a tube it is necessary to divide the change in plate voltage by the change in plate current. Small changes in plate voltage should be taken, say one or two volts.

41. Grid Voltage and Grid Current. — When an electron tube is in action a stream of electrons is shooting across from filament to plate. Since the grid is open like a lattice work or a loose coil most of these electrons pass on through the grid. A few, however, get caught by the grid unless the grid is sufficiently negative to repel them in which case they fly on through to the plate. If the grid is at zero potential or positive it catches some of the electrons and there is a flow of electrons through the grid circuit from grid to filament.

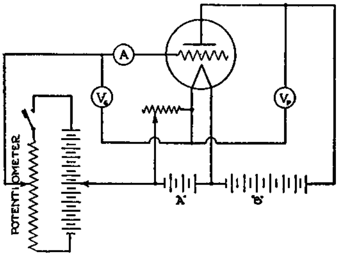


Fig. 57. — Circuit for Testing Grid Voltage and Grid Current

The grid current is, as a rule, much smaller than the plate current. It requires for its measurement a milliammeter sensitive to tenths of a milliampere. A circuit for testing the relation between grid voltage and grid current is shown in Fig. 57. A is a sensitive milliammeter. V_g is a voltmeter for grid voltage. This should have the zero in the center of the scale. Otherwise it is necessary to reverse the connections when the

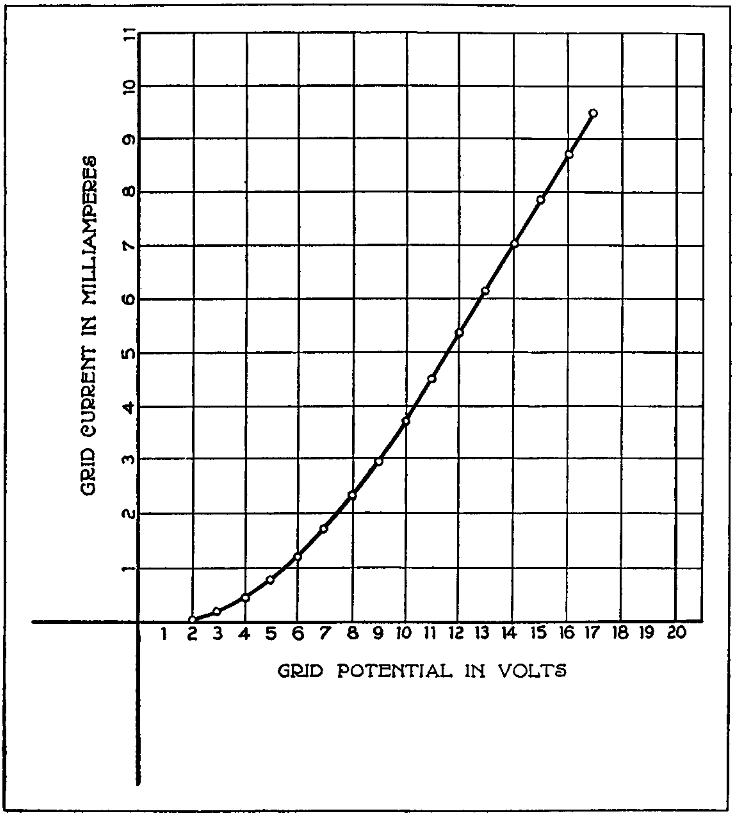


Fig. 58. — Grid Voltage, Grid Current Graph

voltage is reversed. V_p is a voltmeter for plate voltage. The plate voltage should be fixed at a certain value and held at that value during the test. A number of readings of grid current are taken for different values of grid voltage, the grid voltage being changed as desired by means of the potentiometer and a reading of the milliammeter and of the voltmeter, V_g, being taken for each setting of the potentiometer. A graph should then be plotted as in Fig. 58, letting abscissas represent grid voltage and ordinates grid current. The plate voltage may then be set at a different value and a series of readings of grid voltage and grid current again taken and another graph plotted on the same axes as the first.

Such a series of graphs is very instructive in regard to the action of tubes. It is found, for example, that the grid current depends on plate voltage as well as on grid voltage. One of the interesting facts brought out by this experiment is that with a higher plate voltage we get a smaller grid current. The explanation is that when the plate is at a higher potential; that is, more positive, it is able to attract a larger number of electrons past the grid so that a smaller portion of the electron stream enters the grid. The experiment shows also that even with a slight negative grid potential there may be a grid current if the plate potential is sufficiently low but, even with a low plate potential, the grid may be made sufficiently negative to prevent any grid current.

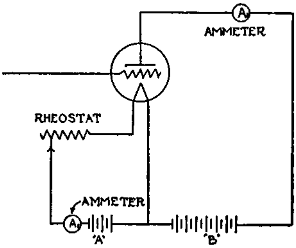


Fig. 59. — Circuit for Testing Filament Current and Plate Current

42. Filament Current and Plate Current. — If an ammeter or a milliammeter having a range sufficient for the maximum current is inserted in the filament circuit with a milliammeter in the plate circuit as in Fig. 59, the value of the plate current for different values of the filament current may be measured and a graph plotted letting abscissas represent filament current and ordinates plate current. A_1 is a milliammeter for measuring filament current and A_2 for plate current. The plate voltage should be left constant during this test at the value which would be used if the tube were in a radio circuit. More electrons are given off by the filament as the filament current is increased and, therefore, the plate current increases.

43. Power Amplification. — An electron tube amplifies the power it receives; that is, there is more power in the plate circuit than in the grid circuit. It should be understood that the tube does not create power but that the additional power developed in the plate circuit is derived from the plate battery. The grid circuit merely serves to control the power of the plate circuit. The power developed in the grid circuit is called the power input. The power developed in the plate circuit is called the power output. Power output is greater than power input. Power amplification will be taken up again in Chapter VII.

44. Hard and Soft Tubes. — Tubes that are exhausted to a very high vacuum are called hard tubes. Soft tubes are those that have an appreciable amount of gas left in them. The action of the soft tube is very different from that of a hard tube on account of the gas in the tube. If practically all the gas has been removed from a tube the electrons can pass from filament to plate with nothing to hinder them, but if a quantity of gas remains in the tube the electrons strike some of the molecules of gas. The result of the collision, if the electron is moving rapidly enough, is that the gas molecule is broken up, some of its electrons are torn away from it and set free. The gas molecule thus becomes a positive ion and the action is called ionization. The electrons set free from the gas molecules are added to those coming from the filament and the plate current is increased. The electrons must have a certain velocity to enable them to knock off the electrons from the gas molecules. When the grid and plate potentials reach the point that gives the electrons this velocity there is a sudden increase in plate current due to the added electrons from the gas molecules. When ionization by collision begins, a hissing or frying sound can be heard in a telephone receiver in the plate circuit. It is on account of ionization that soft tubes are sometimes erratic in their action.

If a soft tube is held by the glass end and any one of the metal terminals touched to one of the secondary terminals of a spark coil that would give a spark of one-half inch or more, there will be a bluish glow in the tube. If a hard tube is tested in the same way there is no glow.

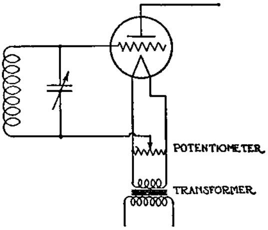


Fig. 60. — Filament Circuit for an Alternating Current Tube

45. Alternating Current Tubes. — The filament of any electron tube may be heated by an alternating current. It is only necessary to use a transformer to secure the correct voltage for the filament. If, however, the grid return is brought to one of the filament terminals, the alternating voltage is impressed on the grid causing a hum in the receiver. The hum can be to a large extent eliminated by connecting a potentiometer across the filament terminals, connecting the grid return to the arm of the potentiometer and adjusting the arm until the hum is reduced as much as possible (Fig. 60). The grid return is then at the neutral point on the potentiometer or the point at which the potential does not change. If the alternating voltage changed according to the ideal curve of Fig. 68, it would be possible to find a point on the potentiometer that would always be neutral. Unfortunately the alternating voltage curve is irregular so that the neutral point is continually shifting. This means that even with the best adjustment of the potentiometer there is a slight variation of voltage acting on the grid. The hum which results from this action is more noticeable when the tube is used as a detector than when used as an amplifier. By designing the tube for low filament voltage the hum is practically eliminated when the tube is used as an amplifier. Such a tube is known as a " heavy filament " or " thick filament " tube. With low voltage across the filament terminals the voltage variations at the mid-point are very slight.

For use as a detector the hum may be eliminated by designing the tube so that the filament through which the current flows heats another element which acts as the cathode. This is known as the " heater " type of tube. In the three element tube the filament itself is the cathode but in the " heater " type of a.c. tube the filament becomes simply a heater. The cathode is a cylinder surrounding the filament (Fig. 61). The electron stream which forms part of the plate current is not given off by the filament but by the cathode which is heated by the filament. The grid return is also to the cathode and since the alternating current does not flow through the cathode it does not produce a hum. The alternating current serves only to keep the heater at a sufficiently high temperature to heat the cathode. A circuit using a tube of the heater type as a detector and two tubes of " heavy filament " type as amplifiers is shown in Fig. 62. The power tube in the last stage is of the same type as a power tube for direct current operation.

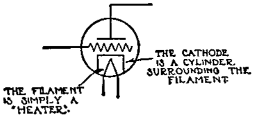


Fig. 61. — Diagram of an Alternating Current Tube, Heater Type

In the use of a.c. tubes it is best to twist the filament leads together and keep them as far as possible from the other wires of the circuit otherwise the alternating current flowing through the filament leads may act magnetically on the coils or grid leads and cause a hum. This effect may also be prevented by shielding the filament leads.

46. Tubes with Two Grids. — In any electron tube the electrons which surround the filament tend to hinder other electrons coming out from the filament. The accumulation of electrons around the filament is called a "space charge." A method of removing the space charge is to place a second grid between the grid which controls the plate current and the filament. If the inner grid is made positive, it attracts electrons from the filament. We have then the arrangement of Fig. 63. The inner grid is called the "space charge grid" because its use is to reduce the space charge around the filament. The outer grid is called the "control grid" because its use is to control the plate current. The control grid is of course connected to the tuned circuit.

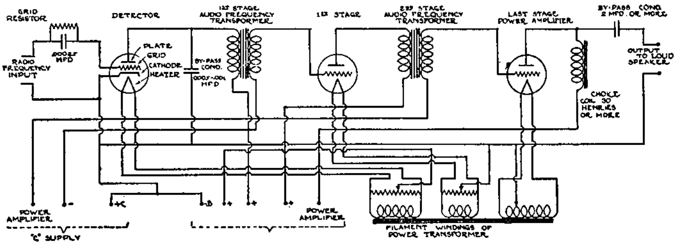


Fig. 62. — A Receiving Circuit Using Alternating Current Tubes

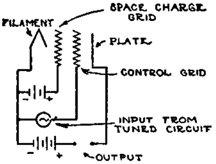


Fig. 63. — Diagram of a Tube of the "Space Charge Grid" Type. From "Q. S. T."

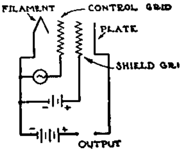


Fig. 64. — Diagram of a Tube of the "Screen Grid" Type. From "Q. S. T."

If the connections are changed so that the tuned circuit is connected to the inner grid which is next to the filament and a positive potential placed on the outer grid which surrounds the plate (Fig. 64), then the outer grid becomes a screen preventing variations in plate voltage from reacting on the stream of electrons coming from the filament. Such a tube has many advantages one of the most important of which is that the feedback through the plate-grid capacity is practically eliminated making it unnecessary to use neutralizing devices. This will be explained in Sections 124, 125, 126 and 127. The " screen grid " tube just described also makes it possible to amplify successfully at very low wave lengths. A receiving circuit having a screen grid tube is shown in Fig. 65. The action of a screen grid tube in a receiving circuit is discussed more fully in Section 126. The pentode tube is discussed in Section 127.

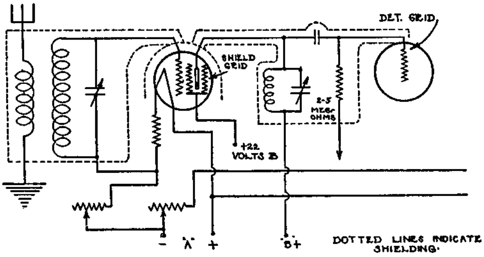
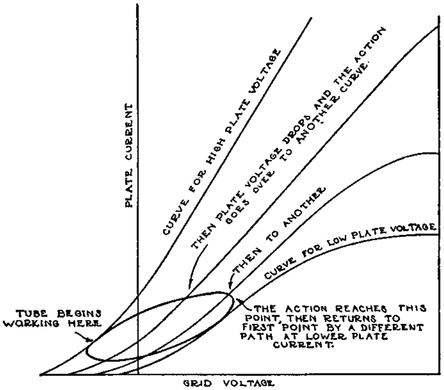


Fig. 65. — Circuit Using a Screen Grid Tube as a Radio Frequency Amplifier

47. Uses to be Made of Characteristic Curves. — The characteristics of a vacuum tube so far described are the characteristics for special conditions. These conditions are arranged for each test. They are not the actual working conditions of a tube when in operation in a receiving or transmitting circuit.

Let us take, for example, the curve showing the relation between grid voltage and plate current. The readings for this curve as shown in Fig. 53 were taken with the plate voltage remaining practically constant. Now this is not what actually happens when the tube is in operation. When the grid becomes more positive, the plate current increases and plate voltage at the same time decreases. The increase in grid voltage has the effect of making an easier path for the electrons from filament to plate which means that the resistance between filament and plate is reduced. Since the resistance is less the voltage is less between filament and plate because in any series circuit the voltage is less across the lower resistance and more across the higher resistance. The higher resistance in this case is the external resistance of the plate circuit.

The result is that the tube starts working on a certain characteristic curve and as grid voltage increases the action of the tube moves over to another curve and then to another as shown in Fig. 66. Then as grid voltage decreases the action of the tube returns to the first point but along a different path. The plate current is now less on account of reduced grid voltage. The heavy line in Fig. 66 illustrates the changes in plate current and grid voltage as they actually occur when the tube is in operation. This is called a dynamic characteristic while the curves described in preceding sections are called static characteristics.



A SIMILAR ACTION TAKES PLACE FOR EVERY COMPLETE OSCILLATION OF GRID VOLTAGE

Fig. 66. — A Dynamic Characteristic of a Tube

The grid voltage-plate current curve has been taken as an example. It is true of other curves as well that the curve is not the same when the tube is in action, the dynamic characteristics are not the same as the static characteristics. This does not mean that the curves for static characteristics are of no value. They show some very important facts regarding tubes, besides the static characteristics are simpler and are a help in understanding the dynamic characteristics. They are, in fact, of great importance but they must be used with the full understanding that they do not show the actual operation of a tube.

Fig. 67 shows a circuit for making all of the tube tests described in this chapter except the dynamic characteristic.

A high resistance voltmeter should be used, both for grid voltage and plate voltage. Such a voltmeter should have a resistance of about one thousand ohms per volt.

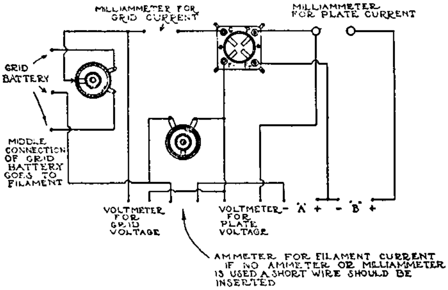


Fig. 67. — Circuit for Tube Tests

Questions

1. What is an electron? What is the relation of an electron to an atom?

2. How does a difference of electric potential across the terminals of a conductor affect the action of the electrons in the conductor?

3. What is the relation between the action of electrons and the heating effect of an electric current? What is the relation between the temperature of a filament and the escape of electrons from the filament?

4. What limits the escape of electrons from the filament in a common electric light bulb?

5. In an electron tube why do electrons flow from filament to plate but not from plate to filament?

6. Why does a positive potential on the grid increase the plate current? Why cannot a negative potential on the grid reverse the plate current?

7. If you had a telephone receiver in the plate circuit and with a battery in the grid circuit were to open and close the grid circuit rapidly what would you hear? Explain.

8. For a certain tube the voltage of one dry cell, one and one-half volts, applied to the grid causes the same change in plate current as 30 volts applied to the plate. What is the amplification factor of the tube?

9. A second tube is tested and it is found that 1½ volts on the grid causes the same change in plate current as 12 volts on the plate. What is the amplification factor?

10. If the two tubes of problems 8 and 9 are used in receiving circuits, the plate circuit of each tube being connected to a transformer, which tube will produce the greater voltage at the terminals of the transformer?

11. For a certain tube the plate current is 0.5 milliampere when the voltage between plate and filament is 10 volts. What is the resistance between plate and filament? For the same tube a plate voltage of 90 volts causes a plate current of 9 milliamperes. What is now the plate resistance?

12. Why is the grid current small compared with the plate current? Is it possible to have a plate current with zero grid current?

13. Why is the plate current stronger when the filament is bright than when it is dim?

14. Why is the power output of an electron tube greater than the power input? Does this mean that the tube creates power?

15. Why does the plate current of a soft tube sometimes increase suddenly?

CHAPTER VI

ALTERNATING CURRENTS

We have seen in Chapter II that in a battery circuit electrons flow around the circuit in one direction. This is an example of a direct current. If the flow of electrons continues not only in the same direction but at the same rate, the current is said to be constant. In many electric circuits the electrons do not flow continuously in one direction but flow back and forth, first in one direction, then the opposite. Such a current is alternating. Alternating current is used more generally than direct current for lighting and power. Wherever electric power is transmitted over long distances, alternating current is used. We have alternating current also in radio transmission. This chapter will deal with the fundamental principles of alternating currents that are necessary to an understanding of currents in radio circuits.

48. Current Produced by a Varying Magnetic Field. — Current generators of all types are based on one simple experimental fact which is fundamental in understanding alternating currents. It is this: Whenever a conductor of electricity moves across a magnetic field an electromotive force is induced in the conductor. This principle can be illustrated by a very simple experiment. If the ends of a copper wire are connected to a milliammeter and the wire is moved between the poles of a strong horseshoe magnet, the milliammeter needle moves showing that a current is flowing in the wire. The current flows only while the wire is moving. If the wire is moved up and down between the poles of the magnet, the milliammeter needle moves first in one direction then in the opposite direction showing that the current is alternating. The direction of the current depends on the direction in which the wire moves across the magnetic field. If the wire is moved repeatedly up and down, the current changes direction every time the wire changes its direction of motion. It does not matter, of course, whether the wire or the magnet moves. All that is necessary is that the wire shall cross the lines of magnetic force or, as it is commonly expressed, " cut the lines of force."

If, instead of a single wire, a coil of several turns is used and the coil rotated between the poles of the magnet, the milliammeter needle moves and changes direction twice for every complete rotation of the coil. The coil cuts the lines of force and its direction of motion changes every half turn.

In some manner, not fully understood, a changing magnetic field is able to set up an electromotive force in a conductor. This is just the converse of the magnetic action of an electric current. Electrons in motion in an electric conductor set up a magnetic force around the conductor. A change in the magnetic force about a conductor tends to set the electrons in motion.

A current produced by the action of a magnetic field is called an induced current. A simple rule for remembering the direction of an induced current is known as Fleming's rule or the right hand rule. Imagine the right hand held in the magnetic field with thumb, forefinger and middle finger extended at right angles to each other, the forefinger pointing in the direction of the lines of force, the thumb in the direction of motion of the wire, then the middle finger points in the direction of the induced e.m.f. (positive to negative).

Another simple rule which may be more easily remembered is this: If one looks in the direction of the lines of force and moves the wire down, the induced e.m.f. is toward the right. The word " downright " helps in remembering this rule. It must be remembered that the direction of the e.m.f. as given in the above rules is that in which positive electrification tends to flow and that the electrons actually flow in the opposite direction.

49. Electromotive Force in a Two-pole Generator. — We have seen that when a coil is rotated between two magnet poles an e.m.f. is induced in the coil and that this e.m.f. changes direction twice in every revolution. Suppose the coil rotates between two magnet poles in a perfectly uniform magnetic field, that is, one of the same strength throughout (Fig. 68). The line drawn through the center of the coil perpendicular to the lines of force, we shall call the zero line. As the coil passes through the position of this line the induced e.m.f. is zero because the coil at this instant is moving parallel to the lines of force. The arrow drawn tangent to the circle at 0° shows the direction of motion at this point and this arrow is parallel to the lines of force. After passing this position the coil cuts lines of force. Taking an ideal case in which the magnetic field is uniform and the speed uniform, the e.m.f. induced in the coil as it passes any given point is proportional to the perpendicular drawn from that point to the zero line. If we draw a number of perpendiculars from the circle to the zero line, these perpendiculars represent the electromotive forces for the respective positions of the coil. Now a graph may be drawn as in Fig. 68 letting the abscissas represent the angles through which the coil has turned and the ordinates the electromotive forces. We may use for the ordinates the perpendiculars which we have drawn from the circumference of the circle to the zero line for, as we have seen, the electromotive forces are proportional to these perpendiculars. We now have a curve which represents the electromotive forces for one complete revolution of the coil. The curve shown in Fig. 68 is a " sine " curve. In an actual generator the curve is not a true sine curve. The

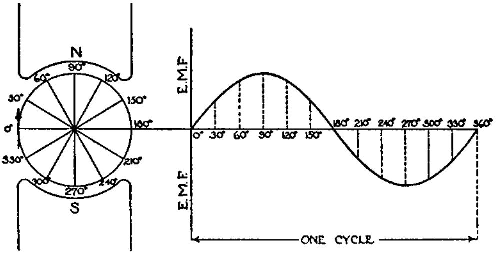


Fig. 68. — Ideal Curve of Electromotive Force for One Cycle

high frequency alternating currents produced by electron tubes differ greatly from the sine wave form.

The curve shows that the electromotive force increases rapidly at first, then less rapidly until it reaches its maximum when the coil reaches the 90 degree position. Then it decreases slowly at first, then more rapidly until the coil reaches the 180 degree position. Then the electromotive force reverses because in the second half of the revolution the coil is cutting lines of force in a direction opposite to that of the first half. For the second half of the curve, therefore, the ordinates are drawn below the zero line to represent negative electromotive forces.

This curve represents one cycle. A cycle is one complete series of changes in the electromotive force. At the end of the cycle the coil is in the same condition as at the beginning. It then starts to do the same thing over again. If it continues to rotate it repeats the cycle once for each rotation.

The number of cycles produced each second is the frequency. In a two-pole generator the frequency equals the number of revolutions per second. Commercial generators, as a rule, have a large number of poles. One cycle is produced by a coil passing one pair of poles. Therefore, in one rotation as many cycles will be produced as there are pairs of poles. In the ordinary commercial lighting circuit the frequency is usually 60. In a 60 cycle current there are 120 alternations per second since the current changes direction twice for each cycle.

50. Magnetic Field of an Alternating Current. — We have seen in Chapter III that, wherever there is an electric current flowing in a wire, there is a magnetic field around the wire. We have seen also that if the current changes direction the magnetic force changes direction. This is just what happens in an alternating current circuit. Suppose we have a coil connected to a source of alternating electromotive force, such as the lower coil in Fig. 69. An alternating current will flow in the coil. The coil will then have a magnetic field. When the current is flowing in a certain direction the upper end of the coil will be a north magnetic pole. When the current reverses the upper end becomes a south pole (See Section 19). Now suppose we have a sixty cycle current in the coil. Then sixty times a second the upper end of the coil will be a north pole and sixty times it will be a south pole. It will change 120 times a second. What happens to the magnetic field around the coil? It reverses each time the current reverses. After each reversal the magnetic force grows stronger as the current increases up to its maximum then it dies down to zero as the current diminishes. This means that the lines of force about the coil are continually changing, that is, they are expanding, contracting and reversing.

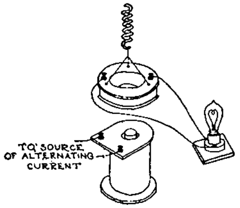


Fig. 69. — Mutual Induction

51. Mutual Induction. — Suppose now we have a second coil placed above the first. The upper coil is in the magnetic field of the lower coil. We have seen that whenever magnetic lines of force move across a coil an e.m.f. is induced. Since the current in the lower coil is alternating, its lines of force are continually moving across the upper coil. Therefore there is an induced electromotive force in the upper coil. This induced e.m.f. is alternating since the magnetic field is repeatedly changing direction. An alternating current voltmeter connected to the upper coil would indicate an e.m.f.

An electric bulb connected to the upper coil will be lighted if the proper voltages are used. For example, if the lower coil has, say 300 turns and a soft iron core approximately two inches in diameter surrounded by iron to concentrate the lines of force but leaving the magnetic field open above, and the upper coil with no iron core has 100 turns and a diameter equal to that of the lower coil, a 7 volt automobile headlight bulb connected to the upper coil will be lighted even when there is a space of an inch between the coils. The bulb is lighted by the current induced in its coil by the alternating magnetic field of the lower coil. If the coils are very close together the bulb will be lighted brightly. If the coils are somewhat farther apart the bulb will be dimmed. In radio we call the first condition close coupling and the second loose coupling. The closer the coupling the stronger is the induced current. It is interesting to suspend the upper coil by means of a steel spring and start it moving up and down. The change in brightness of the bulb illustrates very vividly the difference between close and loose coupling. It is understood that in working this experiment the lower coil is connected directly to the ordinary 60 cycle house lighting circuit. The coil which is connected to the source of current is called the primary and the coil in which an e.m.f. is induced is called the secondary.

If the current in the primary coil is direct and of constant strength there is no effect on the secondary coil because the magnetic field is not changing. If, however, the circuit of the primary is alternately closed and opened so that the magnetic field changes there is an induced e.m.f. in the secondary. The action of a magnetic field of one coil inducing a current in another coil is called mutual induction. The principle of mutual induction which this experiment illustrates is applied in the Ruhmkorff induction coil, the jump spark coil used in gasoline engine ignition, the transformer and the coupler of radio circuits.

52. Lines of Force. — It is necessary now to extend the definition of lines of force. We have seen in Chapter III that lines of force are lines indicating the direction of the force in a magnetic field. A line of force is also a unit used in measuring the strength of force in a magnetic field. We speak of the strength of a magnetic field as so many lines of force per square inch or per square centimeter as we might speak of the air pressure in an automobile tire as so many pounds per square inch. Just how large a unit a line of force is, it is not necessary to discuss here but it is important to remember that lines of force are used to indicate two things, the direction and the intensity of the magnetic force.

53. Induced Electromotive Force. — The strength of the induced e.m.f. in the secondary depends on the rate at which it cuts lines of force. This is expressed in the following equation,

$$\text{E.M.F.} = \frac{N}{t}$$

in which N is the number of lines of force cut by the coil and t is the number of seconds. Therefore $\frac{N}{t}$ is the number of lines cut per second. If the secondary cuts 100,000,000 lines of force per second an e.m.f. of one volt is induced. Therefore to find the e.m.f. in volts we must divide the result obtained in the above equation by 100,000,000.

$$\text{E.M.F. (in volts)} = \frac{N}{t} \cdot \frac{1}{100{,}000{,}000}.$$

The rate at which the secondary coil cuts lines of force depends on a number of conditions. First: It depends on the rate at which the current in the primary is changing for, the more rapidly the primary current changes, the more rapidly its magnetic field changes. This is another way of saying that the higher the frequency of the primary current the greater the induced e.m.f. in the secondary coil. For example, if all other conditions are equal a current of 60 cycles per second will induce a greater e.m.f. than a current of 25 cycles per second. The induced e.m.f. is in direct proportion to the frequency. This point is important in radio circuits. Second: The induced e.m.f. depends on the strength of the current in the primary for, the stronger the current in the primary, the greater the number of lines of force that move across the secondary. Third: The induced e.m.f. depends on the number of turns of wire in the secondary. If ten turns of wire move across a magnetic field the effect is ten times as great as if only one turn moved across the same field.

54. Direction of Induced Current and Lenz's Law. — The upper coil in Fig. 69 is repelled when the circuit of the lower coil is closed. This can be clearly shown if the coil is suspended by a spring and its terminals short circuited. If the primary current is alternating the repulsion continues as long as the circuit is closed. If the primary current is direct with a contact key in the circuit, the secondary coil is repelled at the instant when the key is closed and attracted when the key is opened. This experiment illustrates the magnetic action of the current in the secondary coil. The induced current opposes the action that induces it. This principle is known as Lenz's law.

Take first the case in which the primary current is direct. When the circuit is closed a magnetic field is produced and the lines of force move upward into the secondary coil. A current is induced in the secondary. The secondary then has its own magnetic field and this magnetic field repels that of the primary. There is repulsion then between the two coils. The reverse action takes place when the circuit is broken. On the breaking of the primary circuit there is attraction between the coils. In each case the magnetic field of the secondary is opposing the action of the primary. When the current in the primary is alternating there is repulsion when the primary magnetic field is expanding and attraction while the primary magnetic field is contracting. The repulsion is greater than the attraction, however, so that on the whole the coils repel each other. The reason for this is stated in Section 72.

If the induced current is in a coil rotating in a magnetic field as in a generator, the repulsion effect is felt in a backward push on the coil. The result is that it requires a greater force and more energy must be expended to rotate the coil when there is an induced current than when there is not. This can be clearly shown by means of a small motor driven generator, if the armature is rotated first with its circuit open and then the circuit closed through the proper resistance so that a current is allowed to flow. At the instant of closing the armature circuit there will be a noticeable lowering in pitch of the hum of the machine showing that the motor is being slowed down by the backward push of the magnetic field in the generator. It is clear from this experiment that the motor must do more work when the generator is delivering current than when it is not. If this were not so the electric energy derived from the generator would be obtained without a corresponding expenditure of energy. In other words, the machine would be giving out more work than was put into it which is impossible. Lenz's law is a special case of the conservation of energy. If the two coils are fixed so that they cannot move with relation to each other as in a transformer, the magnetic field of the secondary reacts on the primary in such a way as to oppose the change that is taking place in the primary current.

From the point of view of the electron theory we may consider the opposing action of the secondary current as follows: Suppose we connect a battery with a contact key to a primary coil as in Fig. 70. When the key is closed, electrons begin to flow in the primary coil from D to C. While this stream of electrons is increasing it causes electrons in the secondary to flow from A to B or in the direction opposite to those of the primary. The second stream of electrons now exerts a backward push on those in the primary and tries to stop their flow. If the primary circuit is opened, the stream of electrons in DC dies down and that in AB reverses its direction. Whatever change is taking place in the stream of electrons in DC, the electrons in AB oppose the change. The force by which these streams of electrons act upon each other is called magnetic force.

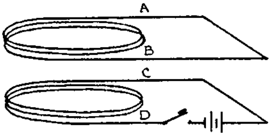


Fig. 70. — Action of Electrons in Mutual Induction

55. Inductance. — If a coil having say 300 or more turns of wire on an iron core is connected in series with a light bulb to a 110 volt alternating current lighting circuit, and the coil at first short circuited by a switch or wire (Fig. 71), the bulb will glow brightly. If now the short circuiting switch is opened so that the coil is thrown into the circuit the light is dimmed. If the same coil and bulb are connected in series to a 110 volt direct current line there is no dimming of the light. This experiment illustrates self-induction in an alternating current circuit. It shows that the effect of self-induction in an alternating current coil, on the whole, is to weaken the current in the coil.

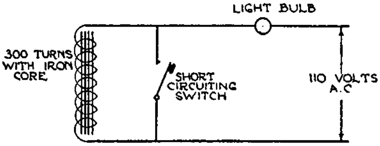


Fig. 71. — Inductance in an Alternating Current Circuit

In the experiment just described no effect of self-induction can be noticed when the current is direct. There is an effect with direct current, however, at the instant when the circuit is opened or closed. Self-induction on opening the circuit can be shown by means of the following experiment. A circuit is set up as in Fig. 72 with a small 6 volt bulb in parallel with a coil of, say, 600 or more turns on an iron core, a battery, a contact key or switch and a rheostat. The rheostat is adjusted so that the bulb is dimmed. When the circuit is broken the bulb flashes up brightly. This shows that on breaking the circuit the self-induction of the coil tends to keep the current going.

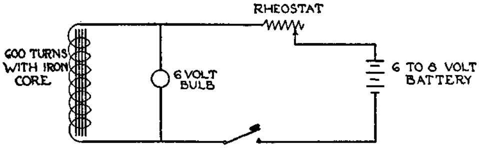


Fig. 72. — Inductance in a Direct Current Circuit

Self-induction in both direct and alternating current circuits can best be understood by comparing the effect with that of mutual induction. If we have a coil, as in Fig. 73, connected to a source of alternating current, a current flows from D to A then from A to D. The action between any two parts of the coil is the same as if there were two separate coils. As the stream of electrons starts to flow in the direction A to D and increases in strength, the moving electrons in AB set up a force which tends to drive electrons back from D to B. This is like the case of the two coils in Section 51. As the magnetic field increases in strength it induces an e.m.f. which opposes the current. After the current passes its maximum and begins to decrease, the electrons in one portion of the coil exert a force which tends to push the electrons along in the other portion of the coil; that is, to increase the current.

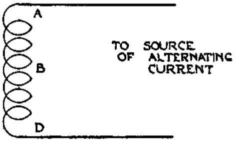


Fig. 73. — To Illustrate the Action of Electrons in a Circuit Having Inductance

The e.m.f. induced in a coil by the magnetic field of the coil itself is called the e.m.f. of self-induction. The property of an electric circuit by which an e.m.f. of self-induction is produced is called inductance.

The e.m.f. of self-induction opposes the current while it is growing stronger and helps it along while it is growing weaker. It might seem, then, that the resulting value of the current would be the same as if there were no self-induction but this is not true. In a coil with an alternating current the first effect more than balances the second so that the net result is to weaken the current.

56. Unit of Inductance. — The unit of inductance is the henry. A henry is defined as the inductance of a circuit in which an e.m.f. of one volt is induced when the current changes at the rate of one ampere per second. It should be understood that the inductance of a circuit is not the same thing as the induced electromotive force. The inductance of a coil remains the same whatever the nature of the current flowing through it but the e.m.f. of self-induction varies as the rate of change of current varies. To illustrate, suppose we have a coil whose inductance is one henry. Then if the current in the coil is increasing at the rate of one ampere per second, the e.m.f. of self-induction is one volt. If the current in the same coil is increasing at the rate of two amperes per second the e.m.f. of self-induction is two volts but the inductance is still one henry.

The henry is too large a unit for convenient use in radio calculations. Two smaller units are used in practical work, the millihenry which is one thousandth of a henry and the microhenry which is one millionth of a henry.

The inductance of a coil depends on the number of turns of wire, the size and shape of the turns and the magnetic permeability (See Sections 19 and 20) of the medium around the wire. As an example, a coil of a single layer of wire of 150 turns wound on a non-magnetic tube, such as cardboard, 5 inches in diameter and 5 inches in length has an inductance of about 1.1 millihenry. Methods of finding the inductance of coils will be given in Chapter X.

The definition of the henry may be stated in algebraic form as follows:

$$L = \frac{E}{I/t}$$

in which L is the inductance in henries, E is the induced e.m.f. in volts and I/t is the change in current per second.

57. Reactance. — The electromotive force in a direct current circuit is opposed only by the resistance of the circuit. An alternating electromotive force, however, is opposed not only by the resistance but also by the e.m.f. of self-induction. Self-induction acts like resistance in the sense of hindering the current. If the wire in the coil of Fig. 71 were unwound and connected in the circuit as a single loop, the bulb would light brightly. The coil might have perhaps only one or two ohms of resistance but when the wire is wound in a coil around an iron core it reduces the current as if it had many ohms of resistance.

The effect of a given e.m.f. of self-induction is equivalent to a certain number of ohms of resistance. The effect of self-induction in hindering the current is known as reactance and is measured in ohms.

While reactance is like resistance in one sense, in some respects it is very different. The resistance of a wire is the same whether the wire is straight or coiled. The reactance is greater if the wire is coiled. The resistance at low frequencies is the same whether a coil has an iron core or an air core. The reactance is greater with an iron core. The resistance at low frequencies is the same no matter at what rate the current is changing. The reactance increases with the frequency. The equation for reactance is,

$$X_L = 2\pi fL$$

in which X_L is the reactance in ohms, f is the frequency in cycles per second and L is the inductance in henrys. Stated in words, the inductive reactance equals 2π times the frequency times the inductance in henries.

To find the total hindrance to the current in an alternating current circuit it is necessary to know not only how to calculate the reactance but how to combine reactance with resistance. The combined effect of reactance and resistance is called impedance. Before discussing impedance it is necessary to explain what is meant by difference of phase.

58. Phase and Phase Angle. — If we refer to Fig. 68, we see that the voltage varies according to the angle through which the coil has turned. The voltage passes through various " phases " corresponding to the various angles. The curve for current is similar to the voltage curve. The current passes through phases as the voltage does. The term " phase " whether applied to voltage or current means position in the cycle.

If there is resistance and no inductance in the circuit the current is zero at the instant when the voltage is zero and reaches its maximum at the same instant as the voltage. It passes through its various phases with the voltage. The current and voltage are said to be " in phase." We might say, in simple language, they are keeping step together.

If there is self-induction in the circuit the current and voltage do not keep step together. Let us see why this is so. The key to the whole matter is that the e.m.f. of self-induction depends on the rate at which the current changes. The more rapidly the current changes the greater is the e.m.f. of self-induction. Now the current is changing most rapidly as it passes through the zero phase. This is clear from the graph for current, Fig. 74. The curve has the steepest slope where it crosses the axis at zero phase. Also there is an instant at the 90 degree phase when the current is not changing. Therefore the e.m.f. of self-induction is greatest when the current is at zero and least when the current is at a maximum. This means that there is a difference of phase of 90 degrees between the e.m.f. of self-induction and the current.

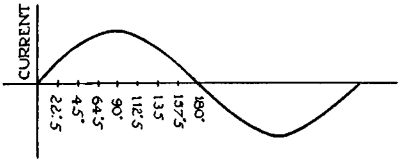


Fig. 74.— Current Graph

The effect of self-induction is to cause the current to lag behind the voltage. When the current is increasing the self-induction hinders it so that it reaches its maximum a little later than it would without self-induction. This is what is meant by the current lagging.

Suppose we had a circuit with inductance but no resistance. Then the applied e.m.f. would have no resistance to overcome. It would have to overcome only the e.m.f. of self-induction. Therefore the applied e.m.f. would be directly opposite to the e.m.f. developed by self-induction. This means that there would be a difference in phase of 180 degrees between the applied e.m.f. and the e.m.f. of self-induction. There would, therefore, be a difference of phase of 90 degrees between the current and the applied e.m.f. The current would lag 90 degrees behind the voltage. This is an ideal case for it is impossible to have a circuit with zero resistance. It is closely approached, however, in certain transformer coils in which the resistance is very low and the reactance very high. Fig. 75 shows the relation between current, applied e.m.f. and e.m.f. of self-induction in an ideal circuit having inductance but no resistance.

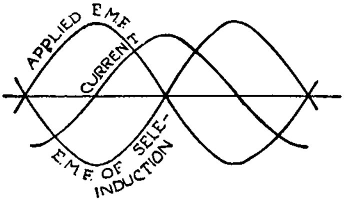


Fig. 75. — Showing Relation between Current, Applied E. M. F., and E. M. F. of Self-induction

If there is resistance but no inductance in the circuit the current and applied e.m.f. are exactly in phase. Increasing the resistance reduces the current but does not change its phase, does not cause it to reach its maximum any sooner or later. Therefore resistance is said to act in phase with the current. Since resistance is in phase with the current and the e.m.f. of self-induction is 90 degrees out of phase with the current, resistance and inductance are like two forces at right angles to each other. We must, therefore, apply the principle of the triangle of forces as in mechanics.

59. Mechanical Illustration of Phase and Phase Angle. — Let us take a simple illustration. Suppose we have a current of water flowing down an inclined pipe as in Fig. 76. It is the force of gravity that keeps the water flowing but there are two opposing forces, the friction between the water and the pipe which acts in direct opposition to the current and the pressure of the pipe which acts against the water, opposing gravity but in a direction perpendicular to the current. The friction corresponds to resistance and the pressure to reactance. These two forces together act in opposition to the force of gravity.

AB in Fig. 76 represents the pressure of the pipe against the stream of water and BC the friction. The resultant of the two is not their sum but the hypotenuse of the triangle of which AB and BC are the sides. The resultant force, therefore, equals the square root of the sum of the squares of the two forces. The same principle holds true of resistance and reactance. Impedance, which is the combined effect of resistance and reactance, equals the square root of the square of the resistance plus the square of the reactance. Letting Z represent impedance, R resistance and X reactance.

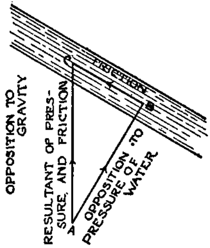


Fig. 76. — Phase Angle

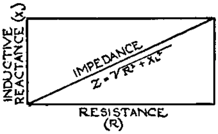


Fig. 77. — Showing the Relation between Impedance, Reactance, and Resistance

$$Z = \sqrt{R^2 + X^2}.$$

For example: If a certain coil has a resistance of 3 ohms and a reactance of 4 ohms, the impedance is not 7 ohms but the square root of $3^2 + 4^2$ or 5 ohms.

60. Effective Current. — If a direct current ammeter were connected in an alternating current circuit the needle would not move or would only vibrate slightly because the rapidly reversing current would tend to move the pointer first in one direction then the opposite. An ammeter must be used in which the pointer will move in the same direction no matter in which direction the current flows.

An alternating current is continually changing in value, rising from zero to a maximum, dropping again to zero and reversing. In all these changes what value is indicated by an alternating current ammeter? Suppose the ammeter indicates one ampere. What relation has one ampere to the whole cycle of changes through which the current is passing? The answer is suggested by the following simple test. Suppose we have an electric light bulb connected in a 110 volt direct current lighting circuit and that a direct current ammeter in series with this bulb reads one ampere. Now if we connect the same bulb in a 110 volt alternating current circuit, an alternating current ammeter will also read one ampere. The bulb glows with the same brightness in either circuit. The alternating current is producing the same heating effect as the direct current. The alternating current ammeter indicates the value of the constant current that would produce the same heating effect. This is called the " effective value " of the alternating current.

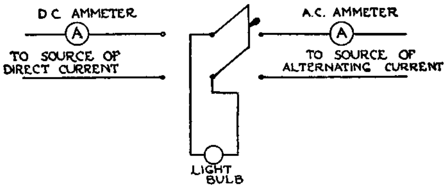


Fig. 78. — Meaning of Effective Value of an Alternating Current

61. Heat Curve. — The curve in Fig. 79 shows the relation between the current and its heating effect for one cycle. The ordinates of the heat curve are the squares of the ordinates of the current curve. The ordinates of the heat curve are all positive and the curve is entirely above the X axis because the square of any quantity is positive whether the quantity is positive or negative. The average heating effect is the average value of the heat ordinates. Now if we had a constant current that would produce the same heating effect, this current would be proportional to the square root of the heating effect. Therefore the effective value of the alternating current is also proportional to the square root of the average heating effect. But the average heating effect is the average of the squares of the current values. Therefore the effective current is the square root of the average square of the current over one complete cycle. This holds good whatever the form of the current curve. Stated briefly: The effective current is the square root of the average square. This is the current that is indicated by the alternating current ammeter. The abbreviated expression used in radio engineering is " root mean square."

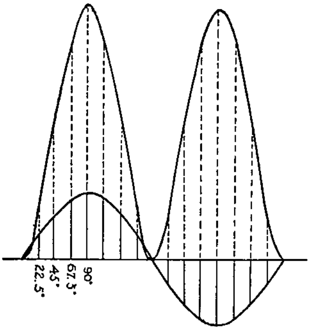


Fig. 79.—The Heat Curve

It is well to note that the effective current is not the average current. This can be shown by plotting a current curve and comparing the average value of the current ordinates with the square root of the average of their squares. Not much attention need be given to the average current for it is of little use in electrical calculations.

62. Effective Voltage.—The same rule applies to voltage as to current. The effective voltage is the square root of the average square of the voltage values throughout a cycle. This is true whatever the form of the voltage curve. Also the effective voltage equals the maximum voltage divided by the square root of 2. The reading of the alternating current voltmeter must be multiplied by the square root of 2 to find the maximum voltage. This equation applies only in the ideal case in which the voltage curve is a sine curve. In an actual generator the magnetic field is not uniform as a rule and the curve is not a sine curve. In a radio oscillation circuit the curve differs very greatly from the sine curve. In these actual circuits, then, the equation does not hold true. In any case, however, the maximum voltage is greater than the effective voltage.

One practical consequence of this is that the strain on the insulation of a coil is greater for alternating current than for direct current of the same voltage. For example, if we apply an alternating e.m.f. of 100 volts to the terminals of a coil the insulation of the coil must stand the strain, not of 100 volts, but of 141 volts or, in some cases, even more.

63. Condensers. — The action of a condenser in an alternating current circuit can be illustrated by the following experiment. Twelve or more one microfarad condensers such as are used in telephone circuits are connected in parallel and this group of condensers connected in series with a 110 volt light bulb to a 110 volt alternating current lighting circuit. (Fig. 80) The bulb will light but with the same arrangement on a direct current circuit it will not light.

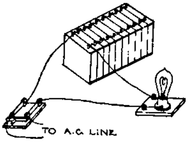


Fig. 80. — In series with condensers the bulb lights if the current is alternating

Referring to Fig. 81, if the bulb and condenser are connected to a direct current circuit, the electrons are trying to go in one direction say from A to B. The result is that electrons accumulate on one set of plates, C. An equal number of electrons leave the other set of plates, D. D is then lacking in electrons and C has an excess. There is a force urging the electrons to cross over from C to D but the insulation between the two sets of plates prevents them from going across. The travelling through the insulation is too hard for them. The movement of electrons soon ceases. There is a flow for an instant only after the circuit is closed.

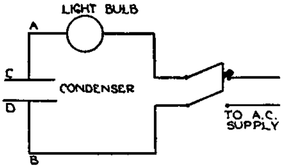


Fig. 81. — The Action of Electrons with a Condenser in the Circuit

Suppose we have an alternating current in the same circuit. There is a flow of electrons into C and away from D as before. Then the electromotive force reverses and electrons rush away from C and into D until D has an excess and C a deficiency of electrons. Then the e.m.f. again reverses and the process is repeated. There is a continual flow of electrons back and forth through the light bulb and the connecting wires. Thus we get an alternating current through the bulb though there is practically an open circuit between the two sets of plates of the condenser. Electric current does not flow through the condenser but electrons flow into and out of the condenser.

64. Capacity of Condensers. — The capacity of a condenser depends on three things.

First, the area of the plates. The larger the surfaces of the plates the more electrons they can hold and therefore, for a given e.m.f. the greater will be the charge on the plates of the condenser. The greater the area the greater the capacity.

Second, the distance between the plates. The smaller the distance between the plates the greater is the capacity for, as the positive and negative plates are brought closer together, the force of attraction becomes greater. This greater force enables the plates to hold more electrons so that for a given applied e.m.f. the charge on the plates is greater.

Third, the nature of the insulating material between the plates. The insulation between the plates of a condenser is known as the dielectric because the electric force acts through it. The word dielectric means electric force acting through. The force acting between the positive and negative plates can act more readily through certain materials than through others. For example, a condenser has greater capacity with mica as the dielectric than with air. For some reason not fully understood the force which causes electrons to accumulate in the negative plate can act more than four times as readily through mica as through air. The ability of a substance to convey the influence of the electric charge through it is the dielectric constant (sometimes called specific inductive capacity) of the substance. The dielectric constant corresponds in a certain way to magnetic permeability or the ability of a substance to allow magnetic lines of force to act through it. The dielectric constant is to the field of electric force what permeability is to the field of magnetic force. The dielectric constant for the materials most commonly used in condensers is as follows:

Air	1.00
Glass	2.8 to 9.9
Mica	4.6 to 8.0
Paraffined paper	2.8 to 3.8

The dielectric constant should not be confused with the dielectric or disruptive strength of a substance. The latter term refers to the voltage necessary to cause an electric charge to break through the substance and, therefore, to the strength of the material as an insulator. For example, it requires about 800 volts to cause a spark to pass through one millimeter of air, from 6,000 to 8,000 volts for one millimeter of glass and from 17,000 to 28,000 volts to break through one millimeter of mica.

65. Unit of Capacity. — The unit of capacity is the farad. A condenser has a capacity of one farad if a difference of potential of one volt between the plates produces a charge of one coulomb. In terms of volts and amperes the farad may be defined as the capacity of a condenser such that an e.m.f. across the plates changing at the rate of one volt per second causes a current of one ampere to flow. The farad is too large a unit for convenient use. The microfarad or one-millionth of a farad is the unit more commonly used particularly in telephone and radio work. In considering tube capacities a still smaller unit is often used, a millionth of a millionth of a farad or a micro-microfarad.

66. **Effect of Capacity on Current.** — We have seen that inductance causes the current to lag behind the voltage. The effect of capacity is just the opposite. Capacity causes the current to lead or go ahead of the voltage. With the capacity in the circuit the current tends to reach its maximum before the voltage does. This can be understood best by considering the action of the electrons. Let us begin at the instant when the voltage starts from zero. The voltage is now rising rapidly and driving electrons into one set of plates and out of the other. A strong stream of electrons flows because there is nothing in the way to hinder them. Now the e.m.f. approaches its maximum. A large number of electrons have accumulated in the negative plate and they repel those that are coming up. Although the e.m.f. is near its maximum, electrons cannot flow into the plate so rapidly as before because other electrons are there to hinder them. This means that the current becomes less as the e.m.f. approaches its maximum. The current or rate of flow of electrons is greatest when the voltage is near the zero point and dies down to zero as the voltage approaches its maximum. If there were capacity but no resistance or inductance in the circuit the current would reach its maximum as the voltage passed through the zero point. In other words the current would be 90 degrees ahead of the voltage.

67. **Capacity Reactance.** — A condenser offers a certain opposition to the flow of current which is known as capacity reactance. As we have seen, the greater the capacity of a condenser the greater the current. In other words the greater the capacity the less the reactance. Again, the more rapidly the e.m.f. changes, the greater the flow of electrons to and from the condenser. In other words, the greater the frequency the stronger the current and, therefore, the less the reactance. In both these respects capacity reactance acts in a manner exactly

opposite to that of inductive reactance for if either the inductance or the frequency is increased the inductive reactance is increased. It is well to keep in mind the opposite effects of inductive reactance and capacity reactance. If we let X_c represent capacity reactance, f the frequency and C the capacity in farads, then

$$X_c = \frac{1}{2\,\pi f\,C}.$$

Example. — The reactance of a condenser of 0.01 microfarad capacity for an e.m.f. having a frequency of 60 cycles per second is

$$\frac{1}{2\,\pi\,fC}$$

which equals, remembering that 0.01 microfarad equals 0.000,000,01 farad,

$$\frac{1}{6.283 \times 60 \times 0.000{,}000{,}01} = 265{,}000 \text{ ohms approximately.}$$

The reactance of the same condenser for a frequency of 600,000 cycles per second is

$$\frac{1}{6.283 \times 600{,}000 \times 0.000{,}000{,}01} = 26.5 \text{ ohms.}$$

It is clear from this example that a given condenser offers much less hindrance to the flow of currents of high frequency than to currents of low frequency. This is particularly important in radio circuits.

68. Impedance in a Circuit Having Capacity. — Since capacity reactance is 90 degrees out of phase with the current and resistance is in phase with the current there is a difference of phase of 90 degrees between capacity reactance and resistance. The same line of reasoning can be applied as in the case of inductive reactance to show that the combined effect of capacity reactance and resistance is the square root of the sum of their squares. If we let Z represent impedance, X_c capacity reactance and R resistance, then

$$Z = \sqrt{X_C^2 + R^2}.$$

A diagram showing the relation between capacity reactance, resistance and impedance is given in Fig. 82. It is customary to draw the line for capacity reactance below the resistance line and that for inductive reactance above the resistance line because the two act in opposite ways. If the capacity reactance and the inductive reactance of a circuit are equal in magnitude the resulting reactance is zero, one reactance neutralizes the other. For example, if the inductive reactance would cause the current to lag 30 degrees and the capacity reactance would cause the current to lead 30 degrees, the two would neutralize each other and the current would be in phase with the voltage. In such a case if the inductive reactance is a certain number of ohms, say 10, the capacity reactance is –10 ohms. A diagram for a circuit having inductive reactance, capacity reactance and resistance is given in Fig. 83. In this figure the

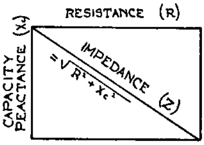


Fig. 82. — Relation between Capacity Reactance, Resistance, and Impedance

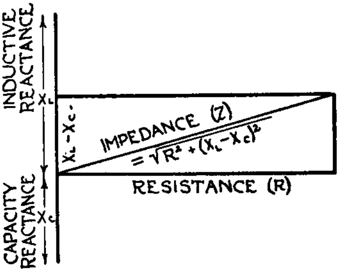


Fig. 83. — Relation between Inductive Reactance, Capacity Reactance, Resistance, and Impedance

inductive reactance is greater than the capacity reactance and the resulting reactance is the difference between the two. This resulting reactance is then combined with the resistance, by the rule for the right angle triangle, to find the impedance.

In diagrams such as those of Figs. 77 and 83, the angle of lag is the angle formed by the impedance line and the resistance line. If the angle is below the resistance line as in Fig. 82 it is an angle of lead.

69. Condensers in Parallel and Series. — The capacity of two or more condensers in parallel is the sum of their capacities taken separately. If we connect two condensers of equal capacity in parallel (Fig. 84) the result is the same as if we doubled the size of the plates. For the same e.m.f. across their terminals the two condensers will receive twice as great a charge as one condenser. If we connect any number of condensers in parallel across a line having an alternating current, the current that flows is the sum of the currents that would flow with the condensers taken separately across the same line.

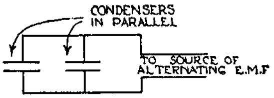


Fig. 84

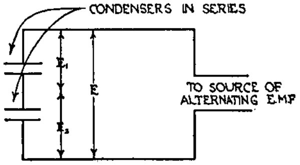


Fig. 85

Connecting condensers in series (Fig. 85) amounts to increasing the thickness of the dielectric and therefore reduces the capacity. If two condensers of equal capacity are connected in series, the capacity of the two together is one-half that of one of the condensers. If condensers of any capacity are connected in series, their combined capacity is less than that of any one of the condensers.

A practical example is that of a condenser in series with the antenna in a radio circuit. The condenser has the effect of reducing the capacity of the antenna and therefore of reducing the wave length (Sec. 81).

The mathematical proof of the laws of condensers in series is given in the appendix.

70. Ohm's Law and Alternating Currents.—The total hindrance to the current in an alternating current circuit is called the impedance. We have seen that when the circuit contains resistance and inductive reactance the impedance equals the square root of the resistance squared plus the reactance squared.

$$Z = \sqrt{R^2 + X_L^2}.$$

If a circuit contains resistance and capacity reactance we have a similar equation.

$$Z = \sqrt{R^2 + X_C^2}.$$

If a circuit contains resistance, inductive reactance and capacity reactance, the capacity reactance must first be subtracted from the inductive reactance to find the resulting reactance. The square of this result plus the square of the resistance equals the square of the impedance.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

In a direct current circuit, the current equals electromotive force divided by resistance. In an alternating current circuit, current equals electromotive force divided by impedance.

For direct current,

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

For alternating current,

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

Substituting the value of Z,

$$I = \frac{E}{\sqrt{R^2 + (X_L - X_C)^2}}.$$

Example. — The primary coil of a certain transformer has a resistance of 2 ohms and an inductive reactance of 100 ohms at 60 cycles. What current will flow in this coil if connected to a 120 volt direct current circuit?

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

$$= \frac{120}{2}$$

$$= 60 \text{ amperes.}$$

What current will flow in the same coil if connected to a 60 cycle alternating current circuit of the same voltage?

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

$$= \frac{E}{\sqrt{R^2 + X_L^2}}$$

$$= \frac{120}{\sqrt{2^2 + 100^2}}$$

$$= 1.2 \text{ amperes nearly.}$$

Example. — What current flows in an alternating current circuit having an e.m.f. of 120 volts, a resistance of 2 ohms, an inductive reactance of 100 ohms and a capacity reactance of 80 ohms?

$$I = \frac{E}{\sqrt{R^2 + (X_L - X_C)^2}}$$

$$= \frac{120}{\sqrt{2^2 + (100 - 80)^2}}$$

$$= 5.7 + \text{ amperes.}$$

71. Power Factor. — If we were to connect a voltmeter and an ammeter in an alternating current circuit having inductance or capacity and multiply volts by amperes the result would not be the true power available for actual use in the circuit but only the apparent power. Let us see why this is so.

It has been shown that resistance and reactance have a difference of phase of 90 degrees. They act like two forces at right angles to each other. Their combined effect is not their sum but the square root of the sum of their squares.

Returning now to the illustration of water flowing down an inclined pipe, the force which causes the water to flow is that of gravity. If the pipe is vertical the entire weight of the water acts to cause the water to flow. If the pipe is horizontal, the weight of the water or the pressure due to gravity has no effect in causing a flow of water. If the pipe is inclined the pressure due to gravity may be resolved into two components, one acting along the pipe in the direction of the current, the other perpendicular to the pipe. See Fig. 86. The latter force is the pressure of the water against the pipe. Because this force is perpendicular to the pipe it has no effect in causing a current to flow or in developing power. Only the component of gravity in the direction of the current develops power. The power of a water current like the power of an electric current equals pressure times rate of flow but we must take the component of pressure in the direction of the current. To complete the comparison, the applied electromotive force

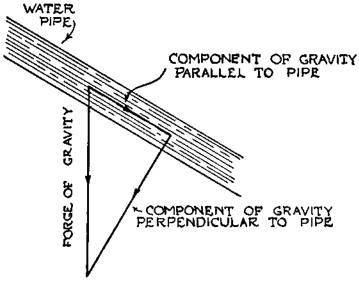


Fig. 86. — Meaning of Power Factor

corresponds to the force of gravity or the weight of the water. The component of e.m.f. in phase with the current corresponds to the component of gravity lengthwise of the pipe. The component of e.m.f. 90 degrees out of phase with the current or in direct opposition to the reactance corresponds to the component of gravity perpendicular to the pipe.

For a direct current,

$$\text{Watts} = \text{volts} \times \text{amperes}.$$

$$P = EI.$$

A similar relation exists in an alternating current circuit but in this case we must take, not the applied e.m.f., but the component of applied e.m.f. which is in phase with the current.

We may use a triangle to represent the applied e.m.f. and the two components similar to the triangle for impedance, resistance and reactance. The same relation exists between the applied e.m.f. and its two components as between impedance, resistance and reactance. This is shown in the triangles in Fig. 87. The product of the current and the voltage is the apparent power. The product of the current and the voltage component in phase with the current is the true power or the power available for actual use as in heating, lighting or running motors. It is evident from the discussion above and from the triangles in Fig. 87 that the ratio of the true power to the apparent power equals the ratio of resistance to impedance.

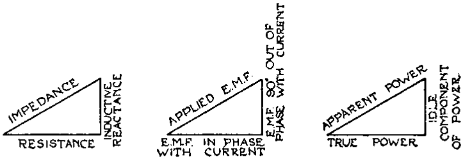


Fig. 87

$$\frac{\text{True power}}{\text{Apparent power}} = \frac{\text{Resistance}}{\text{Impedance}}.$$

$$\text{True power} = \text{Apparent power} \times \frac{\text{Resistance}}{\text{Impedance}}.$$

The factor, $\frac{\text{resistance}}{\text{impedance}}$, by which we must multiply the apparent power to get the true power is called the power factor. Apparent power is measured in volt-amperes to distinguish it from the true power in watts. Letting P be the true power and F the power factor, we have,

$$P = E\,I\,F.$$

If there is no reactance in the circuit the power factor is 1 and we have

$$P = E\,I$$

as in the case of a direct current.

In the coils of a radio circuit the power factor may be very small on account of the high frequency of the currents.

The power factor or ratio of resistance to impedance is the cosine of the angle of lag. The cosine of an angle in a right triangle is the adjacent side divided by the hypotenuse. This is one of the functions of angles frequently used in electrical calculations.

Example. — A voltmeter connected across a coil in an a.c. circuit reads 100 volts and an ammeter shows that a current of 5 amperes is flowing through the coil. The angle of lag is 60 degrees. How many watts of power are being consumed in the coil?

Solution. — Since the angle of lag is 60 degrees the effective component of e.m.f. is one-half the applied e.m.f. The power factor is ½ and

$$P = 100 \times 1/2 \times 5 = 250 \text{ watts.}$$

Example. — What is the true power in a coil having a resistance of 150 ohms, a reactance of 200 ohms and an e.m.f. at its terminals of 250 volts?

Solution. —

Impedance, $Z = \sqrt{200^2 + 150^2} = 250$ ohms,

Current, $I = \frac{E}{Z} = \frac{250}{250} = 1$ ampere,

$$\text{Power factor, } F = \frac{R}{Z} = \frac{150}{250} = 60 \text{ per cent,}$$

$$\text{Power,} \qquad P = E\,I\,F = 250 \times 1 \times 0.60 = 150 \text{ watts.}$$

72. Eddy Currents and the Repulsion Effect. — If a sheet of copper or other non-magnetic metal is held above a coil through which an alternating current is flowing, as in Fig. 88, currents are induced in the sheet of metal by the changing magnetic lines of force of the coil. These currents are called eddy currents. They are simply electric whirls in the metal.

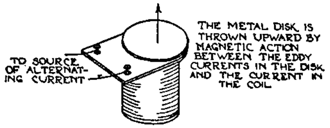


Fig. 88. — The Repulsion Effect

If the magnetic field of the coil is fairly strong the metal sheet will be thrown violently upward on account of the repulsion between its own magnetic field and that of the coil. If slots were cut in the sheet of metal nearly dividing it into narrow strips the eddy currents would be much reduced because they could not cross the gaps between the strips.

The cause of the repulsion here is the same as in the experiment on mutual induction between two coils. It was explained in Section 54 that there is attraction during part of the cycle and repulsion during the other part of the cycle. It can be shown that on account of the lag of the current the repulsion continues during a greater part of the cycle than the attraction.

73. Transformers. — A transformer consists of two windings, a primary and a secondary, operating on the principle of mutual induction (Section 51). An alternating current in the primary winding induces an alternating e.m.f. in the secondary. In order that the magnetic field of the primary may have the greatest possible effect on the secondary, the two coils are wound on the same iron core. The core is laminated; that is, built up of thin sheets of iron, in order that the currents induced in the core itself, eddy currents, may be as small as possible. The oxide film between the laminations is practically an insulation with respect to these currents.

There are two general types of transformers, the shell type and the core type. In the shell type (Fig. 89) the core encloses the coils. The core type may have either of two forms as shown in Fig. 90. As a general rule the shell type is to be preferred on account of having less magnetic leakage than the core type. Radio transformers are made of both types.

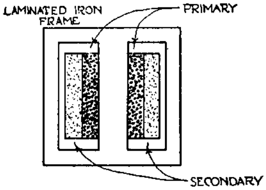


Fig. 89.—Shell Type Transformer

Fig. 90.—Two Forms of Core Type Transformer

Transformers are used principally to deliver current at a higher or lower voltage than that which they receive. On long distance power lines, transformers are used at the power plant to " step up " the voltage. This is done for the reason that, at high voltage, power may be transmitted with much less loss than at low voltage. At the consumer's end of the line transformers are used to " step down " the voltage to that required for light bulbs and motors. Bell-ringing transformers are used to step down the voltage from that of the lighting circuit to the low voltage required for the electric bell. The transformers used in radio circuits operate on the same principle as all other transformers.

The voltage of the secondary of a transformer is to the voltage of the primary as the number of turns on the secondary is to the number of turns on the primary. To state it more briefly, the voltages are directly proportional to the number of turns. This is strictly true only if all the lines of force of the primary act on the secondary; in other words, if there is no magnetic leakage. In practical transformers the leakage is small and this relation is approached very closely. For example, a transformer designed to receive current at 6000 volts and deliver current at 60,000 volts must have ten times as many turns on the secondary as on the primary. A bell-ringing transformer designed to receive current at 120 volts and deliver current at 10 volts must have one-twelfth as many turns on the secondary as on the primary.

The common voltage and current transformers do not change frequency. The frequency of the secondary current is the same as that of the primary. Special transformers designed for changing frequency are sometimes used.

74. Power Lost in a Transformer. — Even though a transformer steps up the voltage it does not increase the power. If it steps up the voltage it steps down the current. For example, if a transformer steps up the voltage from 6000 to 60,000 it will deliver not more than one-tenth as much current as it receives. In fact it will deliver less than one-tenth for some power is wasted in the transformer. No machine can deliver more power than it receives and the transformer is no exception to the rule. The efficiency of transformers, however, is high as compared with most machines and with most other kinds of electrical apparatus. Most transformers will deliver from about 94 to 98 percent of the power they receive.

Power is lost in a transformer in three ways. First; in the eddy currents in the core. The alternating magnetic field of the primary induces currents in the iron core which can do nothing but heat the iron thus wasting power. Thin laminations reduce this loss as explained in Section 72. Second; power is lost in hysteresis; that is, changing the magnetism of the iron (Section 20). Third; power is lost in heating the wires of the coils. This is sometimes called the I^2R loss for it is found by multiplying the square of the current by the resistance of the coil. (See power equation, Section 25.)

75. The Electron Tube as a Rectifier. — We have seen in Chapter V that electrons can flow only in one direction in an electron tube; that is, from filament to plate. Such a tube may be used to produce a direct current from an alternating current. A device used for this purpose is called a rectifier. The most common use of rectifiers is in charging storage batteries where only alternating current is available. The electron tube rectifier has only two electrodes and is a development of the Fleming valve which preceded the three-electrode tube used today in radio.

The circuit of an electron tube rectifier is shown in Fig. 91. A transformer is connected across the a.c. line. The filament is connected across two taps of the secondary which give the proper filament voltage. The storage battery is connected in the plate circuit to a tap which gives the proper voltage for charging. During one half of the cycle when the current is flowing from B to A, that is, when the electrons are flowing from A to B, a current flows through the battery. During the other half of the cycle when the current is flowing from A to B, no current flows through the battery because electrons cannot flow from plate to filament. The current, therefore, can flow only in one direction through the battery. It might seem that power is wasted during the half cycle when current is not

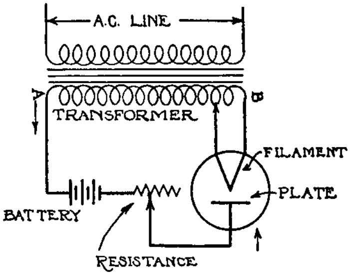


Fig. 91. — Circuit for Battery Charging Using Electron Tube Rectifier

flowing through the battery. This is not the case because, when no current is flowing through the tube, no power is being taken from the line except the small amount needed to light the filament and excite the transformer.

76. Electrolytic Rectifiers. — If a cell is made of a plate of aluminum and a plate of lead in a solution of ammonium carbonate or ammonium phosphate, current can flow in only one direction through the cell. A film of oxide forms at the surface of the aluminum which allows electrons to flow from the aluminum into the solution but not in the reverse direction. Current flows through the cell, then, only when the aluminum is negative. If four such cells are connected with a battery as in Fig. 92, the battery can be charged, both halves of the cycle being utilized. The full-line arrows show the direction of the current for one half of the cycle, the dotted arrows for the other half. A lamp rheostat is shown in series with the cells for regulating current strength.

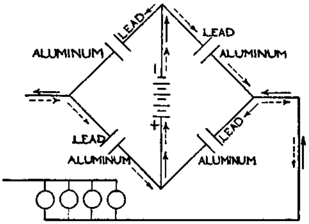


Fig. 92. — Circuit for Charging Battery with Electrolytic Rectifier

A cell which has some advantages over the one just described is made of tantalum and lead in sulphuric acid. The tantalum rectifier is less affected by changes of temperature than the aluminum rectifier. A circuit for charging a battery with a tantalum rectifier of one cell having two tantalum electrodes and one lead electrode is shown in Fig. 93. A step down transformer is used to give the proper voltage for the battery. Four tantalum-lead cells may also be connected in the same manner as the aluminum-lead cells in Fig. 92, the tantalum electrodes having the same connections as the aluminum electrodes in that figure.

Electrolytic rectifiers can be used successfully for small currents not exceeding 2 or 3 amperes but are not successful with heavy currents because of the heat that would be developed and the gassing at the electrodes.

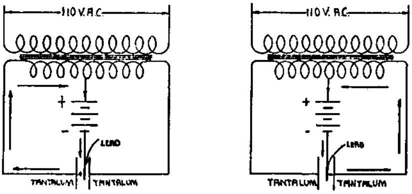


Fig. 93. — Tantalum Rectifier

77. Vibrating Reed Rectifiers. — The rectifier shown in Fig. 94 operates by means of a magnet one pole of which is a permanent steel magnet, the other an alternating current magnet. When the current in the a.c. magnet is flowing in a direction such that its polarity is the same as that of the steel magnet, the two magnetic fields act together and pull in the armature. The armature then makes a contact at the point P and allows current to flow through the battery. When the current in the a.c. magnet flows in the reverse direction its polarity is opposite that of the permanent magnet, the two magnetic fields tend to neutralize each other, the magnetic pull on the armature is released and the spring pulls it back, breaking the contact. The armature, then, allows current to flow through the battery during one half of the cycle. It will operate successfully only if the natural period of vibration of the spring is the same as the frequency of the alternating current. A thumb screw is provided for adjusting the tension of the spring so that it will vibrate in step with the current.

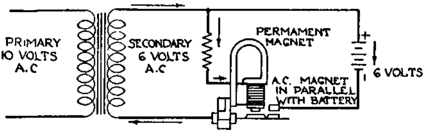


Fig. 94. — Vibrating Reed Rectifier

The vibrating reed rectifier, like the electrolytic rectifier, is suitable for charging a battery at a low rate but is not suitable for heavy currents. For heavy currents a motor generator is best. This consists of an alternating current motor driving a direct current generator which delivers current at the proper voltage for battery charging.

78. Dry Plate Rectifiers. — It has been discovered that certain materials when placed in contact in the form of dry plates allow electrons to flow in one direction across the contact surface but hinder, or entirely prevent, their flow in the opposite direction. Plates of copper and copper oxide may be taken as an example. Electrons can flow more readily into the copper oxide than into the copper. A rectifier can be made, therefore, of alternate plates of copper and copper oxide. The copper plates are negative and the copper oxide plates positive. Such a rectifier can be used in charging a storage battery, the connections being the same as for an electrolytic rectifier.

The cause of the rectifying action of the dry plates is not known. There is probably a definite relation between this action and that of the electrolytic rectifier. The cause probably lies in the structure of the molecules, the nature of the molecules of one substance being such as to hinder the movement of the electrons and, of the other, such as to admit the electrons freely.

79. Resonance. — We have seen that inductive reactance causes the current to lag (Section 58) and that capacity reactance causes the current to lead (Section 66). Suppose we have an inductive reactance which would cause a lag of ten degrees and a capacity reactance which would cause a lead of ten degrees. If the two are connected in series they will neutralize each other and the current will be in phase with the electromotive force. A coil and a condenser in series may be so adjusted that the effect of one just neutralizes the effect of the other so far as the phase relation of current and voltage is concerned and there is neither lag nor lead.

The fact that inductive reactance and capacity reactance in series tend to neutralize each other can be shown by the following experiment: A condenser of 12 microfarads capacity or less, a variable inductance of at least 0.6 henry and a light bulb are connected in series. For the condenser telephone condensers in parallel may be used and for the inductance a coil of 300 turns of number 18 wire on an iron core about 2 inches in diameter fitted with a removable iron frame. This circuit is connected to a source of alternating current, 110 volt 60 cycle, such as the common a.c. lighting circuit. Fig. 95 is a diagram of the circuit. When either the inductance coil or the condenser is short circuited the lamp is dimmed showing that either the inductive reactance or the capacity reactance reduces the current. Now with the short circuits removed the inductance is slowly changed by moving the coil into or out of the iron.[1] For a certain value of the inductance the lamp will glow brightly showing that the reactance of the coil and the reactance of the condenser are neutralizing each other. If the frequency is changed the lamp will again grow dim showing that the inductive and capacity reactances neutralize each other for one frequency but not for another. The inductance may be adjusted to neutralize the capacity reactance again for the new frequency. The frequency can be changed if the alternating current is derived from a converter or motor generator which has a speed control.

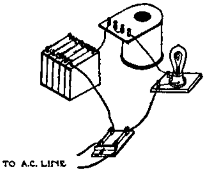


Fig. 95. — Resonance in a 60-cycle House Lighting Circuit

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[1] A dissectible transformer, designed by the writer, suitable for this experiment is manufactured by the Central Scientific Company, Chicago. A suitable inductance may also be made by winding a coil on a cardboard tube and using an iron core which just fits the tube. The inductance can then be varied by moving the core into or out of the tube. A tube of 12″ length and 3″ diameter wound with 1000 turns and having a core of Norway iron or silicon steel may be used. The experiment makes the fact of resonance visible using the ordinary a.c. lighting current.

The experiment just described illustrates the tuning of a radio receiver. Tuning is simply adjusting either the inductance or the capacity until resonance is obtained for a certain frequency.

When a capacity reactance and an inductive reactance of equal magnitude are connected either in series or parallel a condition of resonance is obtained.

80. Equation for Series Resonance. — Let us see what the frequency is at which the two reactances neutralize each other. When the inductive and the capacity reactances exactly neutralize each other, the only opposition to the current is the resistance. The impedance of such a circuit is equal to the resistance as shown in Fig. 96. The reactances are equal and opposite. Their algebraic sum is zero and we have the equation,

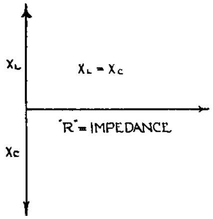

Fig. 96. — When Inductive Reactance and Capacity Reactance are Equal, Impedance Equals Resistance

$$X_L = X_C$$

or

$$X_L - X_C = 0.$$

X_L is the inductive reactance and X_c the capacity reactance, both in ohms. L is the inductance in henries, C the capacity in farads and f the frequency in cycles per second.

Now let us substitute the values of X_L and X_c as given in Sections 57 and 67.

$$X_L = 2\pi fL.$$

and

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

Making this substitution we have,

$$2\pi fL - \frac{1}{2\pi fC} = 0.$$

Clearing of fractions we have,

$$4\pi^2 f^2 LC - 1 = 0.$$

Transposing we have,

$$4\pi^2 f^2 LC = 1.$$

Dividing by $4\pi^2$ LC, we have

$$f^2 = \frac{1}{4\pi^2 LC}.$$

Taking the square root of each side of the equation, we have

$$f = \frac{1}{2\pi\sqrt{LC}}.$$

This might well be called the fundamental equation in radio. From this equation are derived the equations used in calculating wave length in oscillating circuits including grid and plate circuits when tuned, wave meters, filters and antenna circuits.

81. Wave Length of a Resonant Circuit. — In any form of wave motion the length of one wave times the number of waves per second equals the velocity or the distance the waves travel in one second. The number of waves per second is the frequency. Hence wave length times frequency equals velocity. (See Fig. 97.) Let us state this fact in an equation. The Greek

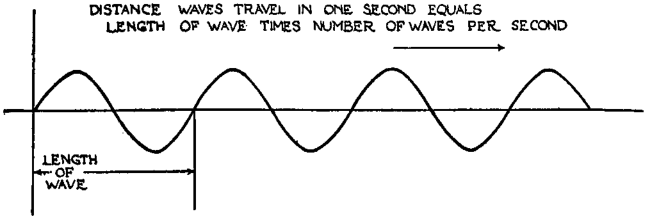

Fig. 97

letter (pronounced lambda) is used to represent wave length. Let v = velocity, f = frequency, then

$$f\lambda = v$$

or

$$\lambda = \frac{v}{f}.$$

The velocity of electromagnetic waves is three hundred million meters per second. Substituting this number for v, we have

$$\lambda = \frac{300{,}000{,}000}{f}.$$

Now substituting the value of f we have

$$\lambda = \frac{300{,}000{,}000}{1/2\pi\sqrt{LC}},$$

or, simplifying the fraction,

$$\lambda = 300{,}000{,}000 \times 2\pi\sqrt{LC}.$$

Taking 6.28 as the approximate value of 2π, we get

$$\lambda = 1{,}884{,}000{,}000\sqrt{LC}.$$

The number, 1,884,000,000 is approximate.

This equation is true if L is in henries and C in farads. It is more convenient to express L in microhenries and C in microfarads. This change must be made without changing the value of the right hand side of the equation. To reduce L to microhenries we must multiply by one million. C must also be multiplied by one million to reduce to microfarads. Hence the quantity under the radical sign must be multiplied by one million times one million. Now since this quantity is under the square root sign it is equivalent to multiplying the right hand side of the equation by one million. To avoid changing the value we must now divide this side of the equation by one million and this we can do by cutting off the six zeros. This gives

$$\lambda = 1884\sqrt{LC},$$

when L is in microhenries and C in microfarads. This is the wave length equation.

Example. — What inductance must a coil have to give resonance if connected in series with a condenser of 12 microfarads capacity in a 60 cycle circuit?

Solution:

$$12 \text{ microfarads} = 0.000{,}012 \text{ farad}.$$

Substituting the values of f and C in the equation,

$$f = \frac{1}{2\pi\sqrt{LC}},$$

we have

$$60 = \frac{1}{2\pi\sqrt{0.000012\ L}}.$$

Solving this equation for L gives

$$L = 0.6 \text{ henry nearly}.$$

Example.— A certain radio circuit has an inductance of 1000 microhenries and a capacity of 0.001 microfarad. What is the wave length for which this circuit will give resonance?

Solution:

$$\begin{aligned}\lambda &= 1884\sqrt{LC},\\ &= 1884\sqrt{1000 \times 0.001}\\ &= 1884 \text{ meters}.\end{aligned}$$

Example. — What inductance is required in series with a condenser of 0.001 microfarad capacity for a wave length of 300 meters?

Solution:

$$\lambda = 1884\sqrt{LC}$$

$$300 = 1884\sqrt{0.001\ L}$$

Solving for L gives

$$L = 26 \text{ microhenries nearly}$$

82. Voltages in a Series Resonant Circuit. — A very interesting condition is found in the voltages of a series resonant circuit. The voltage across either the coil or the condenser may be enormously greater than the voltage applied to the circuit. For example, in the circuit used in the resonance experiment (Section 79), the inductance is 0.6 henry. If we substitute this value for L in the equation,

$$X_L = 2\pi fL,$$

we get approximately 226 ohms for the inductive reactance X_L. Since the circuit is in resonance the capacity reactance is also 226 ohms. Suppose we have 10 ohms resistance in the circuit and apply 110 volts at the outside terminals. Then since the reactances of the coil and condenser neutralize each other, the only effective opposition to the current is the resistance and we have by Ohm's law,

$$I = \frac{E}{R} = 10 \text{ amperes.}$$

Since we have a series circuit the same current is flowing in all parts. The e.m.f. across any part of the circuit equals the current times the impedance (Section 70). The impedance in the coil is practically equal to the reactance of the coil since the resistance is small. The e.m.f. across the coil therefore is

$$226 \times 10 = 2260 \text{ volts.}$$

The e.m.f. across the condenser is also 2260 volts. It should be remembered that this is the effective e.m.f. The maximum e.m.f. is higher. Although these enormous voltages exist in the coil and the condenser, the e.m.f. of the condenser at every instant opposes that of the coil. In other words the two e.m.f.'s are opposite in phase.

83. Electrons in a Series Resonant Circuit. — What happens to the electrons in a resonance circuit? A stream of electrons surges back and forth in the entire circuit. This stream requires only a small pressure at the outer terminals of the circuit to keep it going. It requires a much greater pressure to keep the electrons moving through the coil on account of the reactance of the coil but there is a greater pressure at the terminals of the coil as shown in the preceding paragraph. There is also a greater pressure at the terminals of the condenser on account of the condenser reactance. A large amount of energy is transferred back and forth between the coil and the condenser. When once this surging back and forth of energy is started it requires very little outside force to keep it going. The only outside force required is that necessary to overcome the resistance. The part of the circuit composed of coil and condenser is said to be oscillating.

Let us take a very simple mechanical illustration. We shall suppose that a heavy boy is in a swing and a small boy tries to start him swinging. The small boy cannot move the large boy very far at one push but the swing has a natural rate of vibration and, if the small boy times his pushes according to this rate, he will move the larger boy a little farther with each push until he has set him swinging through a large distance. Now comes the important point. When the small boy has accomplished this he can keep the large boy swinging by feeble pushes, just enough to overcome the friction. While he is doing this, there is much more energy in the motion of the large boy than in the pushes which the small boy gives to keep him going.

The natural rate of vibration of the swing corresponds to the resonant frequency of the circuit. The energy of motion of the larger boy corresponds to the energy of oscillation of coil and condenser. The feeble pushes of the small boy correspond to the small applied e.m.f. needed to keep the oscillations going. The pushes of the small boy overcome only friction. The applied e.m.f. overcomes only resistance.

We may carry the illustration a little farther and imagine that the small boy's pushes are a little too fast or a little too slow to set the large boy swinging. This corresponds to the condition in which the frequency of the incoming signal is not the same as the natural rate of oscillation of the coil and condenser circuit. Then we might suppose the length of the swing to be changed until its rate of vibration corresponds to the frequency of the small boy's pushes. This corresponds to changing inductance or capacity; that is, tuning the circuit until its natural rate of oscillation corresponds to the frequency of the received signal.

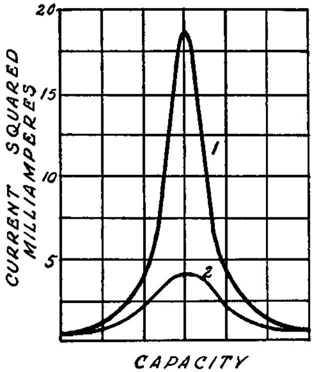

Fig. 98. — Resonance Curves for a Single Tuned Circuit. Curve Number 2 Shows the Effect of Adding Resistance

84. Resonance Curves. — Figure 98 shows two curves in which the ordinates represent current squared and the abscissas represent capacity. Such curves can be obtained by tuning a receiving circuit to resonance with signals of a given frequency, measuring the plate current with a milliammeter, then measuring plate current for a number of settings of the condenser when the circuit is near but not quite at the point of resonance. Curve number 1 is drawn for a circuit having inductance and capacity but very low resistance. This curve has a sharp peak at resonance and drops off rapidly on either side of the peak. This shows sharp tuning. The circuit for curve number 2 has the same inductance and capacity as for curve number 1 but with high resistance. This curve shows that an increase in resistance reduces the current at resonance. It is also noticeable that the curve does not drop off sharply from the peak but flattens out. This denotes lack of sharpness in tuning. The practical conclusion is that the resistance of the tuning circuit must be kept low.[2]

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[2] The derivation of the equation for the second curve involves higher mathematics that are beyond the scope of the present text. Those who care to go into the subject more deeply will do well to look up the derivation of

85. Parallel Resonance. — If the coil and condenser used in the experiment on series resonance (Section 79) are connected in parallel and the combination of coil and condenser connected in series with a light bulb to a 110 volt, 60 cycle circuit the light will be dimmed or extinguished. The same values of inductance and capacity that made the lamp glow brightly in the series arrangement extinguish the light in the parallel arrangement. This is another case of resonance. If the frequency is changed the lamp again glows. The inductance and capacity which we now have in the circuit cut off the 60 cycle current but do not cut off current of a different frequency. For example, if we were to apply to this circuit e.m.f.'s of 60 cycles and 120 cycles, a current of 120 cycles would flow but the 60 cycle current would not flow. This experiment illustrates the filter used in a radio circuit to filter out signals of a certain frequency and allow signals of other frequencies to pass.

86. Electrons in a Parallel Resonant Circuit. — We have seen that in a series resonance circuit the inductive reactance and the capacity reactance neutralize each other so that the current and voltage of the line are in phase and the line current is of the same value as if there were no reactance. A stream of electrons is surging through the coil and into and out of the condenser and this stream of electrons also surges through the line. The lamp in the series resonance circuit lights brightly because it is in the path of this stream of electrons. If the coil and condenser are in parallel, as in Fig. 99, the coil and condenser form a complete circuit, CBDG. Electrons surge back and forth through the coil and into and out of the condenser as in the series arrangement but now the lamp is not in the path of this stream of electrons. The very

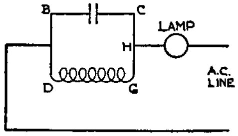

Fig. 99. — Parallel Resonance

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the equation for resonance in a circuit having resistance, inductance and capacity in an advanced text on alternating currents.

fact that electrons are surging back and forth around the circuit, CBDG, is a hindrance to any stream of electrons flowing through the line at the same frequency. At the points of connection of coil and condenser the voltages are high and opposite in phase as they are in the series arrangement.

At any given instant except the instant of reversal a stream of electrons is flowing either from C to G or from G to C. Suppose they are flowing from C to G. Then at H some electrons from the condenser plates flow out into the line. At the same time about as many electrons flow from the line into the parallel circuit in the direction HG. The result is that the net flow of electrons from the parallel circuit into the line is very small.

The more nearly the reactance of the coil and the reactance of the condenser become equal the smaller is the current flowing in the line. The current in the coil and condenser circuit becomes many times as great as the current in the line. If the resistance of the resonant circuit were zero the line current would become zero when inductive and capacity reactances became equal.

If the resistance of the coil and condenser and all the connecting wires could be made actually zero, then for resonant frequency the condenser current would be exactly equal to the current in the coil and no current would flow in the line. This would be a perfect filter. The resistance cannot, of course, be reduced to zero but in radio circuits the resistance can be made so small, compared with the reactance, that the ideal condition of resonance is very closely approached.

87. Equation for Parallel Resonance. — In a parallel resonance circuit the reactances of coil and condenser are equal and opposite as they are in series resonance. Therefore the same equations hold for parallel as for series resonance (Section 80). This is true when the resistance is very small.

$$f = \frac{1}{2\pi\sqrt{LC}}$$

and

$$\lambda = 1884\sqrt{LC}.$$

Example. — What inductance is required in parallel with a condenser of 0.0005 m.f. capacity to give resonance for a wave length of 300 meters? Find the inductive reactance and the capacity reactance.

Solution:

$$300 = 1884 \sqrt{0.0005\ L.}$$

Solving this equation we get

$$L = 50 \text{ microhenries approximately.}$$

$$50 \text{ microhenries} = \frac{50}{1,000,000} \text{ henry.}$$

$$f = \frac{v}{\lambda} = \frac{300,000,000}{300} = 1,000,000$$

$$X_L = 2\pi fL = 6.28 \times 1,000.000 \times \frac{50}{1,000,000}$$

From which we get $X_L = 314$ ohms.

$$X_C = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 1,000,000 \times \frac{0.0005}{1,000,000}}$$

Which gives $X_C = 318$ ohms.

The difference between the two reactances as obtained in this solution is due to the fact that 50 microhenries is only an approximate value of the inductance. If the actual value were taken the results for the two reactances would be equal.

88. Frequencies in Various Electrical Circuits. — Alternating currents for various purposes differ greatly in frequency. Commercial currents used for light and power have, as a rule, a frequency of 60 cycles per second. Twenty-five cycle current is sometimes used for power but is not desirable for lighting because with so low a frequency there is a slight flickering of the light. The time between two reversals, one-fiftieth of a second, is long enough to allow the filament to cool and become slightly dimmed as the current drops to zero. With more rapid alternations there is a practically constant glow. The alternating current which actuates a telephone receiver is of audio frequency. The lowest notes of a bass voice have less than one hundred vibrations per second while a high soprano note may have a frequency of more than 1000. The usual range of the human voice is from 80 to 1096 but the human ear can detect sounds having a frequency as high as 20,000 or as low as about 30. These are the extreme limits of audio frequency. The sensitivity of the ear for frequencies between 10,000 and 20,000 is slight, however, and in radio work the upper limit of audio frequency is usually considered to be 10,000. The oscillations received in the antenna of a radio receiver are too rapid to produce a sound in the telephone receiver. They are said to be of radio frequency. Radio frequencies are usually above 20,000 cycles per second ranging as high as 20,000,000 or even higher. A frequency of 20,000 corresponds to a wave length of 15,000 meters (see Section 81) and a frequency of 20,000,000 corresponds to a wave length of 15 meters.

89. Low and High Frequencies Compared. — The principles of alternating currents apply to currents of all frequencies. There are some effects, however, that are more striking for currents of radio frequency than for those of lower frequency. The differences are due to the greater inductive reactance and less capacitive reactance of circuits in which high frequency currents are flowing. The inductance of a few turns of wire is important in a radio circuit. Radio frequency currents will flow in a condenser of such small capacity that it would effectually prevent the flow of currents of low frequency.

We have seen that inductive reactance depends on the rate of change of magnetic lines of force. The greater the frequency the more rapidly the lines of force change. Inductive reactance is proportional to frequency. For example, suppose a coil has an inductance of 1000 microhenries or 0.001 henry. If the frequency is 500 cycles per second the inductive reactance is

$$X_L = 2\pi fL = 2\pi 500 \times 0.001 = 3 \text{ ohms.}$$

If the frequency is 500,000 the reactance of the same coil is 3000 ohms.

The reactance of a condenser is inversely proportional to the frequency. In other words the greater the frequency the greater the current that will flow in a given condenser. For example, suppose a condenser has a capacity of 0.001 microfarad or 0.000,000,001 farad. If the frequency is 1000 cycles per second, the capacitive reactance is

$$
\begin{aligned}
X_c &= \frac{1}{2\pi fC} \\
&= \frac{1}{2\pi \times 1000 \times 0.000,000,001} \\
&= \text{nearly } 160,000 \text{ ohms.}
\end{aligned}
$$

If the frequency is 1,000,000 the reactance of the same condenser is only 160 ohms.

Mutual inductance between coils is much greater for radio frequency currents than for currents of lower frequency for the reason that mutual inductance as well as self-induction depends on rate of change of magnetic lines of force. The same principle applies to eddy currents and for the same reason. Any piece of metal, such as a hinge, in the magnetic field of a coil in the radio frequency part of a receiving set, has eddy currents induced in it and the result is a considerable loss of energy and a broadening of the tuning. The loss is much smaller if the metal is in the audio frequency part of the set because of the lower frequency.

For currents of radio frequency a small coil may act as if a condenser of low capacity were shunted across it. The turns of the coil act like condenser plates and the insulation of the wire acts as the dielectric. This capacity is called the distributed capacity of the coil. The distributed capacity is sometimes sufficient to make it possible to tune the coil to resonance in a receiving circuit without the use of a condenser.

Another difference between low and high frequency is found in the case of a tapped coil. If a coil is connected in a high frequency circuit by means of taps so that several turns at the end of the coil are not included in the circuit, oscillations may be induced in the part of the coil that is out of the circuit. In fact, on account of its distributed capacity, it may become resonant for a certain frequency. The oscillations in the dead end of the coil cause considerable loss of power.

90. Power Lost in the Dielectric. — In radio circuits the action of the insulating material between the plates of condensers is of considerable importance on account of the high frequency of the currents. An insulator, when placed between two charged conductors, is a dielectric. The electric force acts through the insulator or dielectric. The action of a dielectric can, perhaps, be explained best by means of a mechanical illustration. Suppose we have a cylinder filled with water and divided by rubber diaphragms as in Figs. 100, 101 and 102. Two smaller cylinders are connected with the first and each

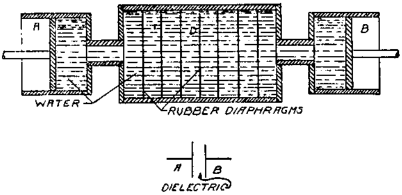


Fig. 100

The Action of a Dielectric. From Magnusson's "Alternating Currents"

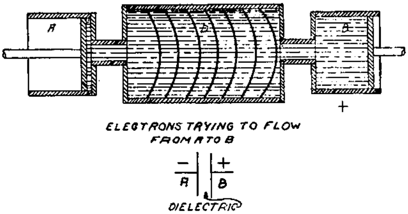


Fig. 101

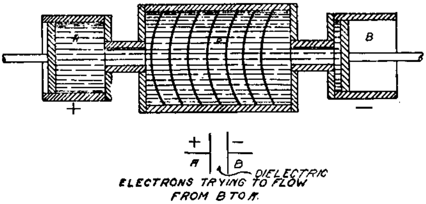


Fig. 102

of the small cylinders is provided with a piston. The middle cylinder represents the dielectric and the two smaller cylinders the two plates of the condenser. Fig. 100 represents the condition when there is no charge. There is no strain on the rubber diaphragms. In Fig. 101 piston A has been pushed over, forcing water into the middle cylinder, and an equal quantity of water is forced out into cylinder B. This represents a condenser in which plate A is negative and B positive. There is an electromotive force urging the electrons across from A to B. This force produces a strain in the dielectric as the water pressure produces a strain in the rubber diaphragms. If the pressure is removed from the piston the rubber diaphragms push back the piston A and return to their first position. If the pressure is now applied in the direction B to A the diaphragms are strained in the opposite direction and we have the condition of Fig. 102. If this action is repeated we have an alternating pressure applied to the pistons and this represents an alternating e.m.f. applied to the plates of a condenser. If the rubber diaphragms were perfectly elastic and without friction they would give back all the energy used in stretching them but in reality there would be some friction and some of the energy would be used up. Similarly the dielectric in a condenser consumes part of the energy of the circuit. The energy is used in reversing the strain in the dielectric. This is called the dielectric loss. The effect may be compared to that of an a.c. electromagnet in which energy is used in reversing the magnetism of the iron.

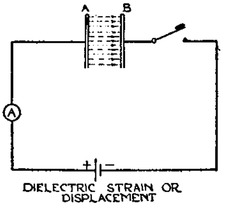


Fig. 103

If a milliammeter is connected in series with a battery and condenser (Fig. 103), when the key is closed the milliammeter shows a sudden deflection which soon drops to zero. There is a momentary flow of electricity as the plates become charged. In Fig. 103 electrons are trying to flow from B to A. An electric strain is produced in the dielectric. It is a sort of electric displacement. The momentary current is called a " displacement current " or " dielectric current."

Another way in which energy is lost in a dielectric is that of the leakage current. No dielectric is a perfect insulator. The best insulator permits electrons to leak through slowly. Returning to the illustration of the cylinders filled with water, it is easy to see that if there were small holes in the rubber diaphragms so that the water slowly leaked through, there would be a loss of energy, for if time enough were allowed for water to leak through sufficiently to relieve all the strain the diaphragms would not be able to push the piston back. In that case the energy would all have been wasted or lost in the middle cylinder. In a similar way it is clear that, if there were time enough between two reversals of the current for all the surplus electrons to leak through the dielectric, no energy could be returned but all the energy would have been lost in the dielectric. The higher the frequency, however, the less the time between reversals to allow electrons to leak through and therefore the less is the loss of energy. This applies to leakage loss. The true dielectric loss; that is, the power consumed in reversing the strain in the dielectric, increases with frequency. Experiment shows, however, that the total loss in a condenser is independent of the frequency but depends on the voltage, increasing approximately as the square of the voltage.

The related topics of specified inductive capacity and dielectric strength are treated in Section 64.

91. Skin Effect. — We have seen that an electric current produces a magnetic field perpendicular to the direction of the current. This magnetic field expands as the current increases from zero to the maximum. Fig. 104 represents a section of wire. Suppose there is an e.m.f. causing a current in the direction of the long arrow at the axis. Applying the right hand rule we can see that the lines of force come out from the paper above the axis and go into the paper below the axis. As the magnetic field increases there is induced in the wire an e.m.f.

which tends to oppose this change. In the section ABCD, for example, the induced e.m.f.'s will be in the direction of the arrows tending to produce lines of force which enter the paper in this area and come out of the paper in the area EFGH, in other words tending to reduce the strength of the magnetic

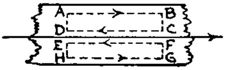


Fig. 104. — Skin Effect

field of the current in the wire. The induced e.m.f. hinders the current at the center of the wire and aids it near the surface. The current, therefore, reaches its maximum in the outer layers of the wire before it does in the central portion. After the current passes its maximum, as it decreases to zero, the induced e.m.f.'s cause the current to reach zero first at the surface of the wire. This could be proven by applying the right hand rule and Lenz's law, the direction of the induced e.m.f.'s being simply the reverse of those given above. It follows that the current at the center of the wire lags behind that at the surface. The greater the frequency, the more rapidly the magnetic field changes and the greater is the lagging of the current at the center of the wire. The lagging effect occurs throughout the wire but increases toward the center. This effect is not large with currents of commercial frequency. With currents of radio frequency, however, the current near the center lags to such an extent that it does not have time to reach its maximum value before the e.m.f. is reversed. The result is that the current at the surface is stronger than at the center. With very high frequency, the flow of electrons is almost entirely near the surface. This action of high frequency currents is called the skin effect.

Since with radio frequency practically all the current flows near the surface it is desirable to give the wire as large a surface as possible, particularly in the antenna circuit. For this reason conductors are often made of fine strands of wire. The strands should be enameled for otherwise current will flow across the contacts and energy will be lost as heat. This has the effect of increasing the resistance of the wire. Stranded wire that is not enameled may even be less effective than a solid wire of the same cross section. A thin copper tubing or a layer of copper plated on the surface of a poor conductor, such as iron wire, is suitable for radio frequency currents. The radio frequency current will flow almost entirely through the layer of copper.

The greater the diameter of the wire the greater is the skin effect because a longer interval is required after the e.m.f. reverses until the effect is felt at the center of the wire. Also the better the conductivity the greater the skin effect because the current at the surface increases with conductivity.

One result of the skin effect is to increase the effective resistance of the wire. Since practically all the current flows near the surface, the result is the same as if the cross section of the wire were reduced. The effective resistance of a wire for radio frequency currents may be many times as great as its resistance for direct currents. To find the effective resistance, the power equation may be used,

$$P = I^2R.$$

If the power in watts is divided by the square of the current the result is the effective resistance. Methods of finding radio frequency resistance by experiment will be given in Chapter X.

These results have an important practical application in the winding of coils for radio circuits. Increasing the size of wire does not reduce resistance for high frequency currents at the same rate as for low frequency or direct currents. For example, a coil of number 28 wire would have for low frequency currents (60 cycle) about four times as much resistance as a coil of number 22 wire having the same number of turns and the same diameter. For currents having a frequency of 500 kilocycles (500,000 cycles) or more the first coil has very little more resistance than the second. The slight gain in favor of the larger wire is more than offset by the necessity of placing the turns closer together in order to keep the size of the coil within the necessary limits. This increases the effect of self-induction or the reactance of the coil. Space winding reduces this effect. Practically, for a given size of coil, finer wire, for example, number 26, space wound, the spacing between turns being about equal to the diameter of the wire, is better than heavier wire closely wound.

Questions

1. Why is the e.m.f. reversed every half revolution when a coil rotates in a two-pole magnetic field?

2. What is meant by a cycle?
What is meant by frequency?
A 25 cycle current makes how many alternations per second?

3. How does the magnetic field produced by an alternating current differ from the magnetic field produced by a direct current?

4. In a common form of induction or spark coil the current in the primary is direct. How is an e.m.f. induced in the secondary? Would there be an induced e.m.f. if the primary current were constant?

5. If the induced e.m.f. in the secondary of a transformer is 220 volts, at what rate is the secondary cutting lines of force?

6. If the frequency of the primary current in question 5 is 60, what change in secondary voltage would occur if the frequency dropped to 25?

7. How does the frequency of the induced e.m.f. in the secondary compare with the frequency of the primary current?

8. Why is a greater force required to drive the armature of a generator when the circuit is closed than when it is open?

9. If a 6 volt light bulb is connected in parallel with a coil and a battery, there is a current surge through the bulb when the circuit is broken. Would this happen if a straight wire of the same size and length were used in place of the coil? Why?

10. What is the induced e.m.f. in a coil having an inductance of one millihenry if the current changes at the rate of one ampere per second? If the rate of current change is 5 amperes per second?

11. In a coil of 1 millihenry inductance what is the reactance in ohms if the frequency is 1000? If the frequency is 1,000,000? Radio frequency transformers as a rule have less inductance than audio frequency transformers. Give one reason for this difference.

12. What is meant by difference of phase? Under what conditions do current and voltage differ in phase? Under what conditions have current and voltage the same phase?

13. What is the impedance of a coil having a resistance of 2 ohms and a reactance of 10 ohms?

14. What is meant by the effective value of an alternating current?

15. Why is heavier insulation needed for alternating current than for direct current of the same voltage?

16. Explain the fact that with alternating current a lamp may be lighted when connected in series with a condenser.

17. Two condensers are made with plates of equal area and with equal distances between the plates but one has air as a dielectric, the other mica. Which has greater capacity? Which has greater dielectric strength?

18. What is the reactance of a condenser of 0.001 microfarad capacity if the frequency is 1000? If the frequency is 1,000,000?

19. What is the impedance of a circuit having a capacity reactance of 100 ohms and a resistance of 5 ohms?

20. What is the impedance if the capacity reactance is 100 ohms, the inductance reactance 150 ohms and the resistance 5 ohms?

21. Two condensers of 0.001 microfarad capacity each are connected in parallel. What is their combined capacity? What is their capacity if connected in series?

22. A condenser of 0.001 microfarad capacity and one of 0.002 microfarad capacity are connected in parallel. What is their combined capacity? What is their capacity in series?

23. What is the current in amperes in a circuit having an e.m.f. of 100 volts, a resistance of 10 ohms, an inductive reactance of 250 ohms and a capacity reactance of 200 ohms?

24. Find the true power, the apparent power and the power factor for the conditions given in question 23.

25. What must be the inductance of a coil to form a resonating circuit with a condenser of 0.0005 microfarad capacity for a wave length of 200 meters? For a wave length of 600 meters?

26. If a fixed inductance of 30 microhenries is used to form a resonant circuit with a variable condenser, what are the lowest and the highest values of capacity needed for a tuning range of 200 to 550 meters?

27. Why is the resistance of a wire greater for high frequency than for direct current? Why is the resistance of a wire greater for currents at radio frequency than for currents at audio frequency?

28. Why is the voltage across the condenser of a resonant circuit greater than the line voltage?

29. What is the effect of resistance in a resonating circuit?

30. What frequency corresponds to a wave length of 220 meters?

31. What wave length corresponds to a frequency of 550 kilocycles?

32. Why is the mutual inductance between two coils greater for currents of radio frequency than for currents of audio frequency?

33. Why is it more important to keep the radio frequency part of a circuit free from metal than it is the audio frequency part of the circuit?

34. What is meant by "skin effect"?

CHAPTER VII

DETECTORS AND AMPLIFIERS

When one talks over a telephone line it is not the sound of the voice that travels over the wire. It is an electric current. The current is alternating and the variations in the current correspond to the variations in the sound of the voice at the transmitter. In the receiver the electric current produces sound vibrations that are similar to those at the transmitter end of the line. The receiver acts as a detector, changing the energy of the electric current into sound vibrations.

When voice is transmitted by radio it is not the sound of the voice that travels through space. It is electromagnetic vibrations or waves. These waves act in a manner very similar to that of the electric current in a wire telephone line. The variations in the waves correspond to the variations in the sound at the transmitter and the waves thus " modulated," as it is called, produce in the resonating circuit of the radio receiver impulses that act on the electron tubes. The tubes in turn translate these impulses into audio frequency currents that reproduce the sounds in the telephone receiver or loud speaker.

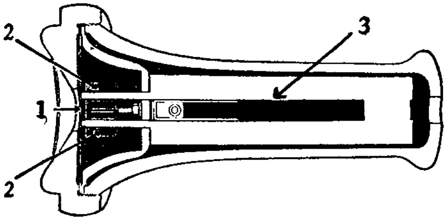


Fig. 105. — Telephone Receiver

1. Diaphragm 2. Coils 3. Magnet

92. **The Telephone Receiver.** — Fig. 105 is a diagram of a telephone receiver. The magnet is a permanent steel magnet.

Around each pole piece is a bobbin wound with fine silk covered or enameled wire. The diaphragm is of soft iron. When a current flows in the coils in one direction it increases the strength of the magnet. This is true when the lines of force produced by the current are in the same direction as those of the magnet. When the current flows in the opposite direction it reduces the strength of the magnet. If an alternating current flows in the coils, the magnetic field is strengthened during one half of the cycle and weakened during the other half. The diaphragm is pulled toward the magnet when the magnetic field is strengthened and is released and springs back when the field is weakened. The diaphragm makes one vibration for each cycle because during one half of the cycle it is pulled toward the magnet and during the other half it springs back. The alternations of the line current correspond in frequency to the pitch of the sound actuating the transmitter diaphragm and the variations in strength of the current correspond to variations in amplitude of the sound waves. The current, therefore, causes the receiver diaphragm to vibrate in step with the transmitter diaphragm and to set the air in vibration so as to reproduce the sound.

It is true of the telephone receiver as of any electromagnet that the magnetizing force is proportional to the number of turns times the strength of the current. The sensitiveness of the receiver may, therefore, be increased by increasing the number of turns of wire around the pole pieces. The head sets used in radio receiving have, as a rule, many more turns of wire than the receivers used for the line telephone. When more turns of wire are wound on the coils the resistance is necessarily increased but it is important to remember that the sensitiveness is increased not because of increased resistance but in spite of it. Increased resistance in itself is a hindrance but is unavoidable if the number of turns is to be increased.

The telephone receiver is a very sensitive instrument for the detection of an electric current. It has been found, by Kennelly, that a sound can be heard in a receiver when the current flowing through its coils is only 0.044 microampere or about four hundred millionths of an ampere. The amount of energy consumed in a receiver is extremely small, the power being of the order of a few millionths of a millionth of a watt.

93. The Microphone Transmitter. — Fig. 106 shows a simple microphone consisting of carbon dust or granules between two carbon plates connected in series with a telephone receiver and a dry cell. When the carbons are pressed firmly together the resistance of the carbon granules is reduced and the current increases in strength. When the pressure is released the contact resistance is increased and the current reduced. This varying current causes a click in the receiver. The sounds emitted by the receiver are much louder than those caused directly by the rubbing together of the carbon plates showing that the microphone, in connection with a telephone receiver, serves to amplify minute sounds.

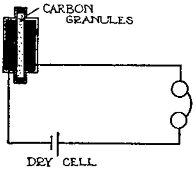


Fig. 106. — A Simple Microphone

This illustrates the principle of the broadcasting microphone. The sound waves cause the diaphragm to vibrate. The vibrating diaphragm modulates a current so that the frequency of the current corresponds to the pitch of the sound and the variations in current strength correspond to the amplitude of the sound waves. This current acts by means of a transformer to produce voltage variations on the grid of a modulator tube as explained in Chapter IX, Section 149. If a graph is drawn it will show that the variations of the current correspond to those of the sound. This is illustrated in Fig. 108.

94. Why the Current Must Be Rectified in Radio Reception. — In the wire telephone, as we have seen, the diaphragm of the receiver is actuated by an alternating current. The alternations of this current are of the same frequency as the sound waves that act on the transmitter. The receiver diaphragm vibrates with the frequency of the line current and produces sound waves in the air of the same pitch and quality as those that act on the transmitter.

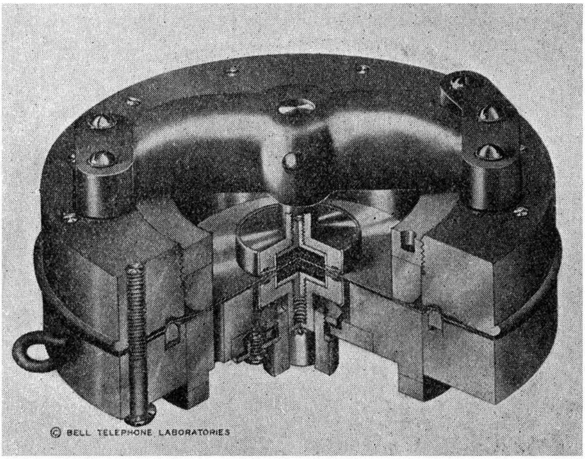


Fig. 107. — Cross Section of a Standard Broadcasting Microphone

In radio we have a different state of affairs because of the high frequency of radio oscillations. If a receiver were connected directly in the antenna circuit, the diaphragm, on account of its inertia, could not vibrate with the frequency of the antenna current. Even if it could vibrate at such high frequency and produce corresponding vibrations in the air, the ear could not detect the sound, for it would be far above the highest pitch to which the ear is sensitive.

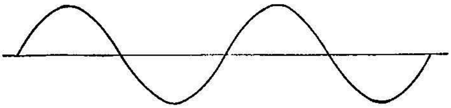


Fig. 108. — Current Variations correspond to variations in the sound

In radio transmission, either telephony or continuous wave telegraphy, an oscillator produces continuous waves; that is, waves of equal amplitude or vibration as represented in Fig. 109. Some means must be used to "modulate" these waves, that is to cause the radio waves to take the form of sound waves. If we have a diagram representing the radio waves as they are modulated and draw a curve just touching the peaks of the waves this curve represents the sound waves. In radio telegraphy the radio waves are sometimes modulated by a buzzer. In radio telephony sound waves acting on the transmitter modulate the radio waves so that they have their greatest amplitude at the crest or condensation of the sound wave and their least amplitude at the trough of the sound wave as represented in Figs. 110 and 111. If the modulated current were to act directly on the telephone receiver it would not cause the diaphragm to vibrate because it would produce equal opposing impulses. To make this clear let us take a simple illustration. Suppose we have a pendulum of such length that

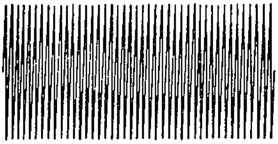


Fig. 109. — An Oscillator Produces Continuous Waves

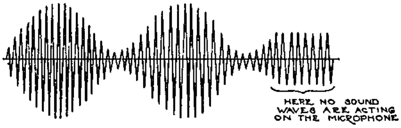


Fig. 110. — Radio Waves Are Modulated by Sound Waves

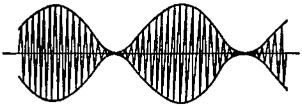


Fig. 111. — If we draw a curve just touching the peaks of the radio waves, the curve represents the sound waves

its natural rate is one vibration per second. Suppose this pendulum is being struck on opposite sides by two small hammers, striking with equal force and each at a rate of one thousand strokes per second. The pendulum would not be set in vibration for the blows of the two hammers would exactly neutralize each other. This would correspond to the action of continuous waves on the diaphragm of a telephone receiver. Suppose now the two hammers, while keeping the same number of strokes per second, were to strike first very hard and then very softly but always keeping step together. They would still fail to set the pendulum vibrating for the strokes of one hammer would offset those of the other. This would correspond to the action of modulated continuous waves on the receiver diaphragm. The radio frequency current, even though modified so that its changes in amplitude correspond to the form of the sound waves, produces equal impulses in opposite directions on the diaphragm so rapidly that the diaphragm cannot respond.

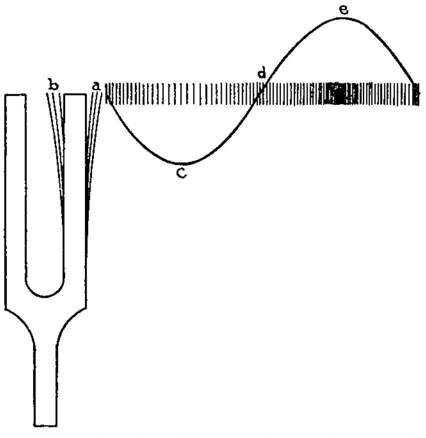


Fig. 112. — Showing How a Curve Can Be Used to Represent a Sound Wave

The wave curves both of sound and electromagnetic waves shown in Figs. 109, 110 and 111 represent amplitude of vibration. To make this clear refer to Fig. 112. The tuning fork is actually vibrating back and forth between the points a and b.

The air particles are set vibrating back and forth as the tuning fork does. The wave curve, c-d-e, illustrates the movement of the air particles. The wave curve goes up and down while the air particles move back and forth so that the curve is not a picture of what actually happens but a diagram showing the amplitude of the movement at one particular instant. The crest of the wave, e, is where the air particles have moved farthest. The trough of the wave at c shows the greatest movement in the opposite direction. At d there is no movement, the air particles are in the same position as when at rest. The curve for electromagnetic waves should be understood in the same way, not as an actual picture of the waves but as showing the amplitude of vibration at different points in a cycle.

We have assumed here for the sake of the discussion that the radio frequency currents can pass through the magnet windings of the reproducer (telephone receiver or loud speaker). As a matter of fact the reactance of the coil is very great since inductive reactance increases in proportion to frequency. It is so great that these currents are practically choked out in the magnet windings. They can readily pass by means of a condenser shunted across the reproducer or even by way of the distributed capacity of the magnet windings.

To return to the illustration, suppose one of the hammers stops acting and the other continues delivering one thousand strokes per second but once each second its strokes are very hard and a half second later the strokes are soft, almost fading out. The pendulum will then be set in vibration because the impulses due to the hard and soft strokes correspond to its natural rate of vibration. This illustrates what happens when the modulated current is rectified. Its impulses on the receiver diaphragm are then in one direction only and the variation of harder and softer impulses corresponds to a rate at which the diaphragm can vibrate. Complete rectification is not essential. The modulated current will cause the diaphragm to vibrate if the impulses in one direction are stronger than those in the opposite direction. A rectified radio frequency current which is also modulated is illustrated in Fig. 113.

95. The Electron Tube as a Detector. — The action of the three electrode tube as a detector should be thoroughly understood, for this is fundamental in radio work. We shall proceed by as simple stages as seem possible, to study this action.

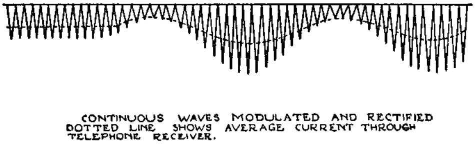


Fig. 113

It is necessary to begin with the characteristic curve showing the relation between grid voltage and plate current (see Fig. 114). It is important also to keep in mind the action of the stream of electrons shooting across from filament to plate. If the grid is made positive it helps attract the electrons from the filament. There is then a stronger stream of electrons flowing to the plate. Some of these electrons enter the grid but most of them go on through the grid to the plate. If the grid is held at a certain definite positive potential, there will be a steady unchanging stream of electrons to the plate. Let this potential of the grid be represented by e_0 in Fig. 114. Then i_0 represents the plate current. If the grid voltage is increased to e_1 the plate current is increased to i_1. The stream of electrons is now stronger than before. Now let the grid voltage be decreased to e_2 or as much below e_0 as e_1 is above e_0. The plate

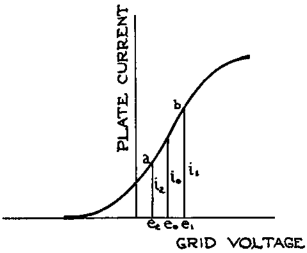


Fig. 114

current is reduced to i_2. The stream of electrons is now less than at first. The important point here is that the decrease in plate current in the one case equals the increase in the other. The average plate current is i_0 and this is the same as the constant value would be if the grid voltage were held at e_0.

Suppose the plate current flows through a telephone receiver. What is the effect of these changes on the receiver? If the grid is being acted upon by a radio signal the grid voltage is varying at radio frequency which is hundreds of thousands or millions of cycles per second. As we have already seen the diaphragm could not follow these rapid changes even if the radio frequency current could flow unhindered through the coil. In the case we are considering the average current remains unchanged. The effect is, therefore, the same as if a constant current were flowing through the coil.

The average current remains unchanged because the action is taking place on a part of the characteristic curve which is practically a straight line. This is true of the part of the curve marked ab in Fig. 114. Since ab is practically a straight line, it follows that between these values the changes in plate current are directly proportional to the changes in grid voltage.

Now using the same characteristic curve as in Fig. 114, we shall represent the changes in plate current and grid voltage by two curves (Fig. 115). The lower curve shows the changes in grid voltage. This curve starting at e_0 goes to e_1, back to e_2 and so on for a number of cycles; two and a half cycles are shown in the figure. The curve at the right shows the corresponding changes in plate current, going up from i_0 to i_1, down to i_2 and so on. For any point on the grid voltage curve there is a corresponding point on the plate current curve. Take any point on the grid voltage curve as P. Draw a line up from P to the characteristic curve as the dotted line in the figure. From the point of intersection, K, draw a line to the right. The intersection of this line with the plate current curve is the corresponding point P′. If the point P is in the second cycle of the grid voltage curve, the line KP′ is drawn to the second cycle of the plate current curve.

We shall next suppose that the grid voltage starts at a higher point with reference to the characteristic curve, e_0 in Fig. 116. The grid voltage as before goes up from e_0 to e_1, drops to e_2 and so on for a number of cycles. This causes the plate current to increase from i_0 to i_1, drop to i_2 and so on. The figure shows that the plate current decreases below i_0 more than it increases above i_0, the difference between i_0 and i_2 being greater than the difference between i_1 and i_0.

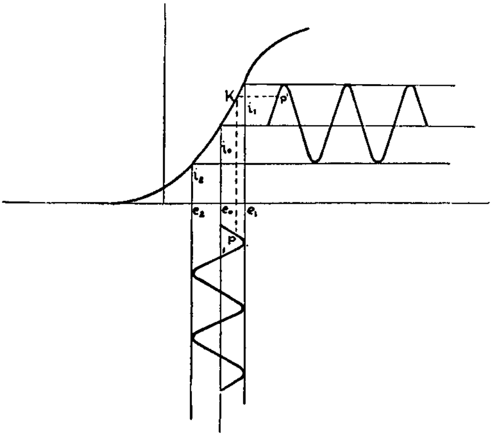


Fig. 115

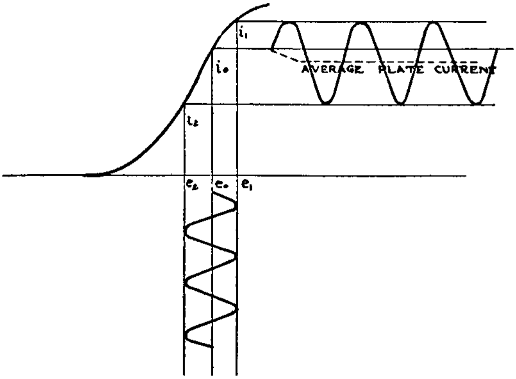


Fig. 116

Let us think of this in terms of electrons. The grid voltage starts at a certain value, e_0, which is near the top of the curve. As the grid voltage increases, only a small increase in the stream of electrons can take place because it is near the saturation point (see Section 38). The grid voltage then reverses and drops below e_0. The stream of electrons is now greatly reduced. The change in grid voltage has its full effect in reducing the plate current. Now suppose the grid voltage to oscillate between the values e_1 and e_2 over a number of cycles. The plate current oscillates between the values i_1 and i_2 and the average plate current is reduced, that is the average plate current is less than i_0.

Let us suppose now that the waves are modulated by means of a buzzer having a vibration rate of one thousand vibrations per second. We now have a series of wave trains with intervals between. A number of wave trains lasting a small fraction of a second makes a dot of the code. The dot consists of trains of electromagnetic waves of radio frequency lasting for a small fraction of a second but it requires many thousands of waves to make the dot signal. As a signal comes in, the plate current drops as shown by the dotted line marked " average current " in Fig. 116. Between wave trains the plate current returns to the value i_0. For each wave train there is a drop and a rise in the plate current and this change in plate current is slow enough to act on the telephone receiver. The result is a short high pitched sound for each dot.

Suppose the signals come in at the rate of one thousand wave trains per second with, of course, one thousand intervals between. Then one thousand times per second the plate current will drop to the " average value " and one thousand times per second it will rise to the value i_0. This changing plate current flowing through the telephone receiver will cause the diaphragm to make one thousand complete vibrations per second which will give a high pitched musical note.

Let us review this whole matter briefly before going on. Wave trains are coming in at the rate of one thousand per second with one thousand intervals between. Each wave train produces oscillations in grid voltage say at the rate of a million oscillations per second. While the oscillations are acting on the grid, the plate current is reduced because the tube is operating near the upper bend of the characteristic curve. During the intervals between wave trains the plate current rises. The plate current, therefore, varies or oscillates between two values, rising and falling one thousand times per second. This rapidly changing current flows through the telephone receiver causing the diaphragm to make one thousand complete vibrations per second and give out a high pitched sound. Suppose this sound lasts only one-tenth of a second. It might be called a dot of the code. This dot would consist of one hundred complete variations of the plate current.

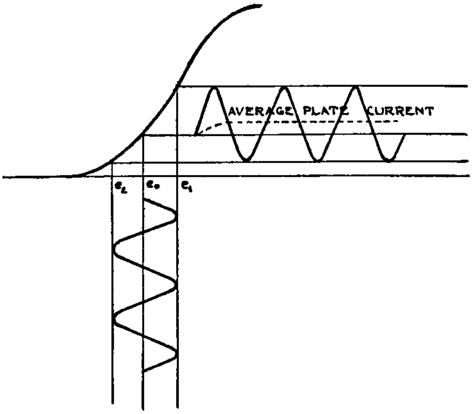


Fig. 117

We shall next take the case of a tube operating at the lower bend of the characteristic curve (Fig. 117). The figure shows that an increase in grid voltage causes a greater change in plate current than is caused by a decrease in grid voltage. The result is that while the grid voltage is oscillating between the values e_1 and e_2 the plate current is greater than it would be if the grid voltage remained at e_0. In other words the oscillations on the grid cause an increase in average plate current. Now suppose we have a series of wave trains as before with intervals between. While the oscillations are being impressed on the grid the plate current is increased. During intervals between wave trains the plate current is reduced. If the impulses are repeated a thousand times a second, the plate current will rise and fall a thousand times a second and we get a high pitched sound in the receiver. The telephone diaphragm as before makes one vibration for each train of waves and since there are one thousand wave trains per second the diaphragm makes one thousand vibrations per second. We have found then that a sound is produced in the telephone receiver when the tube operates on either the upper or lower bend of the characteristic curve but no sound is produced when the tube operates on the straight line portion of the curve. The tube can be made to operate on the upper bend of the curve by using a high plate voltage or it can be made to operate on the lower bend by using a lower plate voltage or a battery in the grid circuit, giving the grid the correct negative potential. For the sake of economy in plate batteries it is better to work at the lower bend of the curve.

If it happens that zero grid voltage brings the plate current above the lower bend the grid may be made negative by connecting dry cells in series in the grid circuit, the negative terminal of the battery being connected to the grid. The grid may be made negative without the use of a battery by inserting a resistance in the filament circuit as in Fig. 118. If the resistance is inserted between the filament and the negative terminal of the filament battery and the grid return is connected to the battery side of the resistance the grid will be negative with respect to the filament because of the voltage drop in the

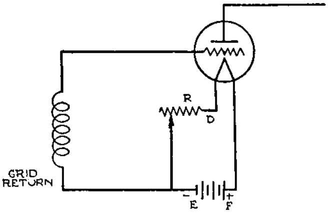


Fig. 118

resistance. For example, if E and F, Fig. 118, are the terminals of a six volt battery there is a drop of practically six volts through the filament and the resistance, R, taken together. Suppose the resistance of the filament is 5 ohms and of R one ohm. Then since the voltage drop is proportional to the resistance the voltage drop across the filament, from F to D, is 5 volts and across R, from D to E, one volt and the grid has a negative potential of one volt with respect to the filament. In an actual circuit R may be the filament rheostat. It should be remembered that the purpose of such adjustments is to locate the action of the tube on the right portion of the characteristic curve.

96. Effect of Grid Condenser. — Thus far we have considered the action of a detector tube without a condenser in the grid circuit. We shall next consider the effect of a condenser in series with the grid. The circuit is shown in Fig. 119. Suppose signals are coming in and oscillations are received by coil L. Let us see first what happens in the tube and the condensers in a single cycle. During one half of the cycle electrons flow from D to E in the coil. A stream of electrons is flowing out of plates 1 of the two condensers and through the coil from D to E and into the filament and plate 2 of the condenser C_2. Plate 1 of the grid condenser is positive because it has lost some of its electrons. Electrons are attracted toward plate 1 and rush from the grid into plate 2. A part of the stream of electrons flowing out from the filament goes into the grid. The insulation of the condenser prevents the electrons that go into plate 2 from crossing over to plate 1. In the next half cycle

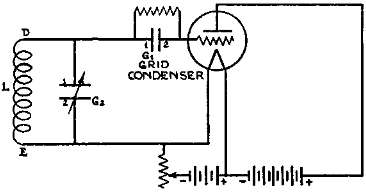


Fig. 119. — Action of Electrons in a Circuit with Grid Condenser

electrons rush into plate 1 but the electrons that have flowed into plate 2 cannot go back to the filament. The electrons that have collected in plate 2 during the first half of the cycle are trapped. The stream of electrons coming over from the filament to the grid repels them and holds them back. There is left, then, a slight excess of electrons on plate 2 of the grid condenser. In the next cycle the same thing is repeated and there is left a slightly greater excess of electrons on plate 2. As the number of electrons accumulating on plate 2 increases the grid becomes more and more negative. This goes on for a number of cycles until so many electrons have collected on plate 2 that they react on the grid and prevent any more electrons entering the grid from the filament. The tube is then blocked and there can be no further action on the grid unless some means is provided for the excess of electrons to escape from plate 2 of the grid condenser. This is done by connecting a very high resistance between the grid terminal of the tube and the filament. Since the resistance is high the electrons flow across at a slow rate. This high resistance is called the grid leak because the electrons " leak " through it to the filament. A better term is " grid resistor." The leak should have just enough resistance to allow the excess of electrons to leak off before the next signal impulse comes in. In ordinary receiving sets a resistance of a million ohms or more is suitable.

It is well to keep in mind that the whole action which has just been discussed takes place very rapidly. The series of cycles during which electrons accumulate on plate 2 might occupy only a thousandth of a second or less and during this thousandth of a second there might be hundreds or even thousands of oscillations.

It is impossible to picture in our minds such rapid action. We must catch these impulses and slow them down, as it were, in our imagination. We might compare this method of studying the action of electrons with a motion picture study of a race horse. It is impossible for the eye to catch the motion but, if we take a motion picture at the rate of a hundred exposures per second and then run the film through the projection machine very slowly, the separate movements can be seen.

In a similar way in studying the action of electrons we must picture very slowly that which takes place with extreme rapidity.

97. Effect of Grid Condenser Action on Plate Current. — We have seen that, while one signal impulse is coming in, the grid is growing more and more negative. The more negative the grid is the more it reduces the plate current. Throughout this series of cycles, then, the average plate current grows less and less. Referring to Fig. 120, the grid voltage instead of oscillating between e_1 and e_2, as it does without a grid condenser (see Figs. 115, 116 and 117), now goes up to e_1, down to e_2 then up to some value less than e_1, down to a value less than e_2 and so on. In each cycle the average grid voltage is decreased. The result is that the plate current instead of varying between two fixed values, as in Figs. 115, 116 and 117, grows less with each cycle. The change in average plate current is much greater than it would be without a grid condenser. This means a greater effect on the diaphragm of the telephone receiver.

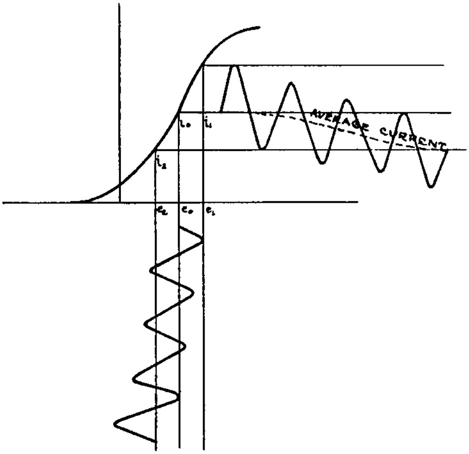


Fig. 120

The action as shown in Fig. 120 is on the straight portion of the plate current curve. It is now the variation in grid voltage that causes the average plate current to change and not the bend of the plate current curve. In fact, it is better when a grid condenser is used, to operate on the straight line portion of the plate current characteristic. This can be understood by referring to Fig. 117 where it is shown that a series of oscillations on the grid, without a condenser, causes an increase in the average plate current whereas, with a grid condenser, there is a decrease in average plate current. The two effects then would tend to neutralize each other if the tube were working at the lower bend.

It is clear that the preceding discussion concerning the action of electrons accumulating on the grid and discharging through the grid leak would not apply if no electrons or practically none entered the grid. This would be the case if the grid were negative with respect to the filament. To obtain the effect of a grid condenser the grid must be positive at least during part of the cycle. There should be no battery in the grid circuit but the grid may be made positive by connecting the grid return to the positive terminal of the filament. The grid of the detector tube may, however, be connected to the negative terminal of the filament but should be on the filament side of the rheostat, not on the battery side. The grid will then have the same potential as the filament and its voltage will become positive during part of each cycle as signals come in. This rule applies to a hard tube such as is commonly used for detection. If a soft tube is used as a detector with a grid condenser the grid return should be connected to the negative terminal of the filament on the battery side. There will then be sufficient grid current on account of the ionization of the gas in the tube (see Section 44).

The initial grid voltage should be such that the tube will operate on the lower bend of the curve for grid current and grid voltage (see Section 41). With a grid condenser it is at the bend of this curve and not at the bend of the plate current curve that detection of signals is obtained.

98. Action of Modulated Waves on Grid and Plate. — For the sake of comparison we shall take first the action of modulated waves on a tube without grid condenser working at the lower bend of the plate current grid voltage curve. We shall now use graphs that show the changes of potential throughout a cycle (see Fig. 121). The high frequency oscillations modulated by sound waves cause the grid potential to oscillate above and below a certain initial value as shown in the upper part of the figure. As explained in Section 95 the increases in the plate current are greater than the decreases and the plate current varies in strength as shown in the middle portion of the figure. The high frequency oscillations do not act on the telephone receiver but, as explained in Section 94, the impulses in one direction are greater than those in the opposite direction and we have as a result a current of audio frequency through the telephone receiver as shown in the lower portion of the figure.

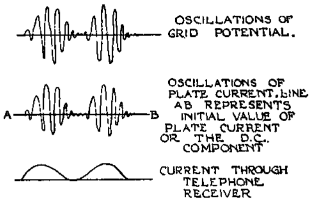


Fig. 121

Fig. 122 represents this action with a condenser in the grid circuit. We have the same oscillations as in Fig. 121. As the incoming oscillations increase in strength (a to b, Fig. 122) the grid becomes more and more negative as already explained. As the incoming oscillations diminish in strength (b to c) the

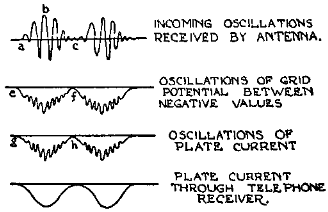


Fig. 122

grid loses its negative potential. These changes in grid potential are shown in the second part of Fig. 122, e to f. This causes the plate current to drop below its initial value and then return to this value as shown in the third part of Fig. 122, g to h. The series of changes in plate current from g to h gives one audio frequency wave. The short waves shown in the figure represent the radio frequency oscillations and these have no effect on the telephone receiver as already explained. The current which actuates the diaphragm of the telephone receiver; that is, the audio frequency current, corresponds in amplitude and frequency to the sound wave which acts on the transmitter to modulate the radio frequency oscillations.

99. Summary of Detector Action of a Tube. — The tube may act as a detector without grid condenser, in which case it is necessary to operate at the upper or lower bend of the grid voltage plate current curve. It is better to operate at the lower bend of the curve. The use of a grid condenser and grid leak makes it possible to detect on the straight portion of the grid voltage plate current curve. The tube is then operated on the lower bend of the curve for grid voltage grid current. With a given intensity of signal the action is stronger with a grid condenser than without.

For receiving faint signals the tube may be brought near to the oscillating point. This has the effect of reducing the resistance of the grid circuit and of greatly increasing the action on the grid as will be explained in Section 103.

In receiving unmodulated continuous waves as in continuous wave telegraphy, the detector tube may be made to oscillate and produce a beat note with the incoming signals as will be explained in Section 130. This is called " autodyne " reception. If one tube is used as an oscillator to produce a beat note with incoming signals and another tube for detection we have " heterodyne " reception.

100. The Crystal Rectifier. — When certain crystalline substances are placed in contact with metallic conductors, electrons can flow more easily across the point of contact in one direction than the other. The electrons can flow more readily from the crystal to the metal than from the metal to the crystal. Another way of stating this is that the resistance at the point of contact is greater in one direction than in the other. Certain crystals in contact with other crystals produce the same effect. Such a combination may be used as a rectifier of radio frequency oscillations and therefore as a detector. Examples of crystals that may be used as detectors are galena, iron pyrites, molybdenite, chalcopyrite, zincite, bornite and carborundum.

A characteristic curve for a crystal rectifier is given in Fig. 123. The curve shows that the current rises abruptly to the right of the zero point and is nearly zero to the left of that point. In other words, as the voltage varies above and below zero, a comparatively strong current flows for the positive voltage and a very small current for the negative voltage. The action on the telephone receiver is similar to that of an electron tube working at the lower bend of the characteristic curve.

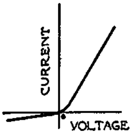


Fig. 123

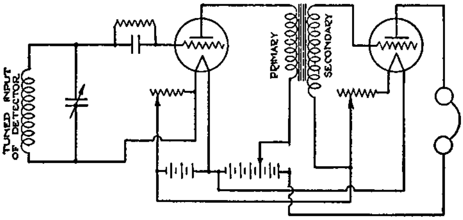


Fig. 124

101. The Electron Tube as an Amplifier. — It has been shown in Section 95 that an electron tube acting as a detector amplifies the received signal, the plate current being stronger than the grid current. The output of a detector tube may be still further amplified by the action of another tube. To accomplish this the plate current of the first tube must act on the grid of the second tube. This may be accomplished by passing the plate current of the first tube through the primary of a transformer and connecting the secondary of the transformer in the grid circuit of the second tube as in Fig. 124. The alternating current in the primary of the transformer induces an alternating e.m.f. of the same frequency in the secondary and this e.m.f. acts on the grid of the amplifying tube. The output current in the plate circuit of the amplifying tube is affected by the oscillations of grid voltage as explained in Section 95.

The action of an amplifying tube is like that of a detector tube with one important exception. It is necessary that the action of a detector tube take place at a bend in one of the curves either the curve for grid voltage and plate current or the curve for grid voltage and grid current. This is not true of an amplifying tube. To amplify without distortion the action should take place on the straight portion of the curves. The reason is that the detector must give out a current that is rectified so that it will act on a telephone receiver while an amplifying tube should give out oscillations of the same form as those which it receives but of greater amplitude. Fig. 125 shows that if the action takes place on the straight portion of the curve the changes in plate current correspond to the changes in grid voltage.

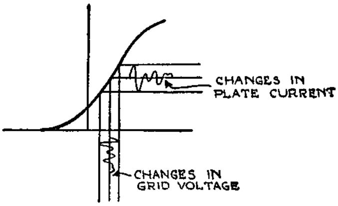


Fig. 125. — Changes in Plate Current Correspond to Changes in Grid Voltage

The steeper the slope of the straight portion of the curve the higher is the amplification because a steeper slope means a greater change in plate current for a given change in grid voltage. In general, if two tubes are compared, the one which has the steeper slope in the straight portion of the characteristic curve is the better amplifier and the one which has the sharper curvature at the lower bend is the better detector.

The grid return of the amplifying tube should be connected to the negative filament terminal. The purpose of making the grid negative is to reduce the grid current with its consequent loss of energy. The grid can be maintained at a negative potential with respect to the filament by inserting a battery in the grid circuit or by taking advantage of the voltage drop in the filament rheostat as explained in Section 26. A higher plate voltage is used on an amplifier tube than on a detector tube. This changes the position of the characteristic curve, as shown in Fig. 126, so that even with a negative grid voltage the tube operates on the straight portion of the curve.

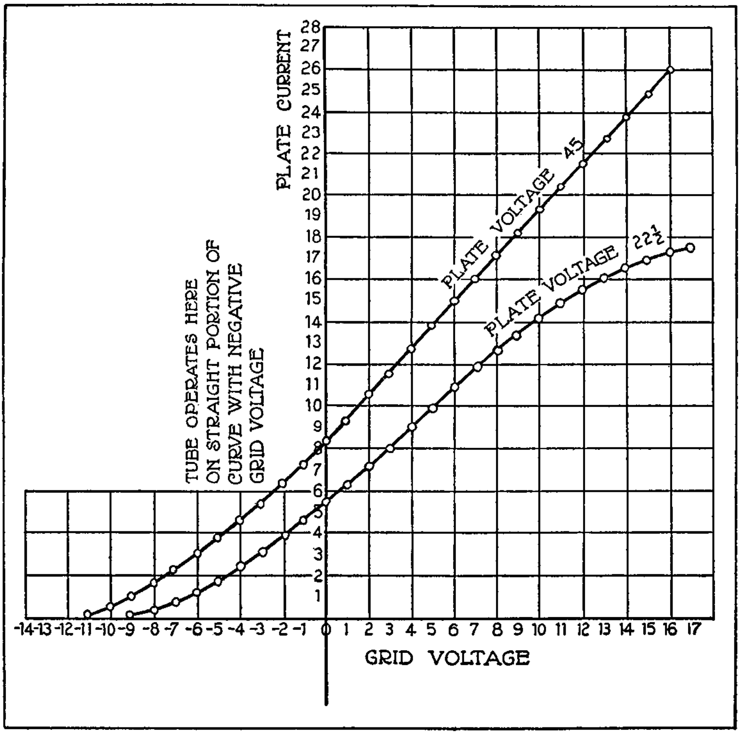


Fig. 126

The grid of an amplifying tube may be coupled to the antenna circuit. The tube will then amplify the signals at radio frequency before they are acted upon by the detector. A series of tubes may be used in this way. The circuits will be discussed in the next chapter. There are some important advantages in amplifying signals at radio frequency before detection. Signals which would otherwise be lost on account of being too weak to be acted on by the detector tube are amplified so that they can be detected. The output of a detector tube under proper operating conditions is nearly proportional to the square of the input voltage. If a radio frequency amplifying tube, for example, amplifies the voltage five times, the detector tube receiving this amplified voltage gives out a detecting current nearly twenty-five times as strong as it would without the amplifier. This is true for weak signals only. Strong signals will cause the detector tube to operate near its limit without the amplifier.

102. Mutual Conductance and Transconductance. — Mutual conductance is a very important quantity with respect to the operation of a tube because it is a measure of the effect of grid potential on plate current. To make clear the meaning of mutual conductance let us begin with the definition of conductance as it applies to any electric circuit. Conductance is the ability to conduct an electric current. In other words it is the ability to permit electrons to flow. Resistance, on the other hand, means a hindrance to the flow of electrons. The greater the resistance of an electric circuit the less is its conductance. Conductance is the reciprocal of resistance.

$$\text{Conductance} = \frac{1}{\text{resistance}}$$
$$= \frac{1}{R}.$$

Now substituting the value of R from the Ohm's law equation, we have

$$\text{Conductance} = \frac{1}{E/I} = \frac{I}{E}.$$

Conductance equals current divided by voltage. For a radio tube where we have rapidly changing current and voltage we divide change of current by change of voltage and since the conductance is mutual, that is, it relates to grid voltage and plate current, we divide change in plate current by change in grid voltage.

$$\text{Mutual conductance} = \frac{\text{change in plate current}}{\text{change in grid voltage}}.$$

It is desirable to have the mutual conductance as large as possible because the greater the mutual conductance the greater is the effect of grid potential on plate current.

We shall show next the relation between mutual conductance, amplification factor and plate resistance. For a rigid demonstration of this relation it would be necessary to go into higher mathematics but that is not our purpose here. We are aiming only to give an explanation that will enable the beginning student to form a mental picture of the action that goes on in a tube.

Amplification factor has been explained in Section 39. This factor is commonly represented by the Greek letter μ (pronounced mu).

$$\mu = \frac{\text{change in plate voltage}}{\text{change in grid voltage}}.$$

The two changes in voltage given in this equation are those that would produce equal changes in plate current.

Plate resistance has been explained in Section 40.

$$\text{Plate resistance} = \frac{\text{change in plate voltage}}{\text{change in plate current}}.$$

Now if we divide μ by plate resistance we get

$$\frac{\text{change in plate voltage}}{\text{change in grid voltage}} \div \frac{\text{change in plate voltage}}{\text{change in plate current}}.$$

This equals

$$\frac{\text{change in plate voltage}}{\text{change in grid voltage}} \times \frac{\text{change in plate current}}{\text{change in plate voltage}}.$$

Change in plate voltage cancels out and we get

$$\frac{\text{change in plate current}}{\text{change in grid voltage}}.$$

The last quantity is the mutual conductance. Thus we see that mutual conductance equals the amplification factor of the tube divided by the plate resistance. Using the symbols that are commonly used, G_m for mutual conductance, μ for amplification factor, r_p for plate resistance, we have the equation:

$$G_m = \frac{\mu}{r_p}.$$

Example: A certain tube has a plate resistance of 4950 ohms and an amplification factor of 3.8. What is its mutual conductance?

Solution:

$$G_m = \frac{3.8}{4950} = 0.000767 \text{ mho} = 767 \text{ micromhos.}$$

Example: A certain tube has a plate resistance of 10,000 ohms and a mutual conductance of 900 micromhos. What is its amplification factor?

Solution:

$$900 \text{ micromhos} = 0.000900 \text{ mho.}$$
$$\mu = 0.000900 \times 10{,}000 = 9.$$

The word "transconductance" came into use in connection with screen grid tubes. It has the same meaning as mutual conductance. When applied to screen grid tubes it relates to plate current and control grid potential. The symbol S_m, used for transconductance, has the same meaning in an equation as G_m.

103. Regenerative Amplification. — The form of amplification in which the same tube acts as amplifier and detector is known as regeneration. Regeneration may be explained as follows: Referring to the circuit of Fig. 127, the oscillating current of the plate circuit flows through the coil L_2 which is placed close to the coil L_1 of the grid circuit so that the magnetic field of L_2 can act on L_1. If weak oscillations are impressed on the grid by the received signals, stronger oscillations are produced in the plate circuit on account of the amplification in the tube itself (see Section 39). The plate current flowing through coil L_2 acts by magnetic induction on L_1.

If the coils are so placed that the oscillations in the plate circuit are in the same phase as those of the grid circuit the result is increased voltage in the grid circuit. The result is the same as if there were an increase of signal strength acting on the grid. These increased voltage changes are amplified in the tube producing still greater oscillations in the plate circuit and these again react upon coil L_1 and increase the strength of the grid oscillations. Thus the plate current builds up until it reaches a limit which is determined by the characteristics of the tube.

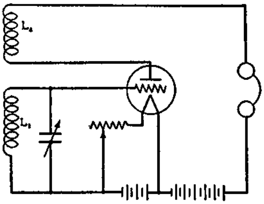


Fig. 127

The nearer coil L_2 is to L_1 and the more nearly parallel the coils are to each other the greater is the magnetic induction. If the coils are parallel and close together they are said to be closely coupled. If they are farther apart or nearly perpendicular to each other so that the magnetic induction is slight they are said to be loosely coupled.

The effect of received signals on the grid can be increased by reducing the resistance of the grid circuit. With less resistance a given impulse from the antenna produces a greater effect. It follows that the effect of the energy fed back from the plate circuit to the grid circuit is very much the same as that of reducing the resistance of the grid circuit. One way, then, of looking at regeneration is that the " feed back " introduces a negative resistance which opposes or neutralizes that of the grid circuit. When this opposing or negative resistance is such that the total resistance of the grid circuit is zero, the oscillations of the tube continue with no external energy being applied. In other words the tube gives out sustained oscillations. One caution is necessary here and that is that the so-called negative resistance does not do away with the need of reducing as much as possible the actual resistance of the coils and condensers to which the grid is connected.

If the coupling is fairly close so that the oscillations of the plate current produce a greater e.m.f. in the grid circuit than is produced by the original signal, the oscillations will continue after the signals have ceased. The tube is then generating an oscillating current. The negative resistance mentioned above is the effect of the voltage fed back from the plate circuit.

The use of an electron tube as an oscillator will be discussed in Chapter IX. The important point here is that the principle of the oscillator is essentially the same as that of the regenerative receiving circuit. In receiving, however, the coupling of the plate circuit or tickler coil with the tuning coil of the grid circuit should be kept just below the point at which the tube oscillates.

The connections of coils L_1 and L_2 must be such that the e.m.f. induced in L_1 by the oscillations in L_2 will aid the e.m.f. of the signal instead of opposing it. If there is no regenerative action; that is, if only feeble sounds are heard in the receiver, it may indicate that the two e.m.f.'s are in opposite phase, in which case it is necessary to reverse the connections of the tickler coil or turn it over through an angle of 180°.

104. Regeneration Through Capacity Coupling. — Another way in which the plate current may be made to react on the grid is by means of a condenser instead of a tickler coil. To illustrate this effect, suppose that a condenser is connected in the part of the circuit that is common to both the grid and plate circuits as in Fig. 128. The oscillations of the plate current act on the condenser c producing voltage oscillations across this condenser. Since the condenser is also in the grid circuit, these oscillations also act on the grid, reinforcing the grid oscillations and still further increasing the amplitude of the plate current. Since the coupling of the grid and plate circuits is through a condenser it is called capacity coupling.

The capacity within the tube itself may act as a coupling by means of which the plate circuit oscillations react on the grid. The grid and the plate of the tube act as the plates of a condenser. The means by which regeneration through the tube capacity may be prevented will be taken up in Chapter VIII.

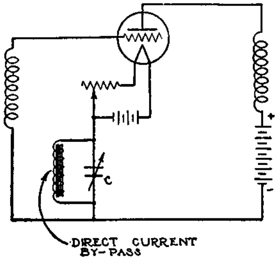


Fig. 128. — Regeneration through Capacity Coupling

105. Power Amplification. — An electron tube whether used as a detector or as an amplifier gives out more power than it receives. In other words the tube develops more power in the plate circuit than in the grid circuit. The tube does not create power from nothing but takes the power of the plate circuit from the plate battery. The grid oscillations serve merely to control this power as explained in Section 38.

The power in the plate circuit may be many thousands of times as great as that of the grid circuit. By making the grid negative the power consumed in the grid circuit may be made extremely small.

Questions

1. Why is the resistance of a radio head set greater than that of a receiver for a wire telephone? Why is one more sensitive than the other?
2. Explain the action of a microphone.
3. Why is it necessary to rectify the current in radio reception? Give at least two reasons.
4. Explain the fact that a tube does not work as a detector when the action takes place on the straight line portion of the characteristic curve.
5. Explain the action of a tube working on the upper bend and on the lower bend of the characteristic curve. Why is it better to work on the lower bend?

6. How may the grid be made negative without the use of a grid battery?

7. Explain the action of a detector tube with a grid condenser.

8. Explain the action of a detector tube in receiving modulated waves.

9. Why should the action of an amplifier tube take place on the straight portion of the characteristic curve?

10. How could you judge from the characteristic curves of two tubes which is the better amplifier and which is the better detector?

11. How can a tube be made to operate on the straight portion of the curve?

12. What advantage is there in amplifying signals before they reach the detector tube?

13. Explain regeneration.

14. An electron tube gives out more power than it receives. What is the source of this power?

Problems

1. Find the mutual conductance of a tube whose plate resistance is 13,000 ohms and amplification factor 9.3.

2. The mutual conductance of a certain screen grid tube is 505 micromhos and the plate resistance 1,150,000 ohms. Find the amplification factor.

3. The plate resistance of a certain power amplifier tube with a grid bias of –50 volts is 1900 ohms, the amplification constant 3.5. What is the mutual conductance?

4. If a grid bias of –33 volts is placed on the same tube as in problem 3, the plate resistance is 1950 ohms, the amplification constant remaining the same. What is now the mutual conductance?

CHAPTER VIII

FUNDAMENTALS OF RECEIVING CIRCUITS

The various forms of radio receivers can be grouped in a few types. It is the purpose in this chapter not to give a compendium of receiving circuits but rather to make clear the fundamental principles of such circuits. The important types of circuits will be used as illustrations. The student who learns the typical circuits and the principles underlying them will be able to design circuits, adapting each circuit to the particular purpose for which the receiving set is to be used.

106. The Essential Parts of a Receiving Circuit.—All radio transmission is by means of electromagnetic oscillations or waves that go out from an oscillator at a transmitting station and travel through space with the speed of light, this speed being about 186,000 miles or 300,000,000 meters per second. These waves when received by an antenna or loop properly designed produce oscillations or a surging back and forth of the electrons in the antenna or loop.

If an antenna is connected to the earth, then the antenna and the earth together act like a condenser, the antenna being one plate of the condenser and the earth the other plate. When electromagnetic oscillations pass over the antenna, electrons in the antenna are caused to surge back and forth between the antenna and the earth. In other words oscillations are produced in the antenna and the wires connected to it. If the tuning coil of a receiving set is connected with one terminal to the antenna and the other terminal to the ground the oscillations pass through the tuning coil.

The same principle holds true of a loop. The electromagnetic waves or oscillations coming through space cause oscillations of the electrons in the loop. The loop itself with a condenser across its terminals may be the tuning element of a receiving circuit or the terminals of the loop may be connected to a tuning element consisting of a coil and condenser.

A detector must be connected or coupled to the antenna circuit. This may be a crystal detector or an electron tube.

If a crystal detector is used there are two distinct circuits.

1. The antenna circuit.
2. The detector circuit consisting of the tuning element, the crystal detector and the telephone receiver.

If an electron tube is used there are four distinct circuits.

1. The antenna circuit or loop in which oscillations are set up by the electromagnetic waves.
2. The grid circuit in which oscillations are induced by the oscillations of the antenna circuit.
3. The plate circuit in which oscillations of greater amplitude are caused to flow by the oscillating e.m.f. of the grid circuit.
4. The filament circuit for keeping the filament heated.

107. The Antenna Circuit.—The antenna circuit is essentially a condenser. If a wire is suspended in the air this wire forms one plate of a condenser and the earth the other plate. Suppose the suspended wire is connected to the earth as in Fig. 129. Electromagnetic waves moving horizontally produce electric oscillations in a vertical direction; that is, they produce an electromotive force between the antenna and the earth. The electromotive force oscillates; that is, it acts first in one direction, then the opposite. The antenna is positive and then negative with respect to the earth. This is the meaning of the double pointed arrow in Fig. 129. Each wave produces one

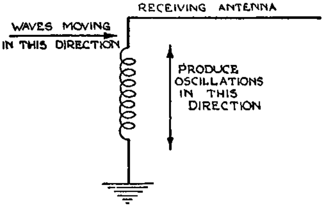


Fig. 129

oscillation so that the oscillating e.m.f. between the antenna and the earth has the same frequency as the received waves. The oscillating electromotive force sets the electrons in motion. If there is a coil in the antenna circuit as in Fig. 129, the electrons surge back and forth through this coil between the antenna and the earth. If there is a condenser in the antenna circuit as in Fig. 130, the electrons surge into and out of this condenser.

The ground side of the antenna circuit may be connected to a wire or network of wires suspended a short distance above the earth and insulated from it. This network of wires is called a counterpoise. The counterpoise acts as one plate of a condenser and the antenna as the other plate. The action is like that described above, the counterpoise now taking the place of the earth. Instead of a suspended wire and counterpoise, two metal plates may be used or two sheets of copper wire netting.

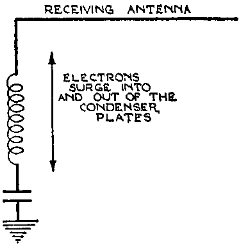


Fig. 130

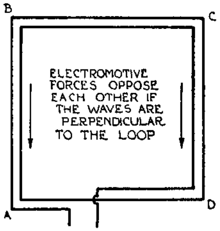


Fig. 131

108. The Loop Antenna. — A loop or coil of wire may be used in place of the antenna and ground. A loop is merely a large flat coil. Fig. 131 represents a loop antenna. As the waves pass over the loop an oscillating e.m.f. is induced between A and B, likewise between C and D. Suppose the waves are traveling in a direction perpendicular to the plane of the coil. This would be true, for example, if the waves were traveling toward the north or south and the coil were placed in an east and west position. The crest of a wave would reach AB and CD at the same instant. As the waves now move over the coil they induce e.m.f.'s in AB and CD that oppose each other. To explain this more fully: During one half cycle both e.m.f.'s act downward and during the next half cycle both act upward. It is clear that if the e.m.f.'s in AB and CD both act downward at the same instant and both act upward at the same instant, they are trying to send currents around the loop in opposite directions. Therefore no current flows.

On the other hand, if the waves travel parallel to the plane of the loop the crest of a wave will reach one side of the loop before it reaches the other side (see Fig. 132). The electromotive forces in the two sides of the loop then differ in phase and there is a resultant e.m.f. that tends to send a current around the loop. If the distance across the loop, BC, were one-half a wave length, the electromotive forces in AB and CD would be exactly opposite in direction at any instant, for just as the crest of a wave would pass over CD the trough would pass over AB. The e.m.f.'s would then act together to send a current around the loop. Practically it is necessary to make the width of the loop, BC, very much less than a half wave length but there is still a resultant e.m.f. The signals are received by the vertical side of the loop, the horizontal parts serving only as electrical connections between the vertical sides.

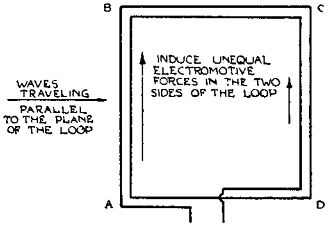


Fig. 132

From this discussion it is clear that the loop will receive signals very faintly when it is placed perpendicular to the direction in which the waves are traveling and that it will receive signals with greatest intensity when placed in a direction parallel to that in which the waves are traveling. As the loop is turned from the parallel to the perpendicular position with reference to the waves the signals gradually decrease in intensity until they almost or quite disappear. On account of this effect a loop antenna may be used to find the direction from which the signals come. A loop used in this way is sometimes called a radio compass or a radio direction finder.

109. Fundamental Wave Length of an Antenna. — It has been shown in Section 107 that an antenna acts together with the earth as a condenser. It has been shown also that for high frequency currents there is inductance in a straight wire (see Section 91). It follows that an antenna has both inductance and capacity. Both the capacity and the inductance are distributed along the entire length of the wire.

The fundamental frequency of an antenna is that for which the maximum possible current will flow when the antenna is not loaded either with a coil or a condenser; that is, when the antenna circuit includes only the capacity and inductance of the antenna itself.

The fundamental frequency of any electric circuit is that for which the circuit is in resonance or that for which the sum of the inductive and the capacity reactances is zero (Sections 79 and 86). It can be shown by higher mathematics that this is true for a single wire antenna either vertical or of the L type when the length of the antenna is approximately one-fourth of the wave length. The length of an L type antenna includes the length of the horizontal portion plus the length of the lead-in.

For example: Suppose it is desired to erect an inverted L antenna which should have a fundamental wave length of 200 meters. Two hundred meters equals approximately 600 feet. Therefore the distance from the ground up through the ground lead and the antenna lead and along the top to the end of the antenna should be about 150 feet. In practice the length may vary considerably from this value.

110. Effect of Inductance and Capacity on Fundamental Wave Length of an Antenna. — The wave length of any resonating circuit may be increased by increasing either its inductance or its capacity. The wave length of an antenna, therefore, is increased by an inductance coil in series. The actual length of an antenna tuning to the same wave length but having an inductance coil in its circuit should be less than that given in the preceding paragraph. The inductance of the antenna circuit is the sum of the inductances of the coil and the antenna. On the other hand, the wave length is decreased by a condenser in series with the antenna, the reason being that a condenser so connected is in series with the capacity of the antenna itself and two condensers in series have less capacity than either of the condensers alone (Section 69).

If the capacity of the condenser in series with the antenna is reduced, the wave length of the antenna circuit is reduced. If we continue to reduce the capacity of the series condenser the wave length is further reduced until we reach the smallest possible capacity of the condenser, which is zero. This would mean simply the lower end of the antenna hanging free. The fundamental wave length would then be one-half that of the antenna when connected to earth. In other words, when the antenna is connected to earth, the antenna length is one-fourth the fundamental wave length, but when hanging free, the antenna length is one-half the fundamental wave length. In practice the wave length may be reduced by means of a condenser to about one-third the fundamental wave length of the grounded antenna. An interesting comparison might be made with the wave length of a resonating air column. In a pipe closed at one end the resonating air column is one-fourth of the wave length. This corresponds to an antenna connected to earth. In an open pipe the resonating air column is one-half the wave length. This corresponds to an antenna hanging free.

111. Tuned and Untuned Antenna Circuits. — An antenna circuit may be tuned to different frequencies or wave lengths by means of a coil having a variable inductance connected in series with the antenna. If shorter wave lengths are desired a variable series condenser may be used.

The antenna circuit may, however, contain only a coil having a few turns and therefore a very small inductance. The circuit is then untuned or rather it is broadly tuned because the resistance of the antenna circuit is large compared with its inductance and capacity. In other words, by making the inductance and capacity small the resistance is made relatively large and it has been shown in Section 84 that resistance in a resonant circuit broadens the tuning. Such an antenna circuit is said to be aperiodic; that is, without definite period or frequency.

112. Harmonics. — A circuit consisting of an inductance coil and a condenser and having very low resistance can become resonant for only a single frequency. An antenna circuit, however, may become resonant for a number of different frequencies. This is because the capacity and inductance are not concentrated in a condenser and coil but are distributed along the antenna and because the effective resistance, inductance and capacity change with frequency. The fundamental frequency is the lowest frequency for which the current becomes a maximum. For a grounded antenna having no inductance coil or condenser in the antenna circuit the other frequencies for which the current is a maximum are odd multiples of the fundamental. If f is the fundamental frequency, then 3f, 5f, 7f and so on are the other resonant frequencies. These higher resonant frequencies are called harmonics. If the antenna is ungrounded it may operate on the even harmonics, 2f, 4f, and so on. The harmonics correspond to wave lengths of $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, $\frac{1}{5}$, and so on, of the fundamental wave length. An inductance coil or a series condenser changes the harmonics as well as the fundamental wave length. In practice, the fundamental itself is called the first harmonic, the next higher frequency is called the second harmonic and so on.

Again we may compare the antenna with a resonating air column such as the air column in an organ pipe. If the pipe is closed at one end the fundamental note has a wave length four times the length of the air column. The same pipe may give out other notes called harmonics which have lengths $\frac{1}{3}$, $\frac{1}{5}$ and so forth, times the wave length of the fundamental.

113. Wave Length for Different Types of Antenna. — Thus far we have discussed only the inverted L type of antenna consisting of a single wire. If the antenna consists of several wires separated on spreaders the wave length is greater than for a single wire. For a T type antenna (Fig. 133) the fundamental wave length is found by taking the height plus one-half the top and multiplying by four. This gives an approximate result as in the case of the L type. A low horizontal antenna has a greater wave length than a high one because, being nearer the earth, its capacity is greater. The high antenna, however, receives more energy than the low one.

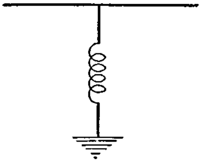


Fig. 133. — T Type Antenna

A loop antenna is always used with a condenser shunted across the loop. The distributed capacity of the loop is small compared with the capacity of the condenser so that the capacity of the loop may be neglected and the resonant wave length of the loop and condenser found by the fundamental wave-length equation,

$$\lambda = 1884\sqrt{LC}$$

L being the inductance of the loop and C the capacity of the condenser.

114. Further Discussion of the Loop Antenna. — The principal advantage of a loop antenna is that it greatly reduces the effect of atmospheric disturbances, strays or static. Strays appear to be due to varying difference of potential between the earth and the space above the earth. Such variation of potential readily affects a flat top antenna because the antenna forms one plate of a condenser with the earth as the other plate. The loop antenna, on the other hand, is not connected to earth and therefore is not affected by any change of potential with reference to the earth.

The disadvantage of the loop is that the signals are much more feeble than with antenna and ground and require more amplification.

115. The Grid Circuit.—The typical grid circuit consists of a coil and condenser with connecting wires leading to the grid and filament terminals of the tube (Fig. 134). The coil and condenser form an oscillating circuit. We have seen in Section 85 that in a parallel resonance circuit a very high voltage is produced at the points of connection of coil and condenser (E and F, Fig. 134). The wires leading to grid and filament are connected at these two points. The high voltage acts on the grid producing on the grid an oscillating electromotive force of the same form and frequency as that of the incoming signals. The discussion of parallel resonance in Sections 85, 86 and 87 applies to the coil and condenser of the grid circuit which form the tuning element of the receiver. Since the resistance of the tuning element is usually small the equation for frequency and wave length may be applied as explained in Section 87.

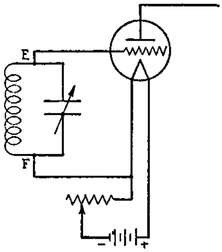


Fig. 134.—The Grid Circuit

Example: The tuning element of a grid circuit contains a variable condenser of 0.0005 microfarad maximum capacity and a coil of 150 microhenries inductance. What is the capacity of the condenser when the circuit is tuned to a wave length of 480 meters?

Solution:

$$\lambda = 1884\sqrt{LC}$$

$$480 = 1884\sqrt{150C}$$

Solving this equation, we get

$$C = 0.00043 \text{ microfarad.}$$

Methods of finding inductance of coils and of constructing coils having a specified inductance will be given in Chapter X.

The grid circuit must be coupled to the antenna circuit so that the antenna oscillations will induce oscillations in the grid circuit when the grid circuit is properly tuned. The coupling is done by means of two coils, a primary in the antenna circuit and a secondary in the grid circuit. " Loose " coupling gives greater selectivity than " close " coupling.

The same principles apply with reference to the grid circuit if more than one tube is used. The grid circuit of the second tube is coupled to the plate circuit of the first tube and so on through the series.

116. The Plate Circuit. — The plate circuit of a detector tube is shown in Fig. 135. The circuit consists of the plate battery, the plate and filament of the tube with the stream of electrons between them, the telephone receiver and the connecting wires. The plate battery must be connected in such a way as to make the plate positive, that is with the positive terminal of the battery toward the plate.

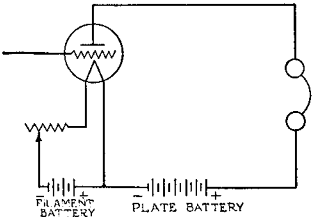


Fig. 135. — The Plate Circuit

If the negative terminal of the plate battery is connected to the positive terminal of the filament battery the voltage of the plate is the sum of the voltages of the two batteries. If the negative terminal of the plate battery is connected to the negative terminal of the filament battery, the voltage of the plate is simply the voltage of the plate battery. The negative terminal of the plate battery may, then, be connected to either terminal of the filament, the only difference being in the voltage of the plate. This voltage can be tested by connecting a voltmeter across the plate terminal and the negative filament terminal of the tube socket. When plate voltage is specified, the voltage of the plate with reference to the negative filament terminal is meant.

If an amplifying tube is added, after the detector tube, the plate circuit of the detector tube includes some form of coupling device in place of the telephone receiver. If transformer coupling is used the primary of the transformer is connected in the plate circuit and the secondary is connected in the grid circuit of the next tube.

117. The Filament Circuit. — The filament circuit consists simply of the filament, the rheostat, the filament battery and the connecting wires. The use of the rheostat in controlling the voltage at the filament terminals is explained in Sections 23 and 24. A resistor whose resistance increases with temperature is commonly used in the filament circuit. This resistor controls the filament current automatically. For alternating current tubes a low voltage winding of the transformer in the power unit takes the place of a filament battery.

118. The Telephone Bypass Condenser. — It is well in any receiving circuit to connect a fixed condenser across the telephone receiver or loud speaker. The capacity of such a condenser may have a value of 0.001 microfarad. The purpose of the bypass condenser is to provide a path for the high frequency oscillations. We have seen that a coil offers much greater impedance to high frequency than to low frequency oscillations. Oscillations of audio frequency can readily go through the windings of a telephone receiver but those of radio frequency cannot. On the other hand a condenser offers less hindrance to the radio frequency oscillations than to those of audio frequency. If no bypass condenser is used the radio frequency oscillations pass by means of the distributed capacity of the windings in the receiver and the wires of the telephone cord but the capacity of these windings is usually too small to form an effective bypass. The result, if an effective bypass is not used, is distortion of the signals.

119. The Simple Electron Tube Detector Circuit. — Some simple receiving circuits were given in Chapter I. The student has now learned the principles on which such circuits operate and is prepared to take up a more thorough study of receiving circuits. For the sake of simplicity we shall first discuss circuits in which batteries are used and then take up the power unit by means of which the direct voltages needed are obtained from an alternating current supply.

Going back to Fig. 8, Chapter I, we have one of the simplest forms of detector circuit using an electron tube. In this circuit we have simply combined the four circuit elements discussed in Section 106. The antenna circuit is of the simplest form possible, a coil of a few turns connected to the antenna and the ground. The coil in the antenna circuit is the primary. Assuming that the circuit is for receiving signals of from 550 to 1500 kilocycles, the primary may have 15 to 20 turns and the secondary 75 to 80 turns, the two windings being about one-fourth inch apart and both on a cardboard or bakelite tube two inches in diameter. The grid circuit is tuned by means of a variable condenser. A condenser of 0.00035 microfarad capacity is satisfactory. The specifications just given are not the only ones that could be used. The cardboard or bakelite tube might be smaller or larger. If smaller, more turns are needed, if larger fewer turns. A good plan is to wind the secondary with a few more turns than one thinks will be needed, then tune in a station of low frequency, one as near 550 kilocycles as possible. If the number of turns is correct the rotor plates of the condenser will be almost completely meshed with the stator plates. If this is not the case, remove turns one at a time and repeat the tuning until nearly the maximum capacity of the condenser is used, that is, until the rotor plates are almost completely meshed.

A method of determining the diameter and number of turns required for a given inductance will be given in Section 182. Specifications for coils and condensers for short wave reception will be given in Section 139.

The filament circuit must include a resistor of the correct value for the tube that is to be used. The plate circuit may include simply a telephone receiver with bypass condenser and plate battery.

Thus we have combined in one of the simplest possible ways the four elements of an electron tube receiving circuit. In this circuit the only amplification is the voltage amplification within the tube itself.

120. Regeneration. — Regenerative amplification has been explained in Sections 103 and 104. It was shown that regeneration is secured by coupling the plate circuit to the grid circuit so that the oscillating plate current increases the amplitude of the grid oscillations. There are various ways in which the two circuits can be coupled.

One of the simplest methods is that of inductive coupling. A coil of a few turns is connected in series in the plate circuit and placed close to the end of the tuning coil in the grid circuit (Fig. 127). This coil is commonly called a tickler coil. The plate current now flows through the tickler coil and by magnetic action induces an electromotive force in the tuning coil. This action is sometimes called " feed-back." To secure regeneration this induced e.m.f. must add to the e.m.f. produced by the signals. In other words the two e.m.f.'s must be in the same phase. If regeneration is not secured it is because the two e.m.f.'s are of opposite phase and the cure is to reverse the connections of the tickler coil. This circuit is the simple detector circuit of Fig. 8 with the tickler coil added.

Regeneration may also be secured by capacity coupling as shown in Fig. 128. The plate circuit oscillations then react on the grid circuit through a condenser. Such feed-back action is made use of in oscillators as we shall see in Chapter IX.

The capacity within the tube itself may be used to secure regeneration. We have seen that the grid and plate of an electron tube form a condenser, one of very small capacity it is true (ranging from about 7 to 14 micro-microfarads) yet sufficient to enable the plate oscillations to react on the grid.

If this action is such as to add to the e.m.f. acting on the grid it has the same effect as reducing the resistance of the grid circuit. This can happen only when the reactance of the plate circuit is inductive and when it exceeds a certain value so as to make the phase angle between impedance and resistance sufficiently large. If this effect is large enough to neutralize the resistance of the grid circuit, that is to make the total resistance of the grid circuit zero or negative, then the oscillations will continue when once started without any external e.m.f. being applied. A tube brought near but not quite to the oscillating point is extremely sensitive and will respond to very faint signals.

121. Audio Frequency Amplification. — The signal oscillations after being rectified by the detector tube may be amplified by one or more tubes. We shall now discuss the means by which this is done.

The plate current or output of the detector tube must be made to act on the grid circuit of the first amplifier tube. This may be done by means of a transformer. The primary of the transformer is connected in the plate circuit of the detector tube and the secondary in the grid circuit of the amplifier tube (Fig. 136). The oscillations of the plate current in the primary induce oscillations of the same form and frequency in the secondary. The secondary winding has more turns than the primary so that the voltage is stepped up. The voltage is then still further amplified in the amplifier tube itself so that the voltage output of the amplifier tube is many times as great as that of the detector tube. The power output is also greater, more current being taken from the plate battery by the amplifier tube than by the detector tube. A negative potential should be placed on the grid sufficient to hold the grid negative as signals are received because, if the grid becomes positive so that there is an appreciable grid current, distortion of the signals

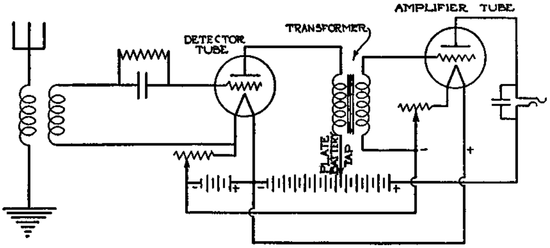


Fig. 136

results. To avoid distortion it is necessary also that the action of the amplifier tube should be on the straight line portion of the grid voltage plate current curve. Since the grid must be negative and the action must be on the straight portion of the curve it follows that the straight portion of the curve must be on the negative side. This required a high plate voltage as compared with the plate voltage of the detector tube. This can be made clear by referring to Fig. 53 where we can see that increasing the plate voltage shifts the curve toward the negative side. Audio frequency transformers have cores of the best electrical iron or annealed silicon steel which can reverse its magnetism rapidly enough for the audio frequency oscillations.

The coupling between the two tubes may be made by means of resistances as shown in Fig. 137. This is a form of conductive coupling. The plate circuit oscillations of the detector tube act directly on the grid circuit of the amplifier tube. In this case less amplification is obtained than with transformer coupling because there is no amplification in the resistance coupling, the only amplification being that of the tubes.

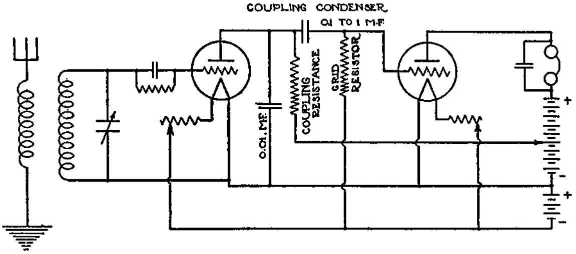
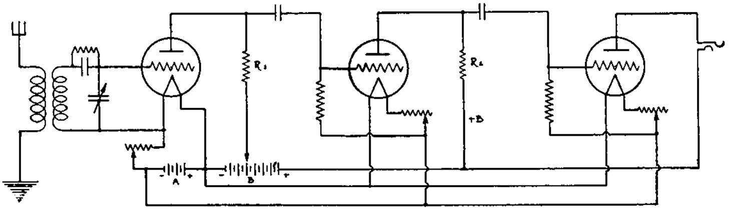


Fig. 137. — Resistance Coupled Circuit

A choke coil or inductance may be substituted for the coupling resistance in Fig. 137. We then have an inductance coupled amplifier. The amplification in this case depends on the ratio of the reactance of the coil to the total plate circuit impedance. Since the reactance of a coil increases with frequency the amplification is greater for high frequency than for low.

A second step of amplification, resistance coupled, may be obtained by connecting the output circuit of the first amplifying tube to another tube by means of a resistance and condenser as in Fig. 138.

Since the output of the detector tube is a current oscillating at audio frequency, the amplifying circuits just described are called audio frequency amplifiers. A third or fourth stage of amplification may be added but, as a rule, it is not advisable to go beyond two stages unless a push-pull amplifier is used.



R₁ AND R₂ SHOULD BE APPROXIMATELY EQUAL TO THE PLATE RESISTANCE OF THE TUBE

Fig. 138

122. The Push-pull Amplifier. — This is an amplifier which is practically free from distortion. It was intended originally for use as a repeater for telephone lines and later was adapted to radio. The inventor is Mr. E. H. Colpitts of the Western Electric Company. It will be seen in Fig. 139 that the output from the two tubes in the push-pull circuit flows through the two parts of the tapped primary of the output transformer in opposite directions. It can also be seen that the input is such as to make the grid of one tube positive when the other is

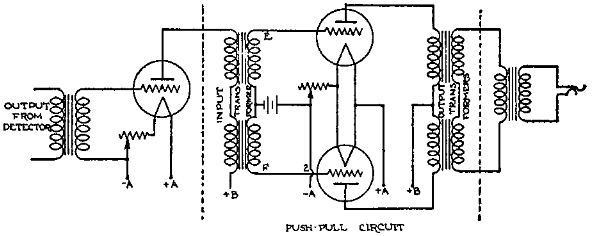


Fig. 139. — Push-pull Amplifier

negative. This is clear if one traces the action of a single impulse in the input transformer. Suppose we catch the impulse at the instant when it is acting in the direction EF. It tends then to make the grid of tube 1 negative and of tube 2 positive. The action then is in opposite directions on the plates of the two tubes. While the plate current of one tube is increasing, that of the other is decreasing. The magnetic action in the primaries of the output transformers is such that a decrease in the current in one tends to increase the current in the other. The magnetic fields, therefore, are greater than they would be if only one tube were used. The current that flows to the loud speaker is the result of the voltages of the two tubes acting together. It is a greater current than either would produce separately. If one tube were used alone there would be distortion because the decreases of plate current would be slightly less than the increases. This action would be the same in both tubes. With two tubes connected as shown the distortion is smoothed out because the increases in one tube are added to the decreases in the other. This produces a current curve almost perfectly symmetrical.

123. Connecting an Amplifier to a Detector. — It should be a simple matter for the student to connect any form of amplifier to any detector circuit. For example, in Fig. 140, a detector circuit and an amplifier circuit are shown with the terminals marked to show which are to be connected together. The telephone receiver is removed from the detector circuit and the two terminals of the plate circuit are connected to the primary of the transformer. The telephone receiver is connected in the plate circuit of the amplifying tube. The fila-

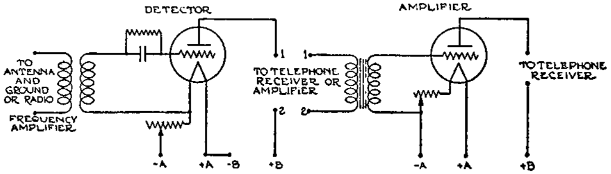


Fig. 140

ment terminals of the amplifying tube are connected back to the same battery that lights the filament of the detector tube. The plate circuit is connected to the positive terminal of an additional plate or " B " battery and the negative terminal of this battery connected to the positive terminal of the plate battery of the detector tube. A similar plan can be followed for connecting a resistance coupled amplifier. A push-pull circuit can be added as a third stage of audio frequency amplification.

124. Radio Frequency Amplification. — Signals may be amplified at radio frequency before they reach the detector tube. The principle is similar to that of audio frequency amplification, the difference being in the transformer or other coupling used. A radio frequency transformer, as a rule, has an air core. To insert one stage of radio frequency amplification between the antenna and the detector tube it is only necessary to couple the antenna circuit to the grid circuit of the amplifier tube and to couple the output or plate circuit of the amplifier tube to the grid circuit of the detector tube. This means, if transformers are used, connecting the primary of the

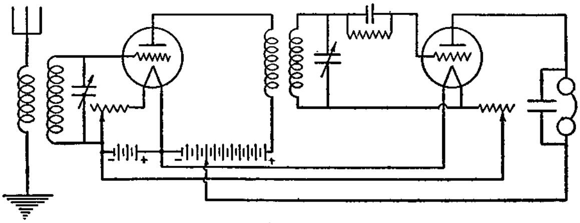


Fig. 141

first transformer in the antenna circuit and the secondary in the grid circuit of the amplifier tube. The complete circuit is shown in Fig. 141.

Better results are obtained if the radio frequency stages are tuned. This is done by connecting a variable condenser across the secondary of each transformer. The grid circuit of each tube is then tuned to resonance with the incoming signal by means of the condenser.

A second stage of radio frequency amplification may be inserted by connecting the output of the first tube to the primary of the second transformer and the secondary of this transformer to the grid circuit of the second tube. A circuit with two stages of radio frequency amplification and a detector tube is shown in Fig. 142. Radio frequency transformers for this circuit are easily made. A transformer may be made simply by winding both primary and secondary on a cardboard tube three inches in diameter. The primary may consist of, say 10 to 15 turns and the secondary of 40 to 60 turns. The wire used may be number 26. If 15 and 60 turns are used the condenser should be of 250 micro-microfarads capacity. If only 40 turns are used on the secondary the condenser should have a capacity of 500 micro-microfarads. These values are for tuning to frequencies of 500 to 1500 kilocycles.

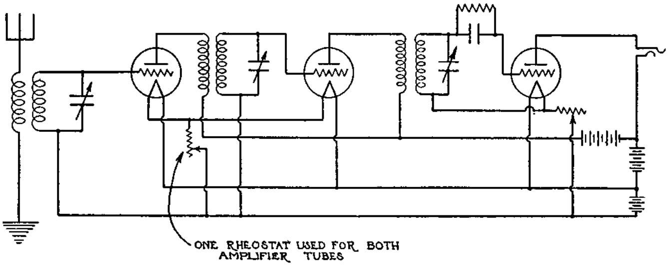


Fig. 142

It was shown in Section 102 that under certain conditions a tube will oscillate, that is, will produce sustained oscillations. The plate circuit is coupled back to the grid circuit and the two circuits are tuned to resonance at the same frequency. We have seen also that the plate circuit can react on the grid circuit through the capacity between plate and grid. The plate-grid capacity acts as the coupling between the two circuits. In a tuned radio frequency amplifier, if the plate and grid circuits are brought to the oscillating point, the oscillations interfere with the reception of signals.

If the number of turns on the primary is made small compared with the secondary the tube is less likely to oscillate. If, however, we have a primary of only a few turns there is considerable loss of energy, we are reducing the efficiency of the tube. We must either tune below the oscillating point or we must have only a few turns on the primary. In either case we are not using the tube at its highest efficiency. Oscillations may be prevented also by introducing a resistance in the grid circuit but this is another inefficient method. This discussion brings us to the next step, that of neutralizing the oscillations caused by the plate-grid capacity of the tube.

125. The Neutrodyne Circuit. — One of the best known means of neutralizing the effect of the plate-grid capacity is the neutrodyne circuit invented by Hazeltine. In this circuit the voltage which would produce oscillations, that is, the voltage across grid and plate, is neutralized by an opposing electromotive force. To understand how this opposing electromotive force is produced, refer to Fig. 143. Here we have condenser C_1 and coil L_1 connected in parallel with C_2 and L_2. Suppose there is an electromotive force which would cause a current to flow from A to B as shown by the heavy arrows. The current starts at zero and increases so that an increasing magnetic field is produced. Suppose now the magnetic field of L_2 induces an e.m.f. in L_1 which is just equal and opposed to the applied e.m.f. as shown by the dotted arrow. No current can flow in L_1 and C_1 because the two e.m.f.'s just neutralize each other. This action takes place in one half of a cycle. During the other half of the cycle all the e.m.f.'s are reversed and again we have neutralization. Now suppose C_1 to be the

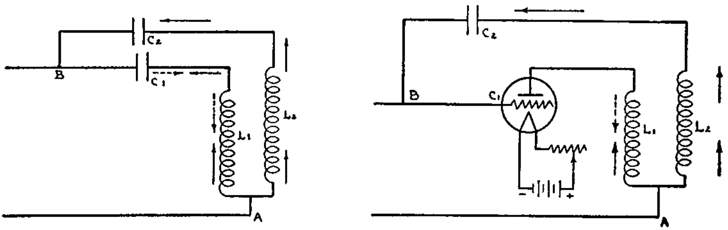


Fig. 143 Fig. 144

The Principle of the Neutrodyne Circuit

capacity between the grid and plate of a tube as in Fig. 144. We can see that if just enough current flows in L_2 its magnetic field induces an e.m.f. in L_1 which exactly neutralizes the e.m.f. across plate and grid. C_2 must be adjusted to such a capacity as to allow just the right amount of current to flow in L_2. The current required is very small, therefore C_2 must be a very small capacity. The neutralizing action in a neutrodyne circuit is due to the electromagnetic induction of a coil. The purpose of the neutrodon or neutralizing condenser is to control the amount of current flowing in the coil. The action of the neutralizing coil and condenser is sometimes called a reverse feed-back.

In the neutrodyne circuit as commonly constructed the secondary winding is tapped and the tap connected to condenser C_2 so that L_2 is part of the secondary. Fig. 145 is a circuit having two stages of tuned radio frequency amplification neutralized with a reverse feed-back, a detector tube and two stages of audio frequency amplification. This is the five tube neutrodyne.

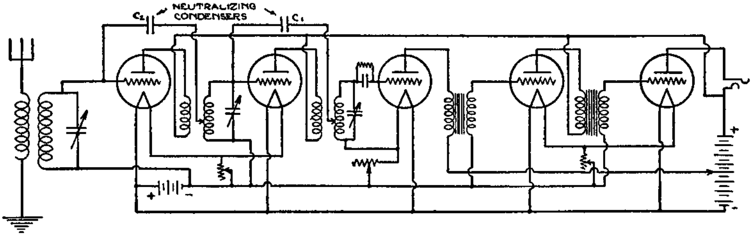


Fig. 145. — A Neutrodyne Circuit

In the neutrodyne circuit the input and output circuits can be tuned up to the point of resonance since oscillation is prevented by the reverse feed-back. The tube is then operating at its highest efficiency.

126. Use of the Screen Grid Tube. — If screen grid tubes are used in the radio frequency stages no neutralizing device is needed. It has been shown in Sections 103 and 104 that the plate and grid of a tube act like the plates of a condenser and that changes in plate voltage react on the grid and that when this feed-back action passes a certain limit, oscillations take place. In the screen grid tube feed-back action from plate to grid is prevented and it is possible, therefore, to secure a high degree of amplification without oscillation.

In the screen grid tube the grid which receives the signal impulses is called the control grid. The screen grid consists of three parts, a fine spiral mesh placed between the control grid and the plate, another fine spiral mesh surrounding the plate and a flat metal disc above the plate connecting the other two parts. Thus the screen grid almost entirely surrounds the plate. The filament, control grid and plate act in the same way as the three elements in a three-electrode tube. Referring to Fig. 146, we can see that a change in the potential of the plate cannot induce a change of potential on the control grid because the screen grid is in the way. The lines of electric force from the plate can act only to a very slight extent through the screen grid. The d.c. potential of the screen grid is made lower than that of the plate and the high capacity bypass condenser between screen grid and ground makes the screen grid practically at ground potential so far as alternating voltage is concerned. Thus for the alternating voltages on the plate the screen grid is a shield at ground potential.

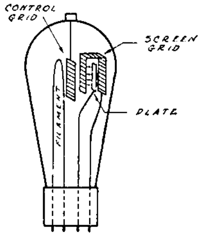


Fig 146.—Principle of the Screen Grid Tube

The plate resistance of a screen grid tube is extremely high, amounting in some tubes to more than a million ohms. This gives a high amplification factor since amplification factor equals plate resistance times mutual conductance. Screen grid tubes are made for both direct and alternating current receiving circuits. Those for alternating current have heater and cathode so that there are six terminals, five prongs at the base, two for the heater and one each for the plate, cathode and

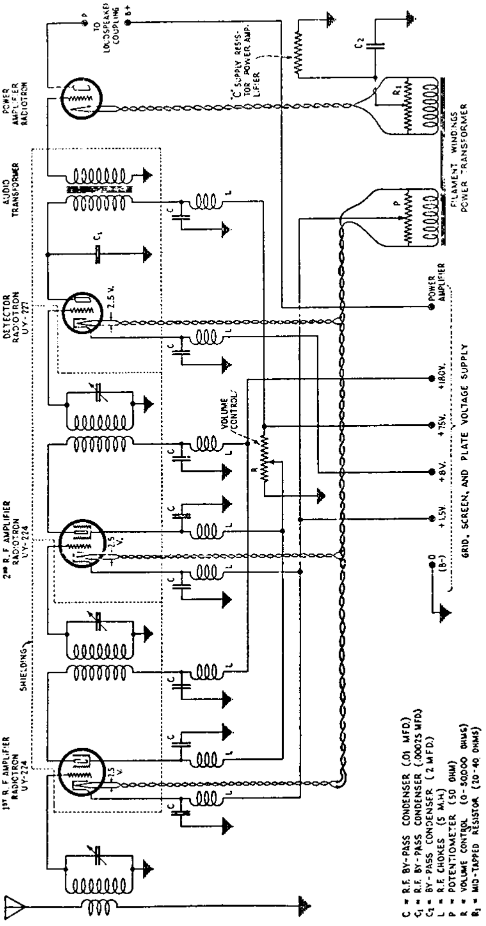


Fig. 147. — A Typical Radio Frequency Amplifier Circuit Using A.C. Screen Grid Tubes

screen grid, the terminal for the control grid being at the top as in direct current screen grid tubes.

127. **The Pentode Tube.** — In the screen grid tube some of the electrons that go through the grid to the plate strike the

plate so hard that they knock off other electrons. This is called secondary emission. There is secondary emission also in three electrode tubes but it does not matter so much there as in the screen grid tube because extremely high amplification is not attempted with the three electrode tube. The electrons that are knocked off the plate are in the way. They hinder the electrons that are coming through in the regular way from filament to plate and if they bounce far enough away from the plate they strike the screen grid and cause trouble. If we try to increase the amplification of the screen grid tube beyond a certain limit the mischievous effects of the electrons knocked off from the plate become very great. In other words secondary emission limits the amplification of the screen grid tube.

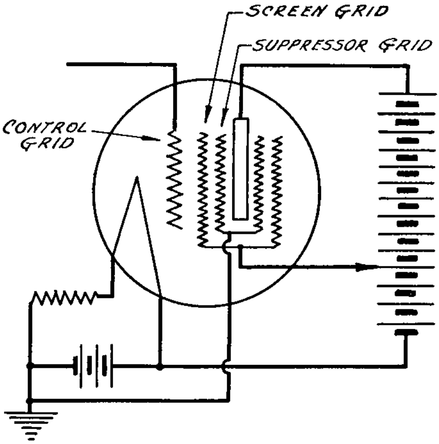


Fig. 148. — Principle of the Pentode Tube

Here is where the pentode tube comes in. In this tube we have a third grid, called a suppressor grid, placed between the screen grid and the plate. The suppressor grid is connected directly to ground so that it is at ground potential. Now when an electron gets knocked off from the plate and starts toward the screen grid it finds the third grid in the way. The electron is not attracted by the third grid because it is at ground potential but it is attracted by the plate. The result is that this erratic electron does not get very far away from the plate but rushes back to it and has no chance to interfere with the action of the screen grid. Thus the control of the electron stream is very much greater in the pentode than in the screen grid tube. By the successive steps of a control grid upon which signal impulses can act, a screen grid to prevent feed-back action through plate grid capacity and a third grid to prevent electrons knocked off the plate from disturbing the regular action of the tube, almost perfect control of the electron stream with very high amplification has been attained.

128. The Variable-μ Tube. — With three electrode or screen grid tubes there is some distortion when signals are being received from a near-by transmitting station so that the signal voltage impressed on the antenna is high. This distortion is due to the fact that a strong signal voltage, by increasing the negative grid potential, causes the tube to operate on the curved portion of its characteristic curve. This is particularly true if the tube has a high amplification factor as in the case

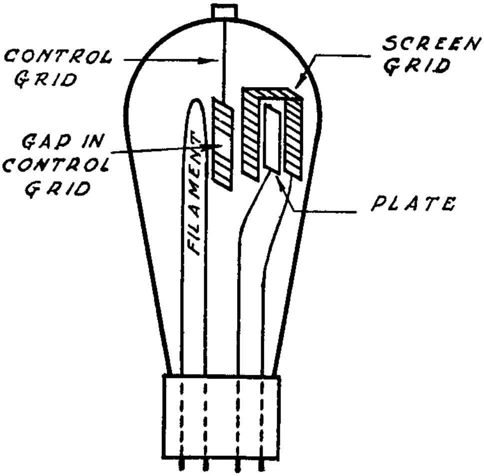


Fig. 149. — Principle of the Variable μ Tube

of the screen grid tube. The variable-μ tube is so designed that on strong signals the tube has a low amplification factor while on weaker signals its amplification factor is high. In this way the distortion mentioned above is greatly reduced.

There are several types of variable-μ tubes but one that will serve very well to illustrate the principle is shown in Fig. 149. There is a gap in the control grid. When ordinary signals are being received, electrons go through the mesh of the grid and also through the gap and the gap has practically no effect. When intense signals are being received and the grid bias is thrown strongly negative the mesh of the grid practically blocks the electron flow but electrons can still flow through the gap. The variations in grid potential now act on the electron stream only at the edges of the gap. This greatly reduces the effect of grid potential on plate current, in other words it greatly reduces the amplification factor. Thus the amplification factor or μ of the tube is made low for strong signals.

129. **The Heterodyne Principle.** — Oscillations of constant amplitude (continuous wave) acting on the grid cause the plate current to change to higher average value and to hold at this value as long as the oscillations continue without interruption. We are assuming now that the tube is operating at the lower bend of the characteristic curve (see Section 95). Continuous wave signals of radio frequency cannot be heard in the telephone receiver except that there is a click at the beginning and at the end of each train of waves. By combining with the continuous wave signals another train of waves of slightly different frequency, beats are produced. The beats may be of such a frequency that they will produce sounds in the telephone receiver.

To make this clear suppose we have two tuning forks which are slightly out of tune. Suppose one makes 64 vibrations per second and the other 60. When both are sounded together there is a rising and falling of the sound which we call beats. When the two trains of sound waves are in step, that is in the same phase they reinforce each other and the sound is louder. When they are out of step or of opposite phase they tend to neutralize each other and the sound is fainter. In the example given, the two trains of waves will be in step four times each second and out of step four times each second. There will be four beats per second. The frequency of the beats is equal to the difference of the frequencies of the two trains of waves (Fig. 150).

We shall take a still simpler illustration. Suppose we have two picket fences as in Fig. 151. In one the pickets are just a little wider than in the other and the spaces between are also wider. Each picket corresponds to the crest of a wave and each space between pickets to the trough of a wave. In the upper part of the figure we see one set of pickets and in the lower part of the figure the other set. In the center of the figure where the two fences are seen together we can see the effect that corresponds to beats. In one place the pickets of one fence are lined up with the pickets of the other. In another place the pickets of one are lined up with the spaces of the

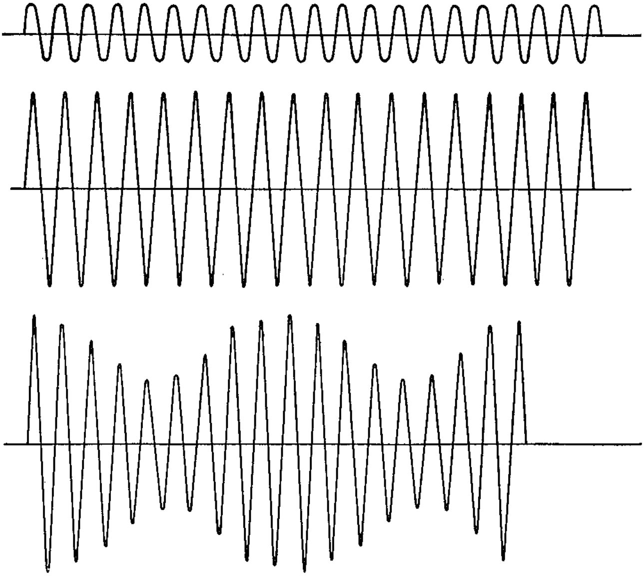
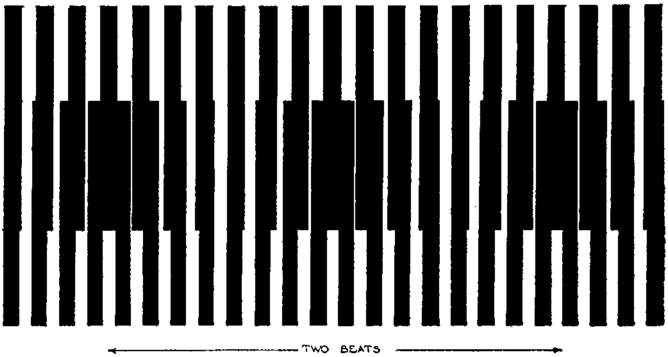


Fig. 150. — Beats Produced by Two Trains of Waves of Slightly Different Frequency

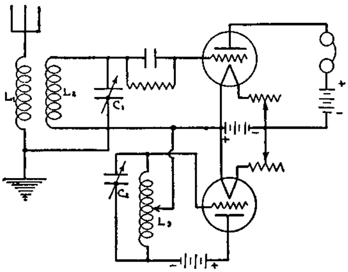
other. These two parts of the figure together correspond to one beat.

The same principle holds true of radio waves. If two trains of waves of different frequency act on the receiver a beat note is produced, the frequency of the beats being equal to the difference between the frequencies of the two trains of waves.



TWO PICKET FENCES, THE PICKETS IN ONE SLIGHTLY WIDER THAN IN THE OTHER ILLUSTRATING BEATS

Fig. 151



L_2 IS AN ORDINARY RECEIVING COIL OF ABOUT 100 MICROHENRIES. L_3 MAY BE 100 MICROHENRIES TAPPED AT CENTER. G_1 AND G_2 EACH 500 MMF.

Fig. 152.—Heterodyne Reception

In the heterodyne method of reception an oscillator is used with a tuning unit so that the frequency of its oscillations can be controlled by the operator. Such a circuit is shown in Fig. 152 together with the values required so that the reader can readily construct such a circuit. When continuous wave signals are coming in and the oscillator is tuned so that signals are heard in the receiver, then the difference between the frequency of the oscillator and that of the incoming signals is a number within the range of audio frequency. The coil L_3 of the oscillator is coupled fairly closely to L_2 of the receiver. In tuning, the tuner and oscillator condensers must be manipulated together, which is a rather difficult operation. The oscillator condenser should be shielded or placed in the set so that it will be some distance from the operator's body. When once adjusted the frequency of the beat note is not changed by small changes in capacity such as might be caused by a swinging antenna. This receiver is suitable only for continuous wave telegraph signals.

130. The Autodyne Method. — Instead of using a separate oscillator we may produce local oscillations in the receiving circuit itself. We then have an autodyne circuit. The autodyne circuit is simply a regenerative circuit using a direct feed-back by means of a condenser or a tickler coil. Such a circuit is shown in Fig. 128. The variable condenser must be adjusted so as to keep the tube near the oscillating point while tuning for the signals.

131. The Superheterodyne Circuit. — In the heterodyne circuit the beats are of audio frequency. The superheterodyne is a circuit in which the beats, while of lower frequency than the received signals are still above audio frequency.

Suppose we are receiving signals having a frequency of 1030 kilocycles per second. If we have an oscillator operating at a frequency of 1000 and these oscillations are combined with those of the incoming signals we get a beat note of 30 kilocycles or 30,000 cycles per second. The impulses from the oscillator and the received signals are both impressed on the first detector tube. In other words the grid circuit of this tube is coupled to the output of the oscillator and to the antenna circuit. As the two sets of oscillations, those from the oscillator and those from the antenna, act together on the grid an oscillation whose frequency is the difference of the two is produced. This is on the principle of beats explained in Section 129. The frequency of the oscillations thus produced is called an intermediate frequency because it is intermediate between the signal and audio frequency. If the signals received by the antenna are modulated, the modulation is automatically transferred to the intermediate frequency oscillations.

The first detector is in reality a mixer tube in which the two sets of oscillations combine to produce the beat note frequency. The output of the first detector flows through the primary of the first intermediate transformer and induces an oscillating e.m.f. of the same frequency in the secondary. These oscillations are amplified usually through two or three stages and then acted upon by the second detector tube which rectifies and reduces the signals to audio frequency as a detector tube does in any radio circuit.

A superheterodyne circuit includes four essential parts: the oscillator, the first detector, the intermediate frequency amplifier and the second detector. Audio frequency amplification is usually added but is not considered an essential part of the circuit because the circuit would operate if a telephone receiver were connected directly in the plate circuit of the second detector. The received signals may be amplified before being combined with the impulses from the oscillator. In this case there is a signal frequency amplifier ahead of the first detector. The general scheme of such a circuit is shown in Fig. 153.

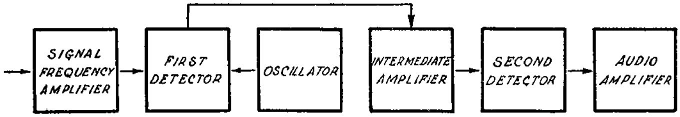


Fig. 153. — General Scheme of the Superheterodyne Circuit

Reducing the signals to an intermediate frequency greatly improves the selectivity of a receiver. This can be shown as follows: Suppose signals are being received from two stations whose carrier waves have frequencies of 1000 and 1010 kilocycles. The difference is 10 kilocycles which is only one per cent of the frequency of one of the carrier waves. Suppose now we are receiving the same signals with a superheterodyne whose oscillator has a frequency of 900 k.c. The beat note frequencies produced will be 100 and 110 k.c. respectively. The difference between these intermediate frequencies is 10 k.c. which is 10 per cent of the lower frequency. We have now a ten per cent separation instead of one per cent. Reducing to an intermediate frequency, therefore, makes it easier to separate signals of stations whose frequencies are only 10 kilocycles apart. In order to have true " ten kilocycle separation " it is also necessary to have a rapid cutoff at 5 kilocycles on either side of the carrier frequency. This will be explained more fully in Section 133.

For any oscillator frequency it is possible to get the same beat notes for two different signal frequencies. For example: If the oscillator frequency is 1000 k.c., signal frequencies of either 1030 k.c. or 970 k.c. will produce a beat note of 30 k.c. In other words the signal frequency may be either 30 kilocycles above or 30 kilocycles below the oscillator frequency and a 30 k.c. beat frequency will be produced. Under these conditions, if the intermediate frequency stages are tuned for resonance at 30 k.c. it would be possible to hear two stations, one at 970 k.c. and the other at 1030 k.c. This is called " image frequency " interference. It is important to choose an intermediate frequency that will eliminate this kind of interference. For this purpose a high intermediate frequency is best. This is true because the difference between the two frequencies that might interfere is twice the intermediate or beat frequency. This is clear from the above example since the difference between the interfering frequencies is 60 k.c. and the beat frequency is 30 k.c. It is possible to choose the intermediate frequency so high that no two stations within the broadcast band can produce image interference. On the other hand if the intermediate frequency is too high its harmonics may produce interfering beats with the input signals. It is found practically that an intermediate frequency of 175 k.c. is a satisfactory compromise between the two requirements.

A superheterodyne circuit in which screen grid tubes are used is shown in Fig. 154. For the sake of simplifying the diagram the power unit is omitted.

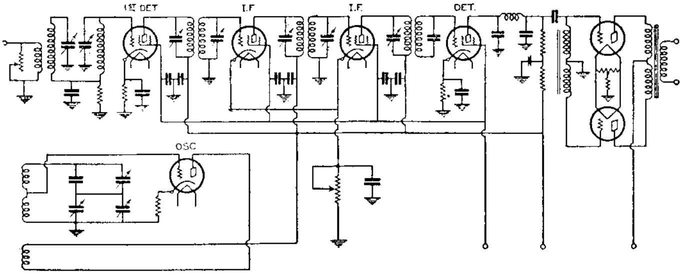


Fig. 154.—A Superheterodyne Circuit Using Screen Grid Tubes

132. The Absorption Circuit or Filter.—A filter for cutting out interfering signals is simply a resonating circuit consisting of a coil and condenser. Fig. 155 shows such a filter connected in series with a receiving set. For frequencies of 500 to 1500 kilocycles the coil should consist of 80 turns on a 1½ inch tube and the condenser should be of 0.00035 microfarad capacity. When the filter is tuned to resonance for a certain frequency, signals of that frequency cannot enter the receiving set. This is an application of the principle of parallel resonance. The resonating circuit has practically infinite impedance for the frequency to which it is tuned. If the filter is shunted across the antenna and ground connections (Fig. 156), the signals to which the filter is tuned will go through the receiver while other signals will be shunted across through the filter. The filter tunes more sharply if it is inductively coupled to the antenna circuit. This may be done by winding a 5-turn coil over the coil of the filter and connecting the 5-turn coil in the antenna circuit.

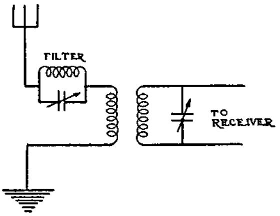


Fig. 155.—A Series Filter

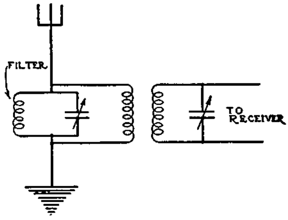


Fig. 156.—A Shunt Filter

A filter known as a low pass filter is shown in Fig. 157. The reactance of a coil increases with frequency as we have seen in Section 57. The coils, therefore, allow low frequency oscillations to pass but above a certain frequency the reactance is so great that practically no oscillations pass. The condensers serve to bypass the higher frequencies. The frequency at the upper limit is called the cut-off frequency. If there were no resistance the cut-off at this frequency would be abrupt.

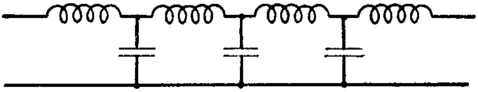


Fig. 157. — A Low Pass Filter

Practically there is a rapid diminution of current above the cut-off frequency. A high pass filter is shown in Fig. 158. The reactance of a condenser is less for high frequency than for low (Section 67). The condensers, therefore, pass high frequency currents and cut off those below a certain frequency while the coils serve to bypass the low frequency currents.

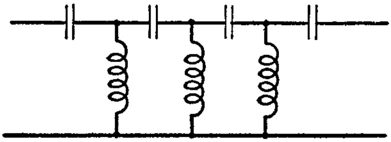


Fig. 158. — A High Pass Filter

133. Sidebands. — When a carrier wave is modulated (See Section 94) a composite wave is produced. The composite wave can be analyzed mathematically into a wave form having varying frequencies, the lowest frequency of the composite wave being the carrier frequency minus the highest frequency of modulation and the highest being the carrier frequency plus the highest frequency of modulation. For example, suppose a station is broadcasting on a frequency of 1000 kilocycles and signals ranging up to 5000 cycles or 5 kilocycles are acting on the microphone. Then, according to the sideband theory, the frequency of the modulated wave ranges from

995 k.c. to 1005 k.c. The modulating frequencies which are added to or subtracted from the carrier frequency are known as sidebands.

There is a difference of opinion among physicists and radio engineers as to whether or not sidebands are a reality. The opposing theory is that the modulating wave causes the carrier wave to vary in amplitude but not in frequency. Whichever theory is correct as to the waves that actually travel through space, it is true that for practical purposes we may consider that sidebands actually exist. Allowance must be made for a band of frequencies for each broadcast signal. For the usual broadcast signal a band 10 k.c. in width is assigned thus allowing for modulating frequencies up to 5 kilocycles.

134. Band Pass Filters. — The ideal receiving circuit for the usual broacast signals would be one that would give equal response for all frequencies within the 10 kilocycle range and cut off sharply at each edge of the band. Thus an ideal receiver for 1000 k.c. would give full response for 1005 k.c. but no response at all for 1006 k.c. The response curve for this ideal receiver is shown by the dotted line in Fig. 159. Curve A in the same figure shows the response as it actually is in a receiver with one stage of radio frequency amplification without some form of band pass filter or some device in the circuit which performs the same function. If we call the response peak 100 per cent, we have a considerable response at 10 k.c. on either side of the peak where there should be no response at all (in this case 60 per cent). We have also in this particular case 80 per cent response at 5 k.c. on either side of the peak. If three stages of amplification are used the curve is sharper as shown by curve B in the same figure. This means sharper tuning but now we have only 60 per cent response at the 5 k.c. limit where there should be full response. This is called cutting the sidebands. It means distortion of the signals. The higher frequencies are cut off so that sibilant sounds like the letter S do not come out clearly.

It is practically impossible to secure perfect response within the 10 kilocycle band and sharp cut off at each edge but this condition can be approximated by a band pass filter. We shall give here simply the fundamental principle of such a filter. Suppose we have two tuning units each consisting of a coil and condenser and the two units tuned to the same frequency.

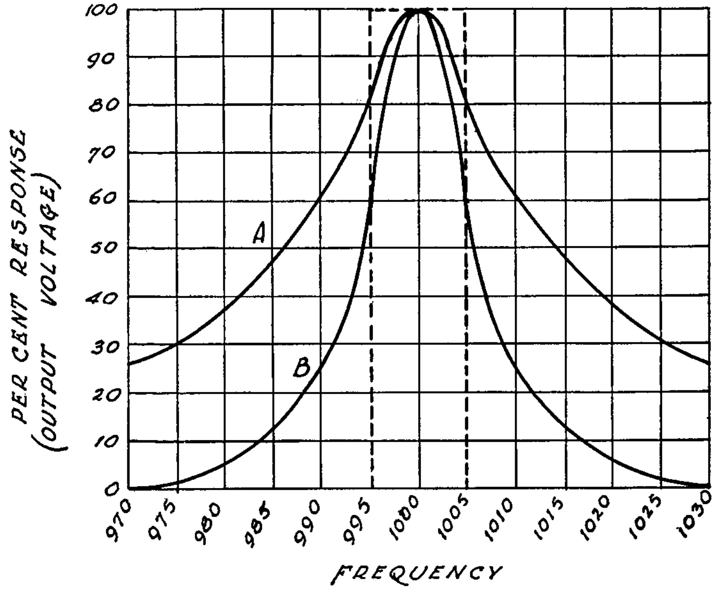


Fig. 159. — Response Curve

Now if we couple these units, that is place the coils near together so that there is mutual induction between them (Fig. 160) and then tune the two units together they will tune

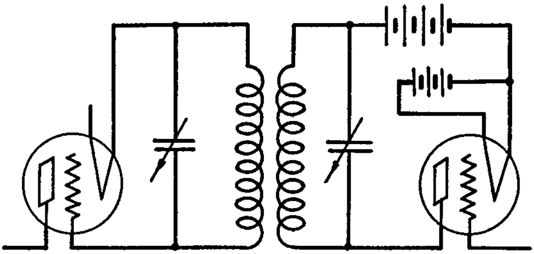


Fig. 160. — A Band Pass Filter Circuit

to two different frequencies. The response curve will have two peaks as in Fig. 161. Let us suppose that the two units are tuned separately to 1000 k.c. and then coupled so that the mutual inductance between the coils is 1 per cent of the inductance of each coil alone. This would be the case for instance if each coil had an inductance of 250 microhenries and the mutual inductance was 2.5 microhenries. The two peaks would then be 10 kilocycles apart. The rule is that the interval between the two peaks bears the same ratio to the resonant frequency that the mutual inductance bears to the inductance of one of the coils, assuming the two coils to have equal inductance. Thus we see that this arrangement which is called a band pass filter gives an approximation to the ideal response curve.

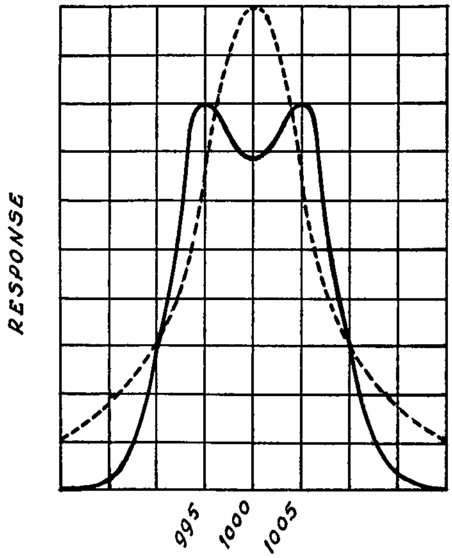


Fig. 161. — Response Curve with Two Peaks

An interesting application of the sideband theory is the suppression of the carrier wave. The schematic diagram of an oscillator circuit used for this purpose is given in Fig. 162. Each of the two tubes acts as an oscillator and it is clear, if one traces the circuit, that the sidebands produced by modulation and acting on the grids of the two tubes produce effects which add up in the plate circuit and therefore add up in the effects on the antenna current. The carrier frequency currents in the plate circuit, on the other hand, neutralize each other so far as the effect on the antenna current is concerned. Therefore the carrier wave is suppressed so that no wave is transmitted except when modulation occurs. It is necessary to reproduce the carrier wave by means of an oscillator at the receiving end. This system is used in commercial transmission. The advantages are that fading is reduced and that less power is required for transmission.

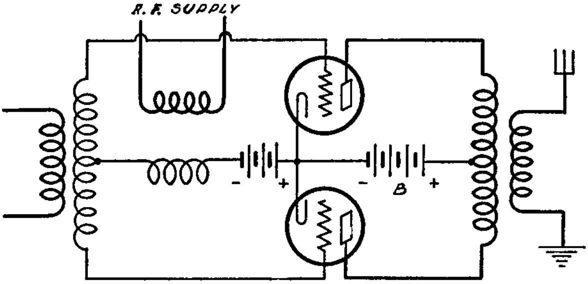


Fig. 162. — Circuit for Suppressing Carrier Wave

135. Shielding. — In a radio receiver the electromagnetic field of a coil or the electrostatic field of a condenser may react on other parts of the receiver with the result of considerable loss of energy. Shielding is a means of reducing this action.

If we have a coil with an alternating current flowing through it, the magnetic field is continually changing (coil A Fig. 163). If a second coil is placed in the magnetic field of the first coil (coil C Fig. 163), an e.m.f. is induced in the second coil. If now we place a third coil having a closed circuit between the first two coils as at B, an alternating current is induced in the third coil. The magnetic field of this induced current opposes the magnetic field of coil A and to some extent prevents it from getting through and acting on coil C. If we use a sheet of metal in place of coil B, the result is the same (Fig. 164). Currents are induced in the metal sheet which react by means of their magnetic fields and hinder the field of coil A from getting through. The metal sheet acts as a shield to coil C.

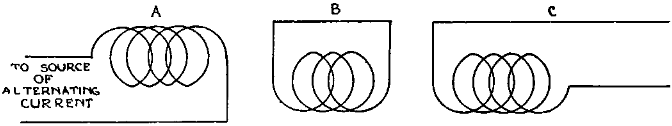


Fig. 163

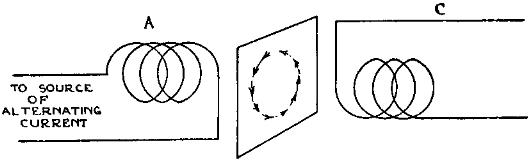


Fig. 164

The shielding effect is due to the eddy currents. This is the important point. Perfect shielding would mean perfect freedom for the flow of the eddy currents. If the shield could be made of metal having zero resistance and made completely to enclose coil A, the shielding would be perfect. Since the sheet of metal has some resistance it is not a perfect shield. There is some magnetic effect outside the shield on account of the fact that the resistance of the shield hinders the eddy currents so that they cannot perfectly counteract the magnetic action of the enclosed coil. We can, however, increase the shielding effect by reducing the resistance of the shield. Up to a certain limit the resistance can be reduced by increasing the thickness of the metal. It must be remembered, however, that for radio frequencies where shielding is especially important, the current is limited to a very thin surface layer (Section 91), so that nothing is gained by increasing the thickness beyond this limit.

Another reason why perfect shielding is not possible is that the coil cannot be completely enclosed, there must be openings for the connecting wires. The electromagnetic field can act through a very small opening. If the shield is made up in sections and soldered, an imperfectly soldered joint reduces the shielding because of its resistance to the flow of the eddy currents.

Some energy is lost in a shield. Since the shielding effect is due to eddy currents and the shield has some resistance, energy must be used up. An electric current flowing through a resistance uses energy. The energy consumed in the shield is taken out of the energy of the current in the shielded coil. This effect is similar to that of increasing the resistance of the coil. The effective resistance of the coil is increased by shielding. The shield should not be connected to any part of the electric circuit, for if the shield becomes electrified the resistance is still further increased.

The higher the frequency the greater is the shielding effect. The higher the frequency of an alternating current the more rapidly the magnetic field changes. The more rapidly the field changes the stronger the eddy currents induced in the shield and therefore the greater is the shielding effect. The shielding effect approaches a limit, however, as the frequency becomes very high. Theoretically, for a shield of low resistance, non-magnetic metal, the shielding approaches 100 per cent as the frequency becomes infinitely high.

Notwithstanding the fact that all shielding is imperfect and that the resistance of a shielded coil is greater than that of the coil alone, shielding produces beneficial results. It prevents to a large extent the interaction of the magnetic fields in the coils of a receiver and so gives more faithful reproduction. It also increases selectivity.

136. Bypass Condensers.—The purpose of a bypass condenser in a receiving circuit is to form a short return path for certain currents and prevent them from interfering with the desired currents that are carrying the signals forward to the reproducer. A bypass condenser across the primary of the first audio transformer is important. This is to bypass any radio frequency currents that pass through the detector tube. Since this condenser is to bypass radio frequency and must not bypass any audio frequency currents, it must have very low capacity. A suitable value is 0.00025 microfarad. This condenser should be connected as shown in Fig. 165a. It is also desirable to connect a bypass condenser across the B battery in the radio frequency stages. This condenser is to bypass audio frequency currents and prevent them from going through the B battery. It must therefore have large capacity. One microfarad is suitable. Fig. 165b shows the correct connection for such a condenser. In alternating current sets the same rule applies to the plate supply from the power unit to the radio frequency stages. It is advisable to connect a one microfarad condenser across this part of the power unit.

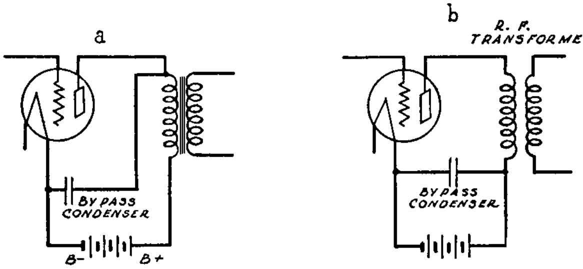


Fig. 165.—Use of Bypass Condensers

137. The Power Supply.—A power unit to supply plate and filament voltage for an alternating current receiving set consists of three essential parts, a transformer, a rectifier and a filter. The secondary windings of the transformer must furnish the maximum voltage needed. Low voltage windings supply current for the filaments. A rectifier is necessary because the plate voltage must be direct. An electron tube rectifier is used. The rectifying tube shown in Fig. 166 has two plates and rectifies both halves of a cycle. It is called a full-wave rectifier. Within the tube electrons flow from filament to plate. In the outside circuit they flow from plate to filament. Therefore with respect to the outside circuit the plate is negative and the filament positive. The direct voltage as it comes from the rectifying tube is fluctuating, going up to a maximum and dying down again twice for each cycle. A filter is needed to smooth out the unevenness in the voltage. The filter consists of choke coils and condensers as explained in Section 132. The condensers must be of large capacity, two microfarads or more, because they are to bypass audio frequency impulses. If the filter is imperfect the unevenness in the voltage causes a hum in the loud speaker. Resistors are connected across the output of the filter and the resistors are tapped for the different voltages needed.

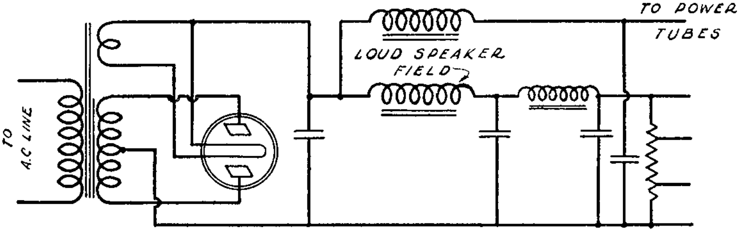


Fig. 166. — Power Supply Circuit
Windings to supply filament current for tubes of radio set are not shown.

138. Short Waves. — There is no definite answer to the question, "How long is a short wave?" The wave lengths used in ordinary broadcasting range from 200 to 550 meters. All waves below 200 meters are sometimes called short waves but it is only for waves of about 100 meters or less that the characteristics are appreciably different from those of waves of the broadcasting range.

The most striking peculiarity of short waves is that which is known as the "skip distance" effect. This effect depends on the action of the Kennelly-Heaviside layer, a layer of ionized air some distance above the earth's surface. Ionized air is air containing free electrons or electrically charged particles or both. Short waves are reflected from the ionized layer to the earth. The result is that the waves skip a certain distance and are received at a greater distance from their source. This effect is pictured in Fig. 167. The skip distance varies, depending on the frequency or the wave length, the time of day and to some extent on the season of the year. By means of a series of observations extending over a number of years engineers have collected data so that they know what frequency to employ for any season and any time of day or night to secure the skip distance desired. These data are arranged in charts which are used in commercial transmission particularly across the ocean.

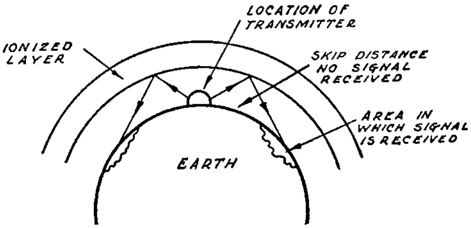


Fig. 167. — Skip Distance Effect

139. Short Wave Receiving Circuits. — There are two principal types of short wave receiving circuits, the superheterodyne and the regenerative. The superheterodyne is to be preferred for receiving telephone signals on account of its greater sensitivity. For receiving continuous wave code signals the circuit must be regenerative because continuous waves can be received only by producing a beat note. A circuit that will oscillate is therefore necessary. A superheterodyne receiver can be used for continuous waves if the second detector is made regenerative.

An ordinary broadcast receiver can be converted into a short wave receiver by means of a two-tube unit comprising an oscillator and first detector. The radio frequency stages of the receiver become the intermediate frequency amplifier. A plan for such a converter is given in Figs. 168 and 169. To

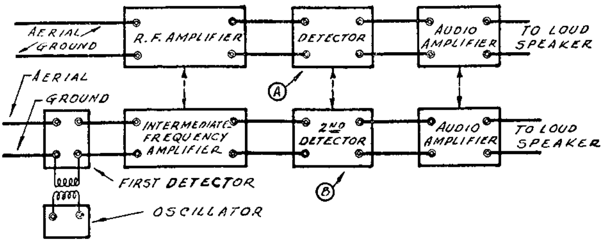


Fig. 168. — Plan of Short Wave Converter

build a complete superheterodyne short wave receiver it is necessary to add to this unit the intermediate frequency amplifier, second detector and audio frequency amplifier, the last three units being built as in a broadcast receiver. A plan for a regenerative short wave receiver is given in Fig. 170.

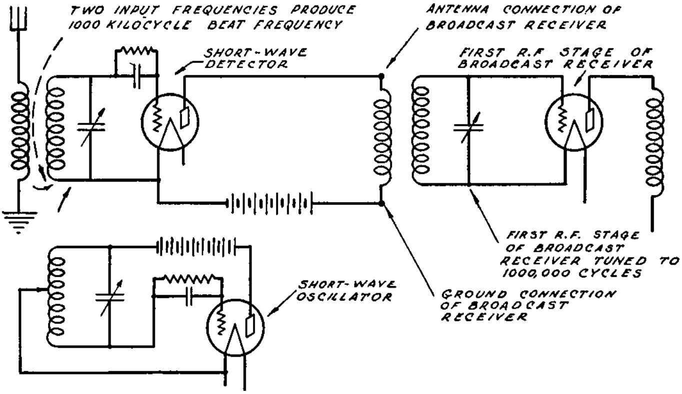


Fig. 169. — Circuit of Short Wave Converter

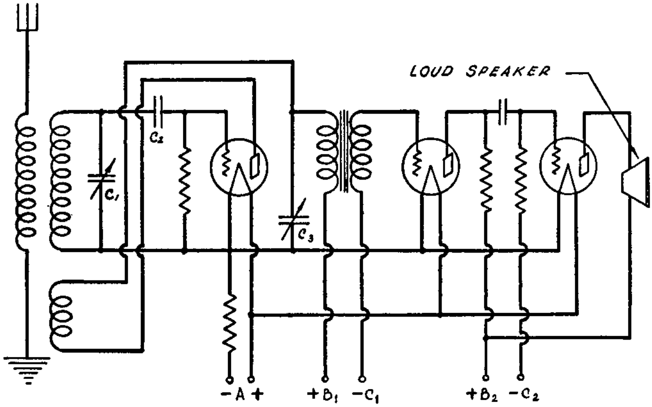


Fig. 170. — A Regenerative Short Wave Receiver

140. Ultra Short Waves. — Waves having a length of less than about 7 meters have some peculiar properties not characteristic of waves above 7 meters. In one respect ultra short waves act like light. The receiver must be in view of the transmitter. The waves cannot be received beyond the horizon. The distance can be increased by increasing the height of the transmitter. Ultra short waves readily penetrate mist, fog, smoke and dust.

With ultra short waves the wide band of frequencies needed for television can easily be secured. This can be shown as follows: If we consider the band of wave lengths from 200 to 600 meters which is a little wider than the broadcast band, we have for the frequency of the 200 meter waves 1,500,000 cycles and for the 600 meter waves 500,000 cycles, a difference of 1,000,000 cycles. The frequency of 5-meter waves is 60,000,000 cycles and of 4-meter waves 75,000,000 cycles. Thus between the 4- and 5-meter waves we have a range of frequencies 15 times as great as the entire range of frequencies in the broadcast band.

CHAPTER IX

OSCILLATORS AND TRANSMITTING CIRCUITS

141. What Makes a Tube Oscillate? — We saw in our study of regeneration (Sections 102 and 120) that if we have a coil in the plate circuit and another in the grid circuit and these coils are placed near to each other, the magnetic field of the plate current will act on the coil in the grid circuit. The plate current as it varies induces an electromotive force in the grid coil. Now there are two electromotive forces in the grid coil, one is received from the antenna circuit, the other from the plate circuit. If the coils have the right relation to each other these two e.m.f.'s will increase and decrease together. They will be in step or in phase with each other. When this is true the e.m.f.'s are added producing a greater e.m.f. There are greater oscillations on the grid. The grid voltage in each cycle swings farther than it would if only the antenna oscillations were acting. Changes in grid voltage cause changes in plate current. If the grid voltage oscillations are greater the plate current oscillations are greater. We get, therefore, an increased or amplified output in the plate circuit.

It is a building up process. A part of the energy of the plate circuit is fed back to the grid circuit and this results in a still greater increase of energy in the plate circuit. If the energy is fed back in sufficient amount and in the right phase relations the grid and plate circuit oscillations are sustained by the action of the tube itself. No antenna or other outside source of energy is needed. There must be a slight surge of plate current to start the oscillations, but when once started they are self-sustaining. The necessary surge is usually caused by a variation in the electron flow from the filament.

We may consider the steam engine as an illustration. A part of the energy of the steam in the cylinder is used in operating the slide valve and this valve in turn controls the admission of steam to the cylinder. In a certain sense we may compare the grid circuit oscillations with the action of the slide valve. The valve controls the energy of the steam in the cylinder as the grid oscillations control the energy of the plate current. The piston of the engine is coupled back to the valve mechanically so that part of the energy of the steam in the cylinder is used to operate the valve. The plate circuit is coupled back to the grid circuit electrically so that part of the energy of the plate current is used to sustain the oscillations on the grid. The engine must receive a supply of energy from the steam. The tube must receive a supply of energy from the plate battery.

Fig. 171 is a schematic diagram of a circuit for producing sustained oscillations. This oscillator circuit is made up of three circuits, the plate circuit, the grid circuit and the oscillation circuit which consists of the coil CA and the condenser. There must be a source of e.m.f. in the plate circuit and a source of filament current. For simplicity these are omitted from the diagram. When the plate is positive, electrons flow in the tube from filament to plate and in the external circuit from plate to filament as shown by the arrows leading from P to A, B and F. When the grid is positive it acts to increase the plate current and the electron flow, if any, in the grid circuit is from grid to filament by way of C and B as shown by

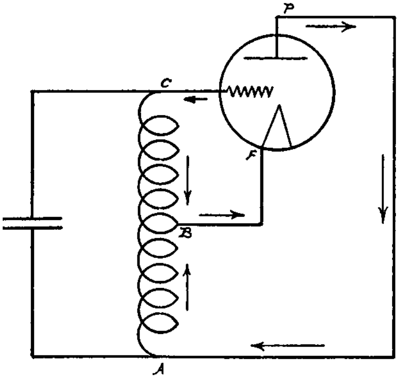


Fig. 171. — Principle of the Hartley Circuit.

the arrows. When the grid is negative it acts to reduce the plate current. Thus, while the plate current never reverses, it varies above and below an average value as explained in Section 95 and the plate current curve is similar to the curve for an alternating current. This can be seen by comparing the plate current curve in Fig. 115 with the alternating current curve in Fig. 74. When this varying plate current flows through a coil there is a varying magnetic field causing self-induction as in the case of an alternating current. For the purpose of this discussion, therefore, we shall consider the plate current alternating.

Now we are prepared to take up the phase relations of the electromotive forces and currents in the three circuits that make up the oscillator. The curves for these electromotive forces and currents are given in Fig. 172. Suppose we have an alternating e.m.f. or voltage applied between grid and filament represented by curve 1. This produces an alternating current in the plate circuit represented by curve 2. As these curves show, the plate current and grid voltage are in the same phase within the tube. (See Section 58). The alternating plate current flows through coil AB and acts by self-induction to produce an e.m.f. in this coil. The e.m.f. of self-induction lags 90 degrees behind the current as shown in curve 3 of Fig. 172 and explained in Section 58. The e.m.f. of self-induction in coil AB causes a current to flow in the oscillation circuit consisting of the entire coil ABC and the condenser. Since this circuit is at resonance for the frequency of the plate current, its capacity and inductive reactances are equal and opposite so that there is no lag or lead and the current in the oscillation circuit is in phase with the e.m.f. which produces it. The oscillation current is therefore in phase with the e.m.f. of self-induction in coil AB and 90 degrees out of phase with the plate current. Curve 4 represents this oscillation current. Of course both these currents are flowing in AB and the actual current in this part of the coil is the resultant of the two. But the oscillation current alone flows through CB which is in the grid circuit. Here again self-induction occurs and the e.m.f. thus produced lags 90 degrees behind the oscillation current as shown in curve 5. Thus we see that the e.m.f. induced in the grid circuit is 180 degrees out of phase with the plate current so far as coil CB is concerned. Thus at the instant when the electrons in the plate circuit are flowing in the direction AB the induced e.m.f. in the grid curcuit acts to urge electrons to flow in the direction CB in the grid circuit. This means that the induced e.m.f. on the grid is positive as the plate current is increasing. In other words the e.m.f. on the grid produced by the inductive action of the circuit is in the right phase to aid the plate current. Thus within the tube the induced grid voltage is in phase with the plate current. While curve 5

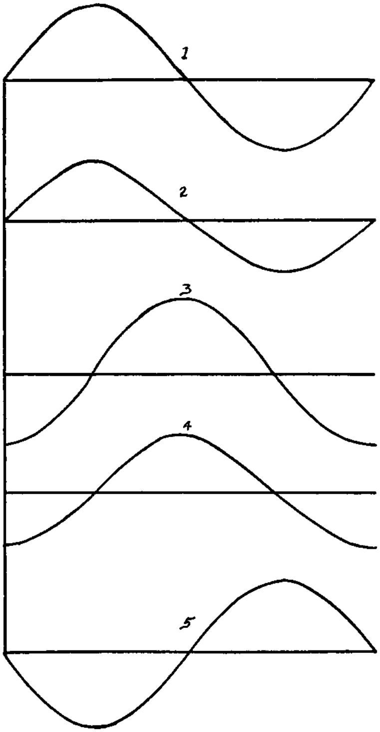


Fig. 172. — Phase Relations in the Hartley Circuit

compared with curve 2 shows the relative phase of induced grid voltage and plate current as applied to the coil of the oscillation circuit, curve 1 compared with curve 2 shows the relative phase of induced grid voltage and plate current as applied to the flow of electrons in the tube. The plate current by its inductive action produces an e.m.f. on the grid which is in the right phase to aid the plate current. Thus the oscillations become self sustaining.

142. Typical Transmitting Circuits. — There are two fundamental transmitting circuits. The various circuits that are used for transmitting signals are modifications of these two.

The first type of transmitting circuit is that in which the energy is fed back from the plate circuit to the grid circuit by means of coils; that is, by inductive coupling. The Hartley circuit is of this type. This circuit was invented by Mr. R. V. L. Hartly of the Bell Telephone Laboratories. Fig. 171 is a diagram illustrating the principle of the Hartley circuit. AB is the part of the coil in the plate circuit and BC is the part in the grid circuit. The point B can be changed by means of a clip at B thus changing the ratio of the turns in the two parts of the coil. A condenser is connected between two points on the coil taken somewhere between the points A and C. In this typical diagram, points A and C are shown connected to the condenser.

The second type of transmitting circuit is that in which the energy is fed back by means of condensers (capacitive coupling). The Colpitts circuit, invented by Mr. E. H. Colpitts of the Western Electric Company, is the typical capacitive coupled circuit. Fig. 173 is a diagram illustrating the principle of this circuit. The energy is fed back from plate circuit to grid circuit through condensers C_1 and C_2. The two con-

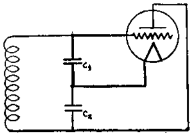


Fig. 173. — Principle of the Colpitts Circuit

densers are connected in series between plate and grid and the filament is connected between the two condensers.

In the Meissner circuit (Fig. 174), named after Dr. A. Meissner of the Telefunken Company of Berlin, the antenna circuit is magnetically coupled to both the plate and grid circuits. The feed-back is through the magnetic coupling of the plate and grid coils.

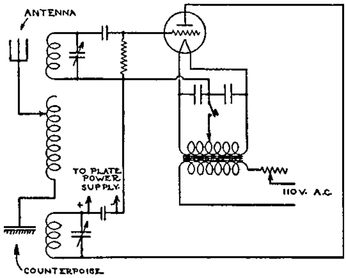


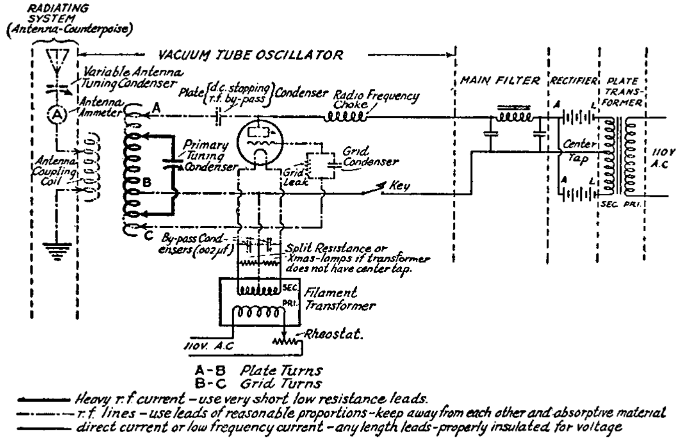
Fig. 174.—The Meissner Circuit

The power for the plate circuit may be obtained from the a.c. 110 volt lighting circuit by means of a transformer, rectifier and filter. The transformer must deliver at its secondary terminals the correct voltage for the tube used. The rectifier changes the alternating current to direct current (Sections 76, 77 and 78). The filter, consisting of choke coil and condensers, smooths out the pulsations of the direct current, making it more nearly constant.

Fig. 175 shows a typical transmitting circuit of the Hartley type including the plate power supply and filament transformer. The plate condenser is necessary to prevent the direct current of the plate power supply from flowing through the coils of the tuning circuit. Radio frequency currents, of course, act through this condenser.

There are two methods of supplying plate current to the tube. In Fig. 176 the parallel or shunt supply method is shown. This consists in connecting the positive power lead to the plate terminal by way of a choke coil and the negative power lead to the filament. The series plate supply shown in

Fig. 177 consists in connecting the power leads in the line leading from the plate to the tuning unit, a condenser being connected between the two terminals of the power leads. There must be a choke coil in each power lead and the positive lead must be connected to the plate side of the condenser.



(*From Radio Amateur's Handbook*)

Fig. 175. — A Typical Transmitting Circuit (Magnetically Coupled Hartley)

143. Oscillators for Experimental Work. — A circuit for a five-watt oscillator is shown in Fig. 178. The oscillator is of the Hartley type. The constants given are for a range of 200 to 550 meters. If a 0.0005 µf. condenser is used in place of the 0.001 µf. the oscillator will have a range of 100 to 250 meters. The arrow points at A, B and C represent clips with

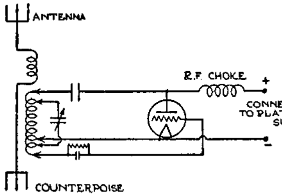


Fig. 176
Shunt Method

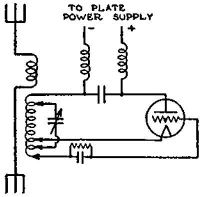


Fig. 177
Series Method

Plate Power Supply

which connections can be made to different turns of the coil. The fixed condenser in the plate circuit must have good mica insulation able to stand twice the plate voltage. If alternating current is used for the plate the arrangement should be as in Fig. 179.

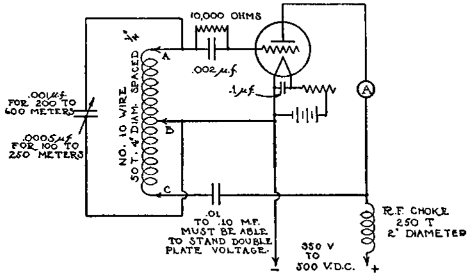


Fig. 178. — A Five-watt Oscillator

The oscillator may be calibrated as follows: Tune a receiving set to the signals from a broadcasting station that is known to adhere to a constant wave length. Now tune the oscillator until its hum is heard in the receiver. If signals from the broadcasting station and from the oscillator are being received at the same time a beat note will probably be heard. The oscillator should be adjusted until the beat note disappears or becomes as faint as possible. This setting of the dial places the

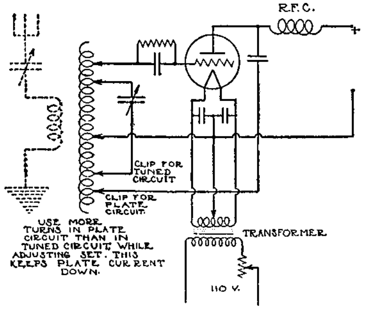


Fig. 179. — A Five-watt Oscillator to Operate on Alternating Current. The Constants of This Circuit Are the Same as in Fig. 169

oscillator at the same wave length as that of the broadcasting station. By repeating this test with other broadcasting stations of different wave lengths a number of points on the dial can be listed with their wave lengths or frequencies. Then the wave lengths for other points between these can be determined with a fair degree of accuracy by the method known as interpolation. To take a very simple example, suppose we find that a dial setting of 75 gives a wave length of 300 meters and a setting of 65 gives a wave length of 280 meters. Then we might assume that a setting of 70 would give a wave length of 290 meters. This would be true only if we are using a condenser in which the angle is proportional to the wave length. Such a condenser is called a " straight line wave length " condenser because if we plot a graph letting the abscissas represent dial readings and the ordinates wave lengths, the graph is a straight line. The example given is to illustrate what is meant by " interpolation." In actual practice the results would not be so simple but the method would be the same. Having found by test the wave lengths for two dial readings it would be assumed that the mean of the two dial readings corresponded to a wave length which was the mean of the two observed wave lengths. The nearer together the two observed readings are, the more accurate will be the computed reading. If a condenser is used for which the dial reading is proportional to frequency, then frequencies must be used instead of wave lengths in interpolating values.

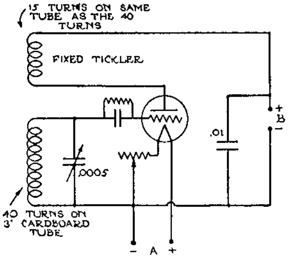


Fig. 180. — An Oscillator for a Tube of Low Amperage

An oscillator or driver can be made using a dry cell tube (Fig. 180). This little driver is very convenient for many tests, particularly for checking receiving circuits. After the oscillator itself is calibrated it can be used in turn to calibrate the dial settings of a receiving set. Other uses for an oscillator will be given in the chapter on " Radio Measurements."

144. Transmitting Circuits. General Discussion. — A transmitting circuit for continuous wave telegraphy is an oscillator having a key for starting and stopping the antenna oscillations. It is best to use one of the standard simple circuits described above. In either of these circuits an inductance and a capacity determine the wave length. The tuning circuit consists of the tuning condenser and the turns of the coil connected across the tuning condenser. In the Hartley circuit the coil of the tuning circuit is partly in the plate circuit and partly in the grid circuit. If the plate part of the coil alone is connected across the tuning condenser we have a tuned plate circuit. If the grid part of the coil alone is connected across the condenser we have a tuned grid circuit.

The Meissner circuit is flexible, easily adjusted to transfer maximum power to the antenna, but it is not suited to wave lengths below one hundred meters.

Whatever circuit is used the power must be transferred to the antenna circuit by inductive not conductive coupling. This means that the coil of the tuned circuit must not be directly connected to the antenna circuit but must be placed so that it will act magnetically on the coil of the antenna circuit. Conductive coupling is prohibited by government regulations.

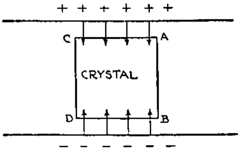


Fig. 181

145. Crystal Control. — The frequency of an oscillator can be kept constant by means of an oscillating crystal. Let ABCD (Fig. 181) represent a quartz crystal placed between two metal plates. If the plates are charged plus and minus as shown, the crystal acts as if it were being compressed by a very great pressure. It becomes shorter in the direction AB and longer in the direction AC. If the electric charge drops to zero, the crystal swings back and beyond the zero position, becoming shorter in the direction AC and longer in the direction AB. It then swings back and forth oscillating at radio frequency. If the polarity is reversed the strain appears again in the opposite direction from the first. If the polarity alternates at a frequency nearly equal to the natural frequency of the crystal, the crystal will continue to oscillate. The natural frequency of the crystal depends on its thickness. The thinner the crystal the shorter is its natural wave length and the higher its frequency.

A crystal can be tested by using the circuit of Fig. 182 using a fairly high plate voltage and a "C" battery of -1.5 to -10 volts. When the tuning condenser is brought near to the frequency of the crystal the milliammeter (hot wire or thermocouple) at A indicates a current. At the frequency of the crystal there is a sudden drop in this current, as shown in Fig. 183, on account of the energy absorbed by the crystal. From the values of C and L the natural frequency of the crystal can be determined. In fact C and L might be the condenser and coil of a calibrated wave meter. In a transmitter the circuit is tuned to a wave length a little less than the natural wave length of the crystal. Another circuit for testing a crystal is shown in

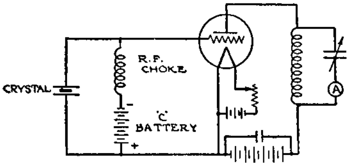


Fig. 182. — A Circuit for Testing an Oscillating Crystal

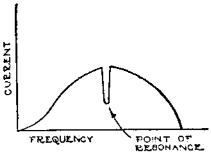


Fig. 183

Fig. 184. The driver described in Section 139 can be coupled to the coil for the test.

A crystal of the correct thickness for the wave length desired can be used to control an oscillator in a transmitting circuit. Slight changes of frequency in the circuit, such, for example, as might be caused by the swaying of an antenna, are prevented from affecting the frequency of the transmitter by the action of the crystal. It tends to hold the circuit at a constant wave length.

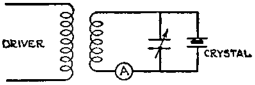
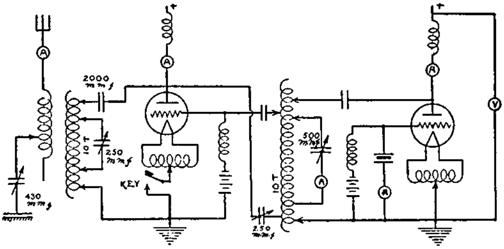


Fig. 184.—Another Circuit for Testing an Oscillating Crystal

It is best to use an amplifying tube between the crystal controlled oscillating tube and the antenna circuit for the reason that the crystal can control only a limited amount of energy. The energy of the oscillating tube must be within the limit fixed by the crystal and the necessary energy for the antenna secured by amplification. A circuit having an amplifying tube between the oscillator and the antenna is called a master oscillator circuit. Such a circuit, crystal controlled, is shown in Fig. 185.



CONSTANTS ARE FOR 80 METERS.
FILAMENT CURRENT AND PLATE
POWER SUPPLY ARE NOT SHOWN

Fig. 185.—A Crystal Controlled Circuit

146. Short Wave Transmitters.—The wave length of a resonant circuit is reduced by reducing inductance or capacity or both. In a short wave transmitter both inductance and capacity are made low. This necessitates extreme care in construction to reduce capacity and inductance in the wiring of the circuit. Either of the fundamental circuits can be used for short wave work. It is necessary only to reduce the inductance and capacity sufficiently to secure the desired wave length.

A good circuit for short wave work is shown in Figs. 186 and 187. The inductance is a single turn tapped in the middle. The two parts are connected by a blocking condenser of .003 microfarad capacity. The condenser must be able to stand the full plate voltage. The variable condensers shown in the diagram are two parts of one variable condenser, each of the parts having only one stator plate. This circuit is given as an example of a circuit for extremely short waves, working at 3 to 5 meters. By increasing the inductance and the capacity the same circuit can be used for longer waves. It is suitable for any wave length up to 100 meters.

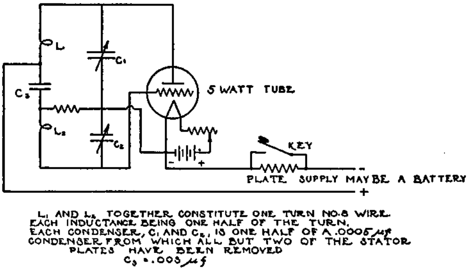


Fig. 186. — A Short Wave Transmitter

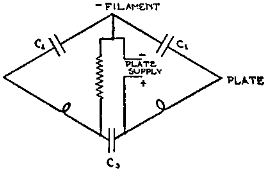


Fig. 187. — Showing That the Circuit of Fig. 177 is a Wheatstone Bridge Circuit

147. Modulation. — If the groove in a phonograph disk could be straightened out and magnified it would be found to consist of irregular depressions. The form of the depressions would correspond to the form of the sound wave. For the sound of "a" as in "father" the groove would look somewhat like Fig. 188. This is the wave form of the current in a telephone line when transmitting this sound. The phonograph needle follows a similar path. In making the record the needle impresses a groove of this form in the plastic material which is to form the disk.

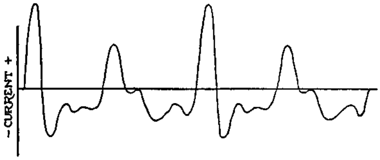


Fig. 188. — Wave Form for the Sound of "A" as in "Father"

Now suppose we have a train of high frequency oscillations as in Fig. 189, generated by an oscillating tube. If a microphone is connected in the proper way to the input circuit of the tube and the sound of "a" is spoken into the microphone, the wave form of this sound is impressed on the high frequency waves. The peaks of the high frequency waves, now, do not all reach the same height. Their amplitude is modified or modulated by the low frequency waves of the sound. This is shown in Fig. 190. If we draw a line over the peaks of the high frequency waves in this figure we have an irregular curve like the wave form of the sound. The low frequency sound waves are impressed on the high frequency waves as the sound waves are impressed on the wax of the phonograph disk. The com-

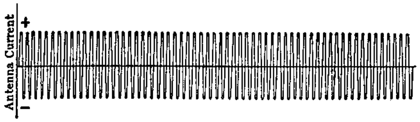


Fig. 189. — High Frequency Oscillations

parison must not be carried too far but it helps us to form a picture of what happens when radio frequency waves are being modulated by voice waves. It is the radio frequency waves as thus modulated that go out through space. These modulated waves impress their oscillations on radio receivers.

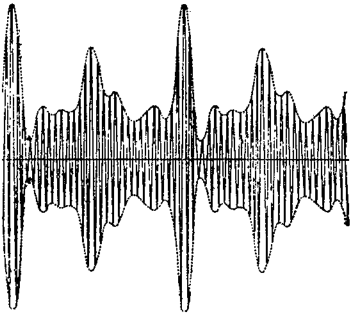


Fig. 190. — Form of Modulated Waves Transmitting the Sound of "A" as in "Father"

The radio frequency wave which is modulated is called the carrier wave. The meaning of this term is obvious, for the radio frequency wave acts as a carrier by means of which the audio frequency wave is transmitted. The carrier wave is said to be completely modulated or to have 100 per cent modulation if the boundary line of the high frequency waves just touches zero at its lowest point.

148. **Buzzer Modulation.** — If a buzzer circuit consisting of a buzzer, key and battery is connected to the primary of a transformer and the secondary of the transformer connected in the grid circuit of an oscillating tube, the current variations caused by the buzzer acting through the transformer cause a varying voltage on the grid of the tube and the plate current is modulated. If the oscillations from this tube are now picked up by a radio receiver a sound similar to that of the buzzer is heard. Any oscillating circuit can be used for this arrangement. A Hartley circuit with buzzer modulation is shown in Fig. 191.

149. **Voice Modulation.** — In place of a buzzer, a micro-

phone may be coupled to the grid circuit of the tube as shown in Fig. 192. The variations in current caused by the vibration of the disk of the microphone act through the transformer to cause corresponding voltage variations on the grid. The grid voltage variations modulate the plate current as explained in Section 147.

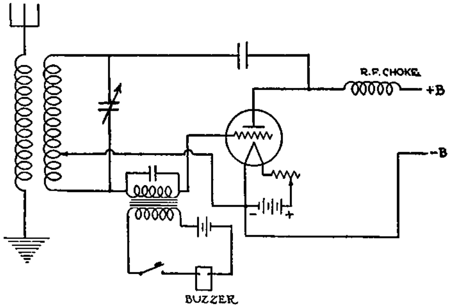


Fig. 191. — Hartley Circuit with Buzzer Modulation

The sound waves may act on the oscillator tube by means of another tube. In this case the second tube is called a modulator tube. The sound vibrations act on the grid of the modulator tube. The output of the modulator tube in turn modulates the plate current of the oscillator. Let us examine this action more in detail. Referring to Fig. 192, the sound waves first produce vibrations of the microphone diaphragm. This causes a fluctuating current in the primary of the modulation transformer. This in turn induces an alternating voltage in the secondary. This alternating voltage acts on the grid of

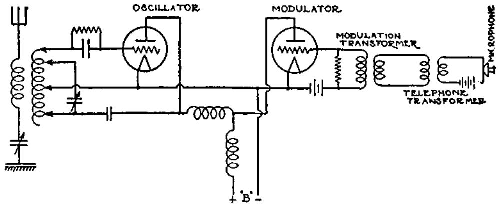


Fig. 192. — Circuit for Voice Modulation

the modulator and causes variations in the plate current of this tube which are of voice frequency. The plate battery furnishes a practically constant current to the two tubes. In other words the sum of the plate currents of the two tubes is practically constant. It follows, then, that when the grid of the modulator becomes more positive so as to increase the plate current in this tube, the plate current in the oscillator is decreased. The reverse is also true. When the grid of the modulator becomes more negative, the plate current of this tube is decreased and that of the oscillator increased. Variations in the output current of the oscillator tube are therefore produced which are of voice frequency. These oscillations act on the antenna circuit to modulate the outgoing radio frequency waves. The choke coil in the " B " battery line prevents the audio frequency currents from flowing back through the plate battery. The radio frequency choke allows audio frequency currents to pass but prevents radio frequency currents from passing back from the antenna circuit. The method of modulation just described is known as the Heising system after Mr. R. A. Heising of the Western Electric Company, who first described a method of applying the system in practice.

Amateur radio telephone operation is restricted to certain very narrow wave bands by government regulation. Anyone planning to transmit signals by any of the methods described should first become familiar with the government regulations regarding amateur transmission and secure the amateur's license which is required by law.

150. Transmitting Antennas. — More care is necessary in erecting a transmitting antenna than a receiving antenna. The length of the antenna should be such that it will operate on its fundamental wave length or a harmonic. It is best to have the natural wave length slightly above the desired wave length and use a series condenser to bring the wave length down to the desired value. For example, if the desired wave length is 80 meters, the fundamental wave length of the antenna may be about 90 meters. The correct wave length can be read from the graph of Fig. 193. For 90 meters the length of the antenna and lead should be 70 feet.

It is good practice to use a counterpoise in place of a ground. A counterpoise is a single wire suspended on insulators a few feet above the ground. The length of the counterpoise with its lead should be the same as that of the antenna. This is the Hertz type of antenna, so called because it is of the same type as the antenna used by Hertz in his experiments on electromagnetic waves. In the Marconi type a ground is used. If this type of antenna is used there must be a good connection to earth. This can be secured by connecting to metal plates buried at such a depth that they are always in contact with moist earth.

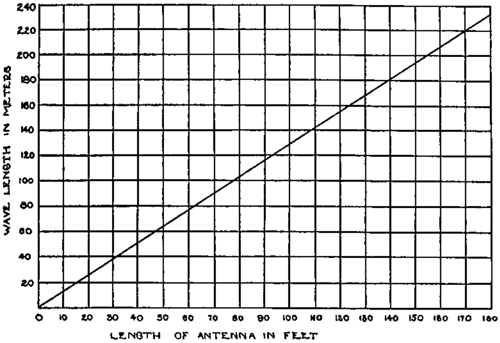


Fig. 193. — **Graph for Length of Antenna and Wave Length**

If it is desired to change the antenna to a higher wave length, this can be done by connecting a variable inductance in series with the antenna and adjusting the inductance until the correct wave length is obtained. The wave length of an antenna can be measured by the method given in Section 174. The wave length of an antenna is increased by connecting inductance in series and decreased by connecting a condenser in series (Sections 55 and 69).

If the antenna has a fundamental wave length of 80 meters it can be operated at 40 meters without change by simply adjusting the tuning circuit of the transmitter to 40 meters. The antenna is then operating on its second harmonic. The fundamental wave length is called the first harmonic. Other harmonics may be used in the same way.

When a Hertz antenna operates on its fundamental the total length of the antenna and counterpoise is one-half a wave length. The current is then greatest at the mid-point and zero at the ends. The voltage is greatest at the ends and zero at the mid-point. Fig. 194 shows voltage and current at different points throughout the length of the antenna for the fundamental or first harmonic. If operating on the fundamental and the transmitter is coupled to the antenna at the mid-point as in Fig. 195, current is fed in at the point where the current is greatest. This is a current-feed system. Voltage feed consists in connecting the oscillating circuit by a single wire to the antenna at a point where the voltage is greatest as in Fig. 196. A single wire antenna of the "inverted L" type is one of the simplest to construct and is fully satisfactory for most work at wave lengths in the bands used for amateur transmission.

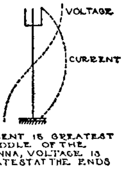


Fig. 194. — Showing Voltage and Current at Different Points along an Antenna

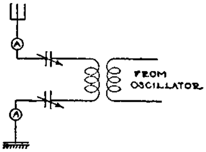


Fig. 195. — Current Feed System

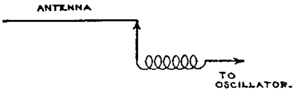
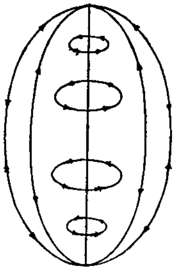


Fig. 196. — Voltage Feed

The oscillations in the antenna set up electric and magnetic fields alternately, the electric fields being parallel to the wire and the magnetic fields perpendicular to the wire (Fig. 197). These electric and magnetic fields following one after the other constitute the electromagnetic waves which go out through space, the so-called "radio waves."

151. Atmospheric Disturbances. — Electric disturbances in the air set up oscillations which interfere with the reception of signals. Lightning discharges near or distant or rapid voltage changes in the air caused by the passing of low, overlying clouds are common causes of such oscillations. There are different kinds of "static" or "strays," as atmospheric disturbances are called, caused by different kinds of electric disturbances. These are placed by DeGroot in three classes:



THE WAVES THAT GO OUT FROM AN ANTENNA CONSIST OF ELECTRIC AND MAGNETIC FIELDS OF FORCE. THE MAGNETIC FIELDS ARE CIRCULAR AROUND THE ANTENNA. THE ELECTRIC FIELDS EXTEND LENGTHWISE WITH RESPECT TO THE ANTENNA

Fig. 197. — Electric and Magnetic Fields about an Antenna

1st. Loud and sudden clicks. These are caused by lightning discharges.

2d. A constant hissing noise in the receiver, caused by the passing of electrically charged clouds. Charges of electricity from the atmosphere passing directly into the antenna produce a similar sound.

3d. A continuous rattling noise. The cause is not fully known.

152. The Transmission Unit. — The human ear is not a very sensitive organ. If an orchestra were to play so softly that the sound could barely be heard and then with a million times as great a volume the music would sound only sixty times as loud as at first. In other words, if the loudness were increased by steps which the ear could detect, there would be only sixty such steps until the volume had increased a million times. The transmission unit represents the smallest gain in volume which the average ear can detect. The name of this unit is the decibel. A bel is a larger unit named after Alexander Graham Bell and a decibel is one-tenth of a bel. The abbreviation for a decibel is db.

If there is a gain of 20 decibels the volume has increased ten squared or 100 times. If there is a gain of 30 decibels the volume has increased 10 x 10 x 10 or 1000 times. Thus the number of decibels is 10 times the power to which 10 must be raised to give the gain in volume. Here we are using the word power in the mathematical sense meaning the number of times 10 is taken as a factor. We may write 10^3 instead of 1000. The figure 3 as used here is the logarithm of 1000. A logarithm indicates a power of ten. By volume gain we mean gain in electrical power but we have used the term, volume gain, to avoid using the word power with two different meanings. Now we can see why it is that a volume gain of one million means multiplying the loudness as perceived by the ear by only 60. One million equals 10 taken six times as a factor or 10^6. The steps which the ear recognizes are logarithmic steps.

The relation between electric power gain and decibels can be remembered by a simple rule. To convert electric power ratio to decibels look up the logarithm of the ratio in a table of logarithms and multiply it by 10. To convert decibels to electric power ratio first divide the number of decibels by 10. This gives the logarithm of the power ratio. Then using a table of logarithms find the number corresponding to this logarithm. The method of using a table of logarithms is usually explained in a note accompanying the table.

Questions

1. Draw a diagram of a Hartley oscillating circuit.
2. Draw a diagram of a Colpitts oscillating circuit.
3. How may an oscillator be calibrated?
4. What is a master oscillator transmitting circuit?
5. What is meant by modulation?
6. Describe the buzzer method of modulating waves in an oscillator.
7. Describe a method of securing voice modulation in a transmitter.

CHAPTER X

PHOTOELECTRIC CELLS AND GLOW TUBES

153. Photoelectric Current. — Television and sound motion pictures depend on cells in which light causes emission of electrons. In the common radio tubes electrons are thrown off from the cathode when it is heated. This is called thermionic emission meaning emission of electrons by the action of heat. There are certain substances on which light produces a similar effect. These are the alkali metals. The best known of these metals are potassium and sodium which, in combination with hydrogen and oxygen, form the alkalis potassium hydroxide and sodium hydroxide commonly called caustic potash and caustic soda. Another alkali metal which is generally used in photoelectric cells is caesium. Caesium and caesium oxide on a plate of silver form the light sensitive element of a com-

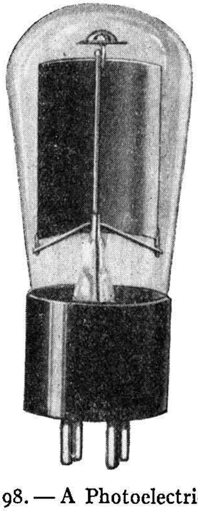


Fig. 198. — A Photoelectric Cell

mon form of photoelectric cell. Potassium hydride cells are also used.

If we have within a tube a plate coated with a film of caesium (See Fig. 198) and throw a beam of light on this film, electrons are thrown off. If we have also within the tube an electrode which is made positive with respect to the film of caesium, the electrons flow to this positive electrode. The film of caesium is the cathode and the positive electrode is the anode. If we have a circuit as in Fig. 199 electrons flow around the circuit. In other words there is an electric current and the stream of electrons in the tube is a part of the current. If the light is cut off, the flow of electrons from the cathode ceases and the current is reduced to zero. Thus the current is controlled by the action of light on the caesium film.

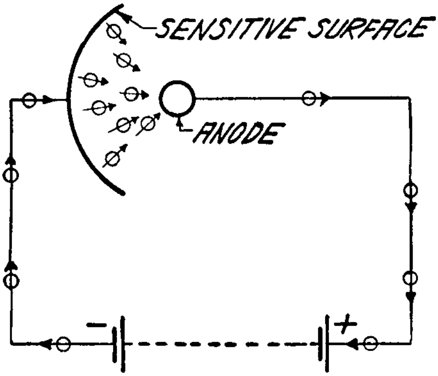


Fig. 199. — Circuit Illustrating Principle of Photoelectric Cell

154. Sensitivity of Photoelectric Cells. — The strength of the current depends on the intensity of the light which falls upon the sensitive surface of the cathode. The more intense the light the greater is the number of electrons set free. In fact the number of electrons emitted per second from a photoelectric surface is directly proportional to the intensity of the light falling upon the surface. This means that if there are no interfering conditions the current is directly portional to the intensity of illumination. This is true up to the point of saturation.

The sensitivity of a photoelectric cell to the colors of the spectrum is more nearly uniform than is that of the human eye. The eye, for example, is much more sensitive to blue than either red or violet. The photoelectric cell is slightly more sensitive to red and violet than to blue. The photoelectric cell is very sensitive to ultraviolet light to which the human eye does not respond.

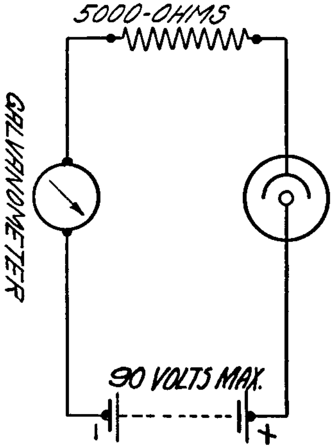


Fig. 200. — A Photoelectric Cell Circuit for Testing Lamp Intensities

Accurate tests have shown that if an instantaneous flash of light such as a spark discharge is thrown on a photoelectric cell the emission of electrons takes place within three billionths of a second. The electron emission stops as quickly when the light is cut off. Thus the response is practically instantaneous.

The current in a photoelectric cell is extremely small, only a few millionths of an ampere. One type of cell contains a trace of an inert gas, such as helium, argon or neon. Electrons from the cathode striking the atoms of gas knock off other electrons, in other words the gas is ionized by the electrons from the cathode. These additional electrons flow on to the anode and thus the current is increased. This does not occur in a vacuum type cell. The sensitivity of the gas filled cell is therefore greater than that of the vacuum cell. The gas filled cell, however, is not so constant in its action as the vacuum cell.

155. Circuits for Photoelectric Cells. — Fig. 200 shows a circuit for testing lamp intensities. The deflection of the galvanometer indicates the intensity of the illumination falling upon the cell. On account of the feeble current produced by a photoelectric cell an amplifier is usually needed. Fig. 201 shows a circuit in which a photoelectric cell with an amplifier is used to operate a relay. A photoelectric cell with amplifier circuit used in television and talking movies is shown in Fig. 202. In television the output of the last tube modulates the transmitter. In place of the one photoelectric cell shown in this figure, a number of cells may be connected in parallel thus obtaining a larger field of view for transmitting television pictures from life.

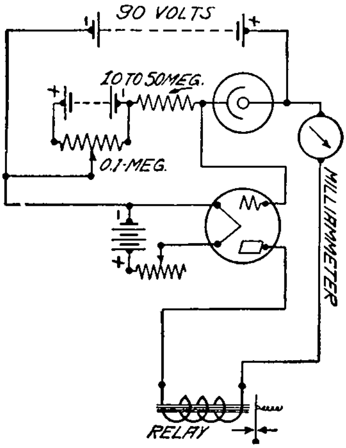


Fig. 201. — A Photoelectric Cell Circuit with Amplifier and Relay

156. Photoconductive Cells. — Another type of light sensitive cell is one in which electrical conductivity varies with the action of light. Selenium is the substance commonly used in such cells. When light falls on selenium its electrical resistance is reduced. The most probable explanation is that light sets electrons free from the selenium atoms. In other words, the atoms are ionized by the action of light. It has been found that light affects selenium to a depth of 0.0014 centimeter. The film of selenium should, therefore, be very thin. The current flowing through a selenium cell is proportional to the square root of the illumination. The change in current for a given change in illumination is less, therefore, for a selenium cell than for a photoelectric cell. The selenium cell will however, carry a much stronger current than a photoelectric cell. In fact a selenium cell will carry sufficient current to operate a relay without the use of an amplifier.

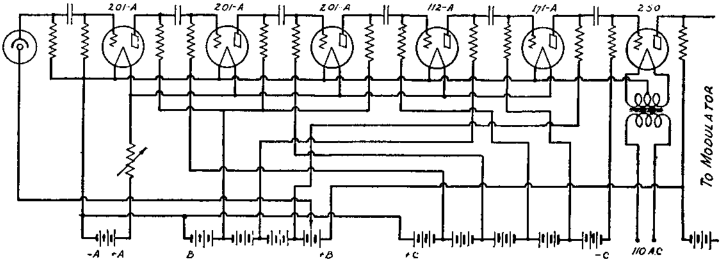


Fig. 202. — A Photoelectric Cell Circuit Used in Talking Moving Pictures

The fault of the selenium cell is its lagging. When light falls on such a cell the current increases fairly rapidly but not so rapidly as in the photoelectric cell. When the light is cut off from the selenium cell, however, the current decreases very slowly instead of dropping at once to its value for the darkened cell. This difficulty has been largely overcome by making the film of selenium extremely thin. By this means selenium cells have been developed that can be used in sound motion picture projection.

157. Glow Tubes. — In television, light sensitive cells are used in transmission. Light from the object whose picture is being transmitted falls on the cell and produces electrical impulses. These impulses act on the grid of a modulator tube.

This tube acts in the same way as a modulator tube in sound broadcasting. In receiving the television signals the electrical impulses must be made to produce changes in light. This is accomplished by means of a glow tube. Such a tube contains a gas, neon, under low pressure. When acted on by high voltage this gas gives out light, the intensity of the light varying as the voltage varies. This tube takes the place of the loud speaker in sound reception.

Another kind of glow tube is the cathode ray tube. If a high potential is placed on two electrodes in a tube having a high vacuum, a stream of electrons flows from cathode to anode. Cathode rays is another name for this electron stream. Moving electrons always produce a magnetic field whether they are moving through a vacuum tube or in a wire. Because of this magnetic field the electron stream in a cathode ray tube can be deflected by another magnetic field for the same reason that a current carrying wire moves in a magnetic field. The cathode rays since they are made up of negative electric charges can also be deflected by an electrostatic field. Such a field can be produced by placing two metal plates one on each side of the cathode beam and making one of the plates positive and the other negative. This deflects the beam in one direction. If the charges are reversed the beam is deflected in the opposite direction.

A diagram of a cathode ray tube as used in television is given in Fig. 203. The stream of electrons forming the cathode beam is thrown off from an oxide coated filament. This beam passes through a small opening in the control electrode which is negative and which controls the intensity of the cathode beam. The beam then flows through the first anode which has a low positive potential. The electrons attain a speed at this point which is not very high, about three million meters per second. They then pass through the second anode which has a much higher positive potential and which gives the electrons a much higher speed. The deflecting plates are placed one above and one below the cathode beam. The beam is deflected up or down according to the potential on these plates.

The deflecting coils are placed one on either side of the beam and deflect it sidewise according to the direction of the magnetic field produced by the current flowing through them. An alternating current flows through these coils keeping step with the horizontal movements of the scanning beam at the transmitter. Therefore the beam moves horizontally in step with the scanning beam. To produce a picture the cathode beam must also move up and down and this is brought about by the varying potentials on the control plates. The potentials of these plates are controlled from the transmitter. This is done by connecting the plates to a condenser and charging the condenser at a constant rate so that the potential moves the cathode beam up across the picture area in the required time and when it reaches the top the condenser is discharged by an impulse from the transmitter and this allows the beam to drop to the bottom of the picture area. Thus the beam is given both a horizontal and a vertical motion. Its intensity also varies according to the intensity of the light acting on the photoelectric cell at the transmitter. Thus the beam traces out the picture on the broad end of the cathode ray tube. On the inner surface of this end of the tube is a fluorescent substance, willemite, which glows with an intensity corresponding to the intensity of the cathode rays. Thus the picture appears on the broad end of the tube. This is electrical scanning.

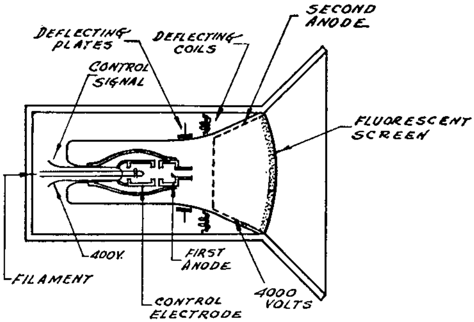


Fig. 203.—A Cathode Ray Tube

CHAPTER XI

RADIO MEASUREMENTS

158. The Wavemeter. — The fundamental instrument in radio measurement is the wavemeter. The wavemeter depends on the principle of resonance (Section 79). It consists of a coil and condenser in parallel. The inductance of the coil and the capacity of the condenser must be so chosen as to give the desired range of wave length. Here we use the wave length formula,

$$\lambda = 1884\sqrt{LC}$$

inductance being in microhenries and capacity in microfarads (Section 80) or we may use the corresponding formula for frequency,

$$f = \frac{1}{2\pi\sqrt{LC}}.$$

In this frequency formula inductance is in henries and capacity in farads. It is more convenient to use the smaller units, microhenries and microfarads. To change the inductance in the formula to microhenries and the capacity to microfarads the fraction is multiplied by 1,000,000. This gives

$$f = \frac{1{,}000{,}000}{2\pi\sqrt{LC}}.$$

If we divide 1,000,000 by 2π or 6.2832 we get

$$f = \frac{159{,}154}{\sqrt{LC}}.$$

We shall have occasion to use the wave length and frequency formulas in a number of tests.

A good beginning in wave length or frequency measurements can be made by connecting a coil of 40 turns wound on a 3-inch cardboard tube across a variable condenser of 0.0005 microfarad capacity and coupling the coil to an oscillating receiving set. The coil and condenser just mentioned constitute a simple wave meter. The coupling may be done by winding a few turns of wire, say 4 or 5, over the coil and connecting these few turns in series with the antenna (Fig. 204). The wiring should be done in such a manner that the resistance is low. The receiving set is now tuned for the signals from a broadcasting station whose wave length is known. Then the condenser of the wave meter is varied until a click is heard in the receiver. The reading of the condenser at which the click is heard is noted. This is the reading for the wave length of the incoming signals. If the click is heard at more than one point on the dial, the coupling should be loosened by removing one or more turns from the secondary winding which is in the antenna circuit. The click should be heard at the same point when increasing as when decreasing the capacity. A very positive result can be obtained by using a regenerative receiver and tuning just to the oscillating point. In this case the secondary coil of the wavemeter may be omitted and the wavemeter simply placed near the receiving set. The wavemeter should then be moved away from the receiving set until the click is heard at the same point when increasing as when decreasing the capacity. The wavemeter acts as an absorption circuit and when tuned to resonance with the received signals absorbs some of the energy, thus causing the click.

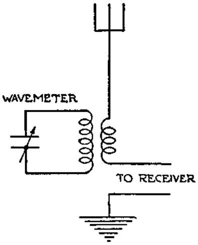


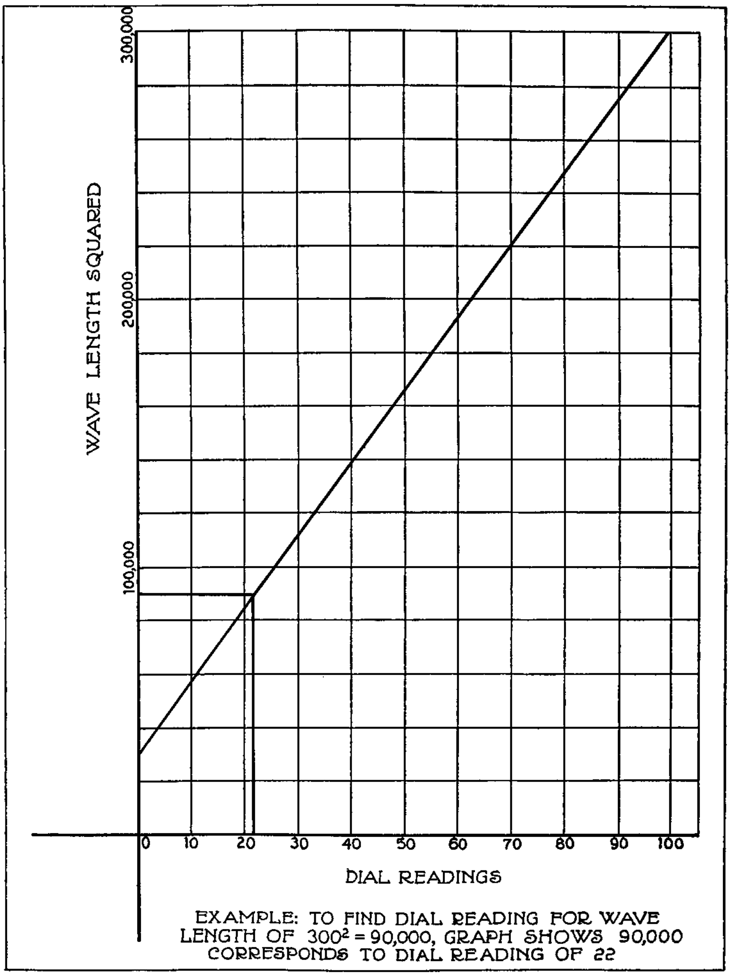
Fig. 204.—Wave Meter Coupled to a Receiver

The process can be continued, using signals from a number of broadcasting stations of different wave lengths. A graph can then be plotted letting abscissas represent the readings of the wave meter condenser and ordinates represent wave lengths.

If a condenser is used for which the wave length is proportional to the angle through which the rotating plates are turned, this graph will be a straight line. Such a condenser is known as a straight-line wave-length condenser. It can be seen from the equation for wave length given above that wave length is proportional to square root of capacity, or to put it the other way, capacity is proportional to the square of the wave length. In a straight-line wave-length condenser, then, the shape of the plates is such that the capacity is proportional to the square of the angle through which the rotating plates are turned from the zero position.

If a condenser is used for which the capacity is directly proportional to the angle we get a different result. The graph drawn as described above will be a curve known as a parabola and it will be necessary to locate a large number of points by test to get the curve at all accurate. It will be better in this case to draw the graph as follows: Let abscissas represent condenser readings and ordinates represent the squares of the wave lengths. The graph will now be a straight line. Two different wave length tests are sufficient to locate this line though it is better to check the results by testing for three or more. To find from this graph the setting of the condenser for any given wave length, first square the wave length then find the point on the graph whose ordinate is the value of this square. The corresponding abscissa is the condenser setting required. This is illustrated in Fig. 205.

Another form of condenser is made with plates shaped so that the frequency is inversely proportional to the readings of the condenser dial. Such a condenser gives a straight line graph, as condenser readings are plotted as abscissas and frequencies as ordinates. It is best to state the frequencies in kilocycles. Two or three readings on standard wave length signals are sufficient. The condenser setting for a given wave length may be found from the graph by first dividing 300,000 by the wave length to find the frequency in kilocycles and then finding from the graph the condenser setting corresponding to this frequency. An example illustrating this is given in Fig. 206.



EXAMPLE: TO FIND DIAL READING FOR WAVE LENGTH OF $300^2 = 90{,}000$, GRAPH SHOWS 90,000 CORRESPONDS TO DIAL READING OF 22

Fig 205. — Graph for Condenser Setting and Squares of Wave Lengths

159. A Wavemeter with a Current Indicator. — A wavemeter is a resonant circuit. When it is tuned to the frequency of the oscillations it is receiving, the current flowing between the coil and condenser of the wavemeter is a maximum. The wavemeter is then in a condition of resonance at the frequency of the incoming signals. It is clear, then, that resonance can be detected by any device that will indicate the current flowing in the wavemeter. The simplest device for this purpose is a hot wire milliammeter. Another is a crystal

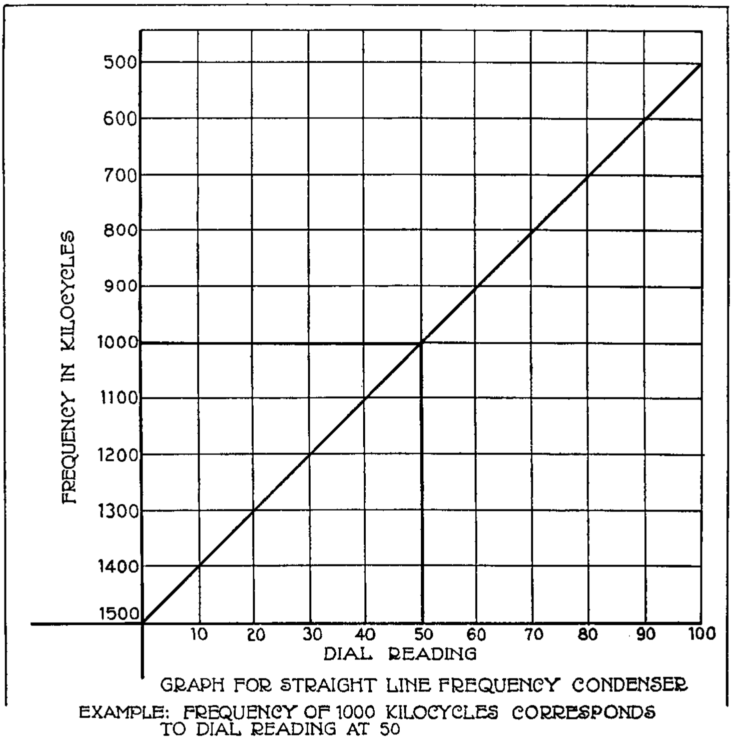


Fig. 206. — Graph for Condenser with Dial Readings Inversely Proportional to Frequency

detector and phones. Fig. 207 shows the circuits for these two methods.

It is also true that when a circuit consisting of a condenser and coil is in resonance the voltage across the condenser terminals is a maximum. Hence a voltage indicating device across the condenser may be used. One that is very convenient is a tube containing neon gas such as is used in testing the ignition of a gasoline engine. The tube should be carefully removed from its case and connected across the wavemeter as in Fig. 208.

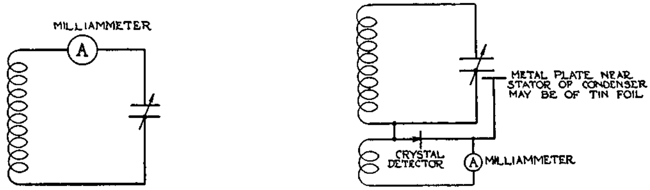


Fig. 207. — Two Methods of Indicating Resonance in a Wavemeter

160. An Oscillating Wavemeter. — An oscillator calibrated for wave lengths is useful for many tests. A circuit diagram for such an oscillator is given in Fig. 209. It will be noted that this is a Hartley circuit. A dry cell tube is used. The condenser has a capacity of 0.001 microfarad. Different inductances may be used for the coil depending on the wave length desired. The inductance should be the same as would be used with the same condenser in a receiving set. It is best to mount all the parts except the batteries on a hard rubber

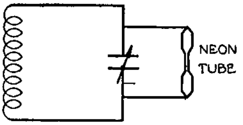


Fig. 208. — Using a Neon Tube to Indicate Resonance

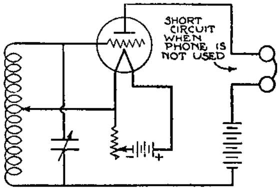


Fig. 209. — An Oscillating Wavemeter

panel. The batteries should be clamped to the cabinet or baseboard in a fixed position because a change in the position of the batteries will change the tuning of the oscillator.

The oscillating wavemeter can be calibrated by means of standard wave length signals. First tune a receiving set to the signals. Then, placing the oscillating wavemeter three or four feet from the receiving set, turn the dial slowly. When the oscillator is tuned almost to the wave length of the incoming signals a whistle will be heard. This is a beat note whose frequency is the difference between the frequencies of the incoming signal and the oscillations given out by the oscillating wave meter. As the dial is turned farther the beat note changes to lower and lower pitch until it ceases. Turning the dial still farther, the beat note comes in again and rises in pitch. The point at which the beat note just ceases is the setting for the wave length of the incoming signal. This is known as the zero beat method. Tests should be made for a number of different wave lengths and a graph plotted letting abscissas represent dial readings and ordinates wave lengths or frequencies. An oscillating wavemeter is sometimes called a driver.

161. Using a Driver to Calibrate a Wavemeter. — The driver may be used to calibrate a non-oscillating wavemeter more accurately than can be done by the method described in Section 148. The method about to be described is the zero beat method similar to the method just described for calibrating the driver. It is necessary to use a receiving set and tune it for signals from a broadcasting station whose wave length is known to be constant. The receiver should be tuned for maximum signal but not adjusted to oscillate. A non-oscillating receiver may be used. The driver is then tuned until the beat note is heard. The beat note will come in as a whistling sound which will vary in pitch as the tuning of the driver is varied slightly in either direction. This note, as we have seen, is produced by the oscillations sent out by the driver combining with the carrier or high frequency oscillations from the broadcasting station. When the driver is tuned exactly to the same frequency as that of the broadcasting station the beat note ceases The driver is now tuned for zero beat. The wavemeter placed near the driver is now tuned until the current indicator connected with the wavemeter shows maximum current. If this current is too large the wavemeter should be placed farther from the driver. This setting gives the reading of the wavemeter for the wave length of the received signals.

Unmodulated waves can be received only by producing a beat note. Such signals can be picked up by using a regenerative receiver adjusted to oscillate. The receiver oscillations then will combine with the received signals to produce a beat note when the receiver is nearly in tune with the signals. The receiver can then be stopped from oscillating and the driver and wavemeter used as with a non-oscillating receiver.

The waves given out by an oscillating wavemeter may be modulated by coupling a buzzer circuit to the wavemeter (Section 148, Fig. 182).

162. A Standard Condenser. — We shall now proceed to methods of measuring capacity and inductance and, following this, a number of tests and measurements that can be made with a wavemeter.

In order to measure the capacity of a condenser it is necessary to have a standard with which to compare the condenser under test. A standard condenser can be purchased or one may be made of two heavy plane brass or aluminum sheets separated by small pieces of sheet glass.[1] Use as little glass as possible to keep the metal sheets parallel to each other. The sheets should have ten or more square feet of surface. They may be cut into a number of sheets of convenient size and separated by glass of uniform thickness. The thickness of the glass can be measured with a vernier or micrometer caliper to make sure that it is uniform. Alternate sheets, 1, 3, 5, etc., are connected to form one plate of the condenser and the remaining alternate plates, 2, 4, 6, etc., to form the other plate. The capacity is found from the formula,

$$C = \frac{A}{4\pi d},$$

in which A is the area in square centimeters of one set of plates

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[1] From "Experimental Radio," Professor R. R. Ramsey, University of Indiana. By permission.

and d is the distance between the plates, which is the thickness of the glass used to separate the plates. This thickness must be expressed as a fraction of a centimeter. The result must be divided by 88,500 to reduce to microfarads.

163. A High Pitch Buzzer. — In a number of the following measurements it is necessary to use either a high pitch buzzer or an audio frequency oscillator. Directions are given here for making a high pitch buzzer since it is very difficult to obtain such a buzzer on the market. The construction of the buzzer is shown in Fig. 210. The core of the magnet is a piece of soft iron wire about one-eighth inch in diameter (stove pipe wire can be used). The coils are made with number 32 enameled wire. It is best to make a paper tube for each coil by winding a strip of thin paper on a straight piece of wire the same size as the core. The paper is shellaced and the wire wound on the tube, shellac being applied during the winding. The straight wire is then drawn out and the coil slipped on the magnet core. A brass strip is used to hold the magnet in place. The vibrating armature is a strip of the thinnest commercial tin one-eighth inch in width from which the tin has been removed with a file or emery paper. The contacts are made of platinum wire which can be obtained from a jeweler. Number 30 is a good size to use. The spring is made of a piece of the platinum wire hammered thin at the contact end and soldered at the other end to the armature. A very fine pointed soldering iron should be used and as little solder as possible. The armature is attached at one end to a brass plate as shown. Of

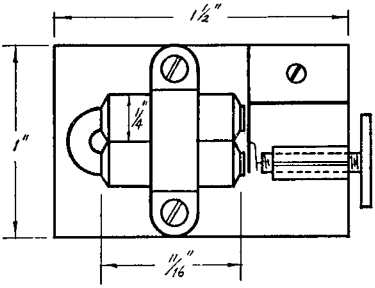

Fig. 210. — A High Pitch Buzzer

course the coils must be joined to give the correct polarity and the proper connections made for passing current through the coils and the contact points.

164. An Audio Frequency Oscillator.—In the following measurements where a high pitch buzzer is indicated, an audio frequency oscillator can be used instead. It is only necessary to couple the oscillator to the testing circuit in the same manner as indicated for the buzzer. It should be noted that the oscillator described in Section 159 oscillates at radio frequency and therefore is very different from the one about to be described.

The audio frequency oscillator is a Hartley circuit using the coils of an audio frequency transformer (Fig. 211). The primary is connected in the plate circuit and the secondary in the grid circuit, the common connection going to the negative filament terminal. A key can be placed in the grid circuit if it is desired to start and stop the oscillations at frequent intervals. If a condenser of higher capacity, say 0.001 m.f., is used the oscillations will be slower and can probably be counted.

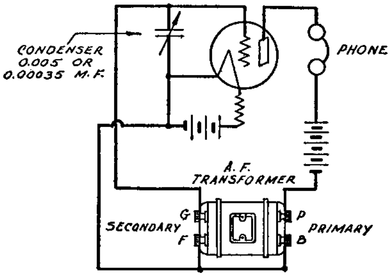

Fig. 211.—An Audio Frequency Oscillator

165. Measuring the Capacity of a Condenser.—A simple method of measuring the capacity of a condenser is by means of a Wheatstone bridge. The four arms of the bridge consist of two resistance boxes, R_1 and R_2, a standard condenser C_s and the condenser to be tested C_x as in Fig. 212. Alternating current is supplied to the bridge through the coil M which is coupled to the buzzer circuit. A telephone induction coil can be used, connecting the secondary to the bridge terminals and the primary in the buzzer circuit, or the primary and secondary may be simply two coils wound together on a cardboard tube. A telephone receiver is used as a current detector. A small inductance, L, in series with the telephone receiver helps to make a sharper adjustment for minimum sound. The resistances, R_1 and R_2, are adjusted until the sound disappears or is as faint as possible. The capacity C_x is then found from the proportion,

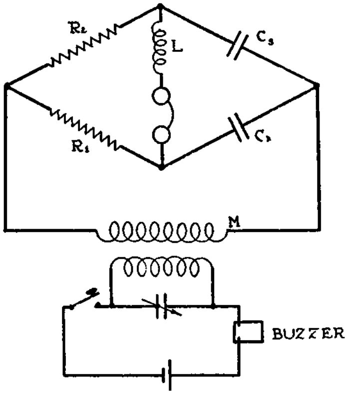

Fig. 212. — Measuring Capacity of a Condenser, Wheatstone Bridge Method

$$\frac{C_x}{C_s} = \frac{R_2}{R_1}.$$

It will be noted that this is an inverse proportion. The reason is that, if resistance is increased, current is reduced, while, if capacity is increased, current is also increased. Thus capacity and resistance act in opposite ways so far as affecting the strength of the current is concerned.

If a variable condenser is used for this test the capacity should be measured for a number of settings and a graph plotted letting abscissas represent dial readings and ordinates represent capacity.

To make this test accurately the room must be quiet, for noises will interfere.

166. Measuring the Inductance of a Coil. — The resistance of the coil must first be found by means of a Wheatstone bridge using direct current. The bridge is now balanced for direct current resistance. All four resistances must be left as they are for the rest of the experiment. The battery connected to the bridge is now replaced by a source of alternating current. A buzzer and induction coil may be used as in Section 165. A variable condenser which has been calibrated is shunted across R_1 (Fig. 213). The inductance L to be measured forms one arm of the bridge as shown in the diagram. A small inductance coil L_1 is inserted in series with the telephone receiver to obtain a sharper adjustment for the faintest sound. Now the condenser C is adjusted until the sound is as faint as possible. When this has been done the bridge is balanced for alternating current. The resistance of L may be left out of account for that has been balanced out by the other three resistances. The four arms of the bridge so far as the alternating current is concerned are L, C, R_2 and R_3. L may be found from the equation.

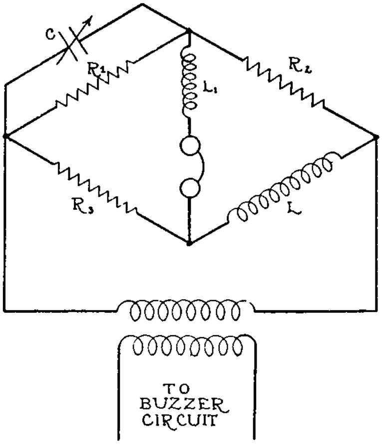

Fig. 213. — Measuring Inductance, Wheatstone Bridge Method

$$\frac{L}{R_2} = \frac{R_3}{1/C}$$

$$\text{or} \quad L = CR_2R_3.$$

The quantity 1/C must be used for the reason explained in Section 165. The resistances R_2 and R_3 must be such that the product CR_2R_3 may equal the inductance L considering the range of the condenser. For example, if C has a capacity varying from 0.00005 to 0.0005 microfarad, then with R_2 and R_3 each equal to 100 ohms the smallest inductance that can be measured is

$$L = 100 \times 100 \times 0.00005 = 0.5 \text{ microhenry}.$$

This method of measuring inductance is suitable for small coils.

167. Inductance of a Coil, Impedance Method. — For large coils it is better to find the inductance by first measuring the resistance and the impedance. The resistance is measured by the voltmeter-ammeter method using direct current (Section 31). To measure impedance alternating current of known frequency is used. The voltage across the coil is measured with an a.c. voltmeter and the current with an a.c. ammeter. The connections are the same as for measuring resistance except that a.c. instruments are used. Impedance equals volts divided by amperes. After finding the impedance the inductive reactance is found by subtracting the square of the resistance from the square of the impedance and taking the square root of the result.

$$X_L = \sqrt{Z^2 - R^2}.$$

Having found the reactance the inductance can be found from the equation,

$$L = \frac{X_L}{2\pi f}.$$

168. Mutual Inductance of Two Coils. — If two coils are placed so that a current in one will not have any inductive effect on the other, then, if the coils are connected in series their combined inductance is the sum of their separate inductances.

$$L = L_1 + L_2$$

If the coils are placed parallel to each other with the turns running in the same direction and connected in series, there is mutual induction between them. The current in the first coil induces a certain e.m.f. in the second and the current in the second coil induces the same e.m.f. in the first. If we let M stand for the effect of one coil on the other the combined effect is 2M and the total inductance of the coils is 2M plus their separate inductances.

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

The combined inductance of the coils may be measured by the method given for a single coil in Section 166. If the coils have been coupled as closely as possible in this test the value of L just found is the greatest or maximum inductance for the two coils. We may denote this value by L_{max}. The coils may then be set for minimum inductance; that is, with the current flowing in opposite directions in the two coils and the combined inductance again measured. In this case we have

$$L \quad . = L_1 + L_2 - 2M$$

because the e.m.f. induced by each coil in the other opposes the e.m.f. of self-induction so that the mutual inductance, 2M, opposes the inductances L_1 and L_2. Now, if we subtract the second result from the first we get,

$$L_{max} - L_{min} = 4M,$$

from which we can easily find the value of M.

169. Calibrating a Wavemeter by the Inductance and Capacity Method. — A wavemeter can be calibrated if the inductance of the coil and the capacity of the condenser for the different scale readings are known. Suppose the inductance of the coil has been measured by the method of Section 166 and the condenser has been tested and the graph drawn from which the capacity for any reading of the dial may be found as in Section 165. The wave length may now be computed from the equation,

$$\lambda = 1884\sqrt{LC}.$$

L must be in microhenries and C in microfarads. λ is then the wave length in meters. It will be well now to compute the wave length for dial readings 10, 20 and so on to the end of the scale. Then plot a graph for the wavemeter, letting abscissas represent dial readings and ordinates represent wave lengths.

It is well also to compute the frequencies for the same scale readings and plot a frequency graph. The frequency for each dial reading can be found by dividing 300,000,000 by the corresponding wave length. The wavemeter is sometimes called the frequency meter, for it measures either frequency or wave length, depending on the way in which the results are computed or which of the graphs is used.

The wavemeter is useful in measuring the wave lengths to which a receiving set may be tuned, the wave length of an oscillator or transmitter, the wave length of signals received from distant stations and in measuring the inductance of coils and the capacity of condensers. It is also useful in measuring the resistance of antennas and coils at high frequencies. We shall take up these uses of the wave meter in order.

170. Measuring the Wave Length of a Receiving Set. — This may be done with an oscillating wave meter having buzzer modulation. Tune the receiving set for longest waves by setting the condenser at the highest point on the dial; that is, having the rotating plates entirely meshed within the stator plates. Then tune the oscillating wavemeter until its signals are heard in the receiver. Have the coupling between the wavemeter and the receiver as loose as possible. The wave length reading of the wavemeter is the wave length for which the receiving set is tuned. Next tune the receiving set for its shortest wave length and again tune the wavemeter until the signals are heard. The two readings give the range of wave lengths or frequencies within which the receiving set can be tuned.

171. Measuring the Wave Length of an Oscillator or Transmitter. — This requires a calibrated wavemeter with a current indicator. If the frequency of the oscillator lies within the range covered by the wavemeter it is necessary only to couple the wavemeter to the oscillator; that is, place the wavemeter near enough so that the magnetic field of the oscillator can act on the wavemeter, then turn the wavemeter dial until maximum current is indicated. The wave length reading of the meter is then the wave length of the oscillator.

172. Measuring the Inductance of a Coil and Capacity of a Condenser by Means of a Wavemeter. — Inductance and capacity may be measured by a very simple method requiring an oscillating wavemeter and an oscillating receiving set. The latter may be an oscillator with telephone receiver inserted in the plate circuit. (Caution. It would be dangerous to use a high power oscillator in this way. Use only one of low power, such as the dry cell tube oscillator, or one using a tube taking only 0.25 ampere in the filament circuit.) The wavemeter and the oscillator are both started to oscillating and adjusted to zero beat. The condenser reading of the wavemeter is noted and the condenser to be tested is then connected in parallel with the condenser of the wavemeter as in Fig. 214. The wavemeter condenser is again adjusted to zero beat and the difference between the two capacity readings of the wavemeter condenser is the capacity of the condenser that is being tested.

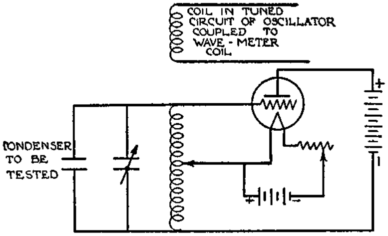

Fig. 214. — Measuring the Capacity of a Condenser by Means of a Wavemeter

The inductance of a coil can be measured approximately by a similar method. The wavemeter is tuned to resonance with the receiving set as before. The capacity of the wavemeter condenser is read. Let this be denoted by C_1. The coil to be tested is then connected in parallel with the coil and condenser of the wavemeter as in Fig. 215. The wavemeter is again adjusted to zero beat and the capacity of the condenser noted. Let this be C_2. Then the unknown inductance L_x may be found from the equation,[2]

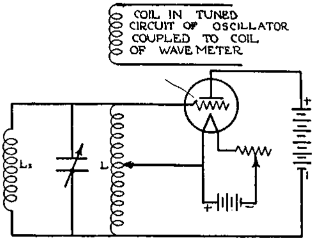

Fig. 215. — Measuring the Inductance of a Coil, by Means of a Wavemeter

$$L_x = \frac{LC_1}{C_2 - C_1}$$

in which L is the inductance of the wavemeter coil.

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[2] This equation is derived from the fact that for a given wave length the product of inductance and capacity is constant. This can be easily proven by the wave length equation,

$$\lambda = 1884\sqrt{LC}.$$

Now since the product LC remains the same in this experiment, we have

$$LC_1 = \frac{L_xL}{L_x + L} \cdot C_2.$$

The fraction $\frac{L_xL}{L_x + L}$ is the total inductance of the two inductances in parallel. The principle is the same as that of resistances in parallel.

Now, solving the second equation, we get,

$$LC_1(L_x + L) = L_xLC_2.$$

This gives, by removing the parenthesis and transposing,

$$LL_xC_1 - L_xLC_2 = -L^2C_1,$$

or

$$L_x(LC_1 - LC_2) = -L^2C_1$$

Dividing by $L(C_1 - C_2)$, we get,

$$L_x = \frac{LC_1}{C_2 - C_1}.$$

173. Measuring the High Frequency Resistance of a Coil. — We have seen in Section 91 that the resistance of a wire for a current of high frequency is greater than for a current of low frequency or for direct current. Because this is true it is not possible to use the same methods for measuring high frequency resistance that are used for direct current resistance.

We shall take up first a method of measuring high frequency resistance that is fairly simple and while not very accurate is accurate enough for many practical purposes. It is known as the substitution method. A resistance standard such as a dial resistance box, a driver and a wavemeter are needed. The wavemeter should be coupled loosely to the driver. This may be done by means of a "pick-up coil" of say four turns in series with the coil of the wavemeter, the pick-up coil being placed near the coil of the driver and the leads from the pick-up coil being rather long, say 3 feet (Fig. 216). The resistance to be measured, R_x, is in series with the coil and condenser of the wavemeter. The capacity of the condenser is varied until resonance is obtained and the ammeter reading is noted. The wavemeter is in resonance when the ammeter reading is greatest. A hot wire or thermocouple ammeter may be used which gives full scale deflection for 2 milliamperes. The resistance box is then connected in the wavemeter circuit in place of the resistance, R_x. The resistance in the box is then varied until the same current is obtained at resonance as before. The unknown resistance is then equal to the resistance in the box.

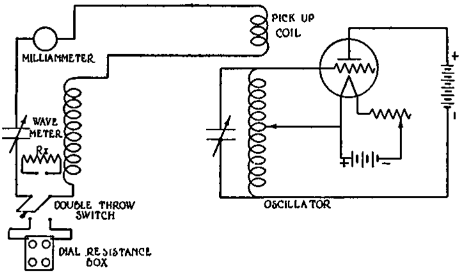

Fig. 216. — Measuring High Frequency Resistance of a Coil, Substitution Method

Another method which is more accurate than the above is known as the resistance variation method. The resistance of the wavemeter itself must first be measured. To do this the wavemeter is coupled to a driver by means of a pick-up coil as in Fig. 217. The dial resistance is set at zero. The wavemeter is then tuned to resonance and the current reading taken. Since the inductive reactance and the capacity reactance of the circuit neutralize each other at resonance (Section 79) the only opposition to the current is the resistance of the circuit and we have by Ohm's law,

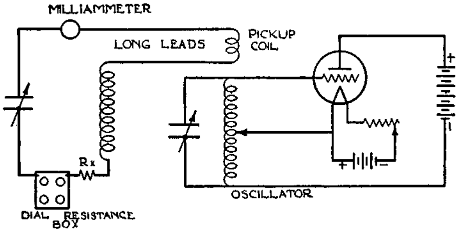

Fig. 217. — Measuring High Frequency Resistance of a Coil, Resistance Variation Method

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

The dials of the resistance box are now changed until there is some resistance. Call this R_1. The wavemeter is again adjusted to resonance and current reading taken. Now we have

$$I_1 = \frac{E}{R + R_1}.$$

Solving these two equations for R we get,

$$R = \frac{R_1}{\frac{I}{I_1} - 1}.$$

Since R_1, I and I_1 are known, R is easily found.

If a "current squared meter" in which the deflection is proportional to the square of the current is used we may substitute $\sqrt{d}$ for I, d being the deflection of the meter. The equation for R then becomes

$$R = \frac{R_1}{\sqrt{\frac{d}{d_1}} - 1}.$$

If R_1 is so chosen that $d_1 = \frac{1}{4}d$, then $\sqrt{\frac{d}{d_1}} = 2$ and $R = R_1$.

It simplifies the work, therefore, to make the resistance in the resistance box such that the second deflection is $\frac{1}{4}$ of the first.

Knowing the resistance of the wavemeter we may insert a coil or other device whose resistance is to be measured as in Fig. 217. With the resistance box at zero the wavemeter is now adjusted to resonance and the current reading taken. A resistance is put in the resistance box as before and current reading again taken. The value of R is found by the same equation as before but now R includes the resistance of the wavemeter and the unknown resistance. The difference between the two values of R will therefore be the value of the unknown resistance.

It is assumed in the above discussion that the e.m.f. remains constant. This will be the case if no changes are made in either circuit except those required in changing the resistances. It is well to have two binding posts near together for the unknown resistance and to connect a short wire across these binding posts when the unknown resistance is not in the circuit. The resistance box must be one which has a practically constant resistance at all frequencies. Special radio resistance boxes are on the market and these are best but the dial resistance mentioned above gives satisfactory results. In any case the current used must be small, say not over one or two milliamperes.

174. Measuring the Fundamental Wave Length of an Antenna.— Since an antenna has both inductance and capacity it forms a resonating circuit for a certain wave length or frequency. The principle applied in measuring the fundamental wave length of an antenna is to supply oscillations to the antenna and change the frequency of the oscillations until the antenna comes to resonance, then measure the wave length.

A simple method of making this test is shown in Fig. 218. A coil of about 35 turns 3 inches in diameter, tapped at every second turn, is placed in the antenna circuit, one end of the coil being connected to ground and the antenna connected by means of a clip to the other end. The inductance of the coil is now added to the inductance of the antenna increasing its wave length. A detector consisting of a crystal detector and phones is connected across three turns of the coil. A buzzer wavemeter is coupled loosely to the coil in the antenna circuit. The wavemeter condenser is adjusted until the loudest sound is heard in the detector. The antenna is now in resonance. The wave length is read from the wavemeter. The antenna clip is then moved down the coil two turns and the test repeated. A shorter wave length is found, because the inductance is less. Moving the antenna clip two turns farther another test is made and so on as far as it is possible to get the resonance point clearly. A graph is then plotted as in Fig. 219, abscissas representing number of turns of the coil in the antenna circuit and ordinates representing wave lengths. The curve is then extended until it meets the Y axis and the value indicated on this axis is the fundamental wave length of the antenna. If it is possible to go as low as four turns in the test the wave length at this point will be practically the same as the wave length of the antenna because the inductance of the four turns is very small compared with the inductance of the antenna. A driver with buzzer modulation could, of course, be used in place of the buzzer wavemeter.

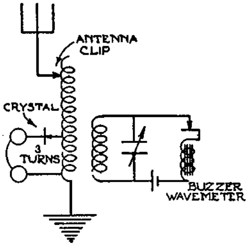

Fig. 218.—Measuring the Fundamental Wave Length of an Antenna

175. Measuring the Inductance and Capacity of an Antenna. — Having found the natural wave length of the antenna by the method just described, the inductance and capacity may easily be found. Using a coil of larger inductance than the one described in Section 174, connect the coil in the antenna circuit, using a clip, and increase the inductance until the wave length is four times that of the antenna. The inductance of the part of this coil connected in the antenna circuit must be known or must be measured. We may consider this the entire inductance of the antenna circuit, since the antenna inductance is very small compared with that of the coil. Also practically all the capacity of the circuit is that of the antenna, since the capacity of the coil is relatively small. We may, therefore, compute the capacity of the antenna from the wave length equation,

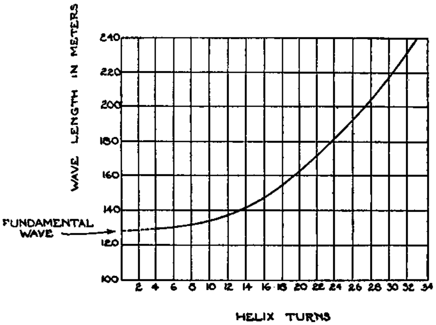

Fig. 219. — Graph for Finding Fundamental Wave Length of an Antenna

$$\lambda = 1884\sqrt{LC}$$

in which λ is the measured wave length with the coil in the circuit, L is the inductance of the coil and C the capacity of the antenna.

Now, knowing the capacity of the antenna we may use the wave length of the antenna alone and compute the antenna inductance from the same equation. λ is now the wave length of the antenna alone, L is the inductance of the antenna and C the capacity of the antenna. In these calculations L is in microhenries and C in microfarads.

The capacity of an antenna can also be measured by the bridge method (Section 165). The antenna and ground are connected in the bridge as if they were the two plates of a condenser (Fig. 220). If the wave length of the antenna has been measured by the method given above and the capacity measured by the bridge method, the inductance can be computed by means of the wave length equation.

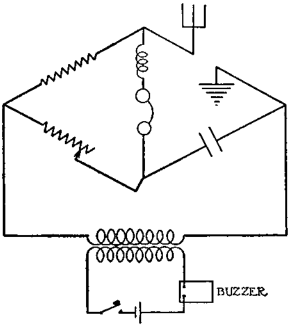

Fig. 220. — Measuring Inductance and Capacity of an Antenna

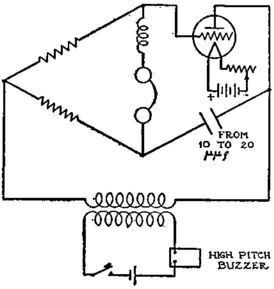

Fig. 221. — Measuring Capacity of an Electron Tube

176. Measuring the Capacity of an Electron Tube. — When high frequency oscillations are acting on a tube the plate and grid act like the plates of a small condenser so that oscillations may pass through the tube either from grid to plate or from plate to grid in the same way as through any condenser. The capacity between plate and grid may be measured by the bridge method (Section 165) in the same way as the capacity of a small condenser (Fig. 221). The capacity between plate and filament and between grid and filament may be measured in the same way. The filament battery should be connected and the tests made both with the filament cold and hot.

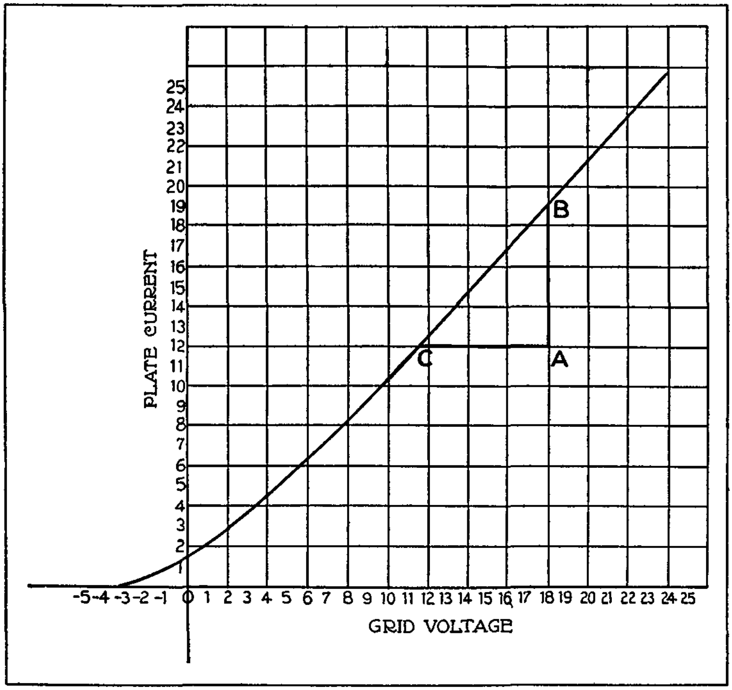

Fig. 222. — Graph for Mutual Conductance of a Tube

177. Other Tube Tests. — A number of tests of electron tubes have been given in Chapter V. There are other tests that are of value in determining the merits of a tube. One of the most important characteristics of a tube is its mutual conductance. Mutual conductance is change in plate current divided by change in grid voltage.

The mutual conductance of a tube can be readily found if the curve for grid voltage plate current has been plotted (Section 38). Using the straight line portion of the curve draw vertical and horizontal lines as in Fig. 222. AB represents the change in plate current caused by a change in grid voltage AC. Dividing AB by AC gives the mutual conductance of the tube.

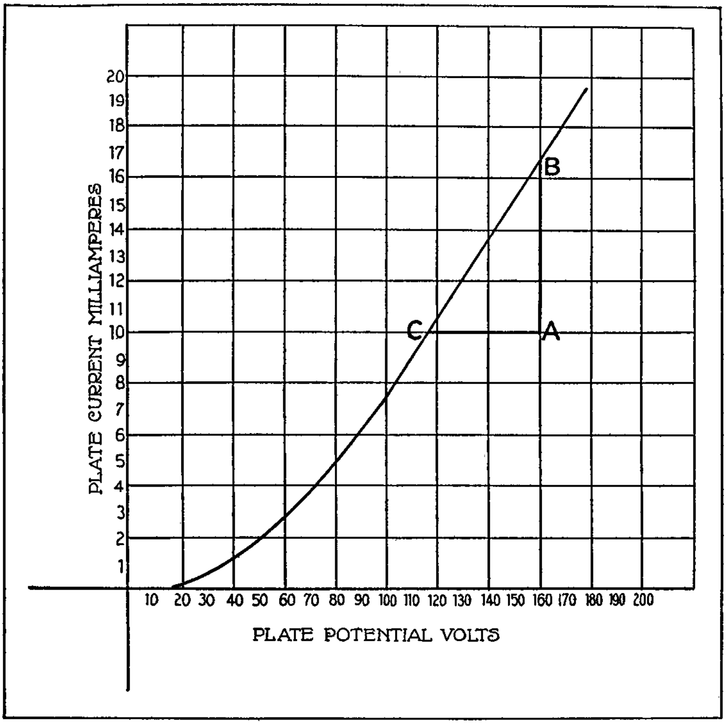

Fig. 223. — Graph for Plate Conductance and Plate Resistance

The plate conductance of a tube with respect to plate voltage plate current can be found from the plate voltage plate current curve (Section 37). In Fig. 223 AB is the change in plate current caused by a change AC in plate voltage. Conductance equals change in current divided by change in voltage or AB divided by AC. The plate resistance of the tube is the reciprocal of plate conductance. Plate resistance, therefore, equals AC divided by AB.

178. Bridge Method of Testing Tubes.—A circuit for measuring the amplification constant of a tube known as the Miller bridge is shown in Fig. 224. R_2 is a fixed resistance of from 10 to 100 ohms. R_1 is a variable resistance, preferably a decade resistance box. It is clear that the circuit is arranged so that opposite potentials are applied to grid and plate. For example, when the generator is making the point A positive it is making the point B negative. The resistance R_1 is adjusted until the sound in the phone is as faint as possible. The voltage applied to the plate is, then, just balancing the voltage applied to the grid. When this is the case the ratio of plate voltage to grid voltage is the amplification constant. But these voltages are directly proportional to the resistances. We have, then, amplification constant equals R_1 divided by R_2

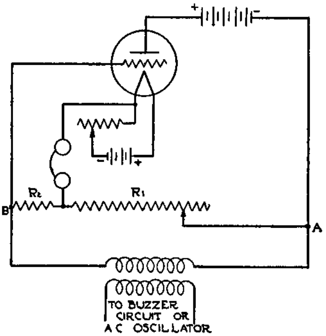

Fig. 224.—The Miller Bridge

$$\mu = \frac{R_1}{R_2}.$$

The plate resistance may be found by means of a Wheatstone bridge using for the source of current a buzzer wavemeter, or better, a driver having buzzer modulation. The circuit is shown in Fig. 225. R_2 and R_3 are the ratio arms of the bridge. Suitable values would be $R_2 = 1000$ ohms, $R_3 = 100$ ohms. R_1

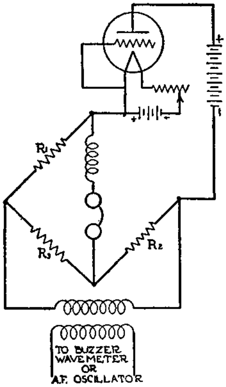

Fig. 225. — Wheatstone Bridge Method of Finding Plate Resistance

is an adjustable resistance preferably of the dial form. R_1 is adjusted until the sound in the phone is a minimum. Then the plate resistance r_p is found from the proportion

$$\frac{r_p}{R_1} = \frac{R_2}{R_3}.$$

Since alternating current is used the batteries in the circuit have no effect on the operation of the bridge.

179. Voltage Ratio of a Transformer.[3] — The circuit for this test is shown in Fig. 226. The buzzer circuit is coupled to the testing circuit by means of the transformer which may be simply a telephone induction coil. The transformer, T, to be tested is connected with the secondary reversed. C_1 and C_2 should be calibrated variable condensers. The condensers are adjusted until the sound in the telephone receiver is a minimum. Then if n_2 is the number of turns on the secondary and n_1 the number of turns on the primary, we have the equation,

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[3] This experiment is due to Professor R. R. Ramsey, University of Indiana.

$$\frac{n_2}{n_1} = \frac{C_1}{C_2}.$$

This ratio is the voltage amplification of the transformer.

It would be an interesting exercise for the experimenter to work out the explanation of this equation. It is an application of the principles of induced currents.

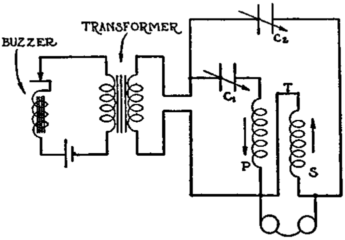


Fig. 226. — Finding the Voltage Ratio of a Transformer

180. Audibility of a Signal. — It is of interest to compare the audibility of signals from different stations with the same receiving set. This is done by connecting a variable resistance in parallel with the phone. A potentiometer connected as a rheostat could be used (Fig. 227). The resistance is then adjusted until the limit of audibility is reached, that is, until the signal is as faint as possible to be heard. The law of parallel currents is then applied. If I is the total current, I_t the current through the phone, s the impedance of the shunt for the frequency of the signals and z the impedance of the phone, then

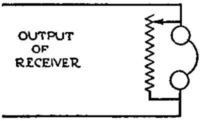


Fig. 227. — Measuring the Audibility of a Signal

$$\frac{I}{I_t} = \frac{s+z}{s}.$$

The quantity $\frac{s+z}{s}$ is called the audibility. For a rough approximation resistances may be taken in place of impedances.

The sensitiveness of two phones may be compared by connecting the phones in series in the same receiving circuit with a shunt resistance across each and adjusting each resistance for a minimum sound. Then if I_1 is the current through the first phone, R_1 the resistance of the first phone and S_1 the resistance of its shunt, and I_2, R_2, S_2 are the corresponding quantities for the second phone, I the total current, then from the laws of parallel circuits we have,

$$I_1 = I\frac{S_1}{S_1 + R_1}$$

$$I_2 = I\frac{S_2}{S_2 + R_2}.$$

The greater the sensitiveness of a phone the smaller the current it will detect. Therefore the sensitiveness of the two phones is inversely proportional to the currents, I_1 and I_2.

$$\frac{\text{Sensitiveness of first phone}}{\text{sensitiveness of second phone}} = \frac{I_2}{I_1} = \frac{S_2}{S_2 + R_2} \cdot \frac{S_1 + R_1}{S_1}.$$

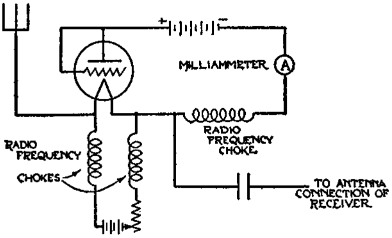


Fig. 228. — Measuring Very Small Radio Frequency Currents

181. Measuring Very Small Radio Frequency Currents. — An electron tube can be used to measure very small currents of radio frequency such as the currents produced in an antenna by an oscillating receiver. The circuit is shown in Fig. 228. It will be noticed that the current to be measured flows through the filament of the tube. The effect is to increase the plate current, for the heating effect of an alternating or oscillating current is the same as that of a direct current. The plate current is read from the milliammeter before and after connecting in the current to be measured. Then, from a filament current plate current graph for the tube used, the increase in filament current can be found.

182. Constructing a Coil Having a Specified Inductance.—It is often important in radio work to make a coil having a certain inductance and to do this with as little guess work as possible. The inductance at high frequencies varies somewhat with frequency on account of skin effect. This variation is small however. The effective inductance at high frequencies also depends to some extent on the distributed capacity of the coil which in general cannot be calculated.

For a single layer coil the following formula can be used to determine approximately the diameter, number of turns and length of coil for a specified inductance.

$$L = \frac{0.03948\ a^2n^2}{b} K.$$

In this formula a is the radius of the coil, n is the number of turns, b the length and K a number by which the fraction must be multiplied. K is found from the table given below. The first column gives the ratio of diameter to length, the second column the value of K. The first value given is for a coil in which the diameter equals one-fourth the length. The last is for a coil whose diameter equals three times the length. In using the formula the radius and length of the coil must be in centimeters. If measured in inches, multiply by 2.54 to reduce to centimeters. The formula is known as Nagaoka's formula. In making a coil by this formula a good method is to choose first the diameter of coil desired, then work out the number of turns and length to give the desired inductance. Length, of course, will depend on size of wire chosen.

183. The Vacuum Tube Voltmeter.—An electron tube can be used to measure either direct voltage or alternating voltage of any frequency. It takes no current and therefore does not change the voltage drop which it measures. A simple form of

Diameter/Length	*K*	Diameter/Length	*K*
0.25	0.9016	1.50	0.5950
.30	.8838	1.55	.5871
.35	.8665	1.60	.5795
.40	.8499	1.65	.5721
.45	.8337	1.70	.5649
0.50	0.8181	1.75	0.5579
.55	.8031	1.80	.5511
.60	.7885	1.85	.5444
.65	.7745	1.90	.5379
.70	.7609	1.95	.5316
0.75	0.7478	2.00	0.5255
.80	.7351	2.10	.5137
.85	.7228	2.20	.5025
.90	.7110	2.30	.4918
.95	.6995	2.40	.4816
1.00	0.6884	2.50	0.4719
1.05	.6777	2.60	.4626
1.10	.6673	2.70	.4537
1.15	.6573	2.80	.4452
1.20	.6475	2.90	.4370
1.25	0.6381	3.00	0.4292
1.30	.6290		
1.35	.6201		
1.40	.6115		
1.45	.6031		

vacuum tube voltmeter is shown in Fig. 229. The milliammeter should have a full scale reading of not more than 1½ milliamperes. The plate voltage should be low, say 22½ volts. The grid voltage should be adjusted so that the reading of the milliammeter is nearly zero, say one tenth milliampere. The tube is then operating at the lower bend of its characteristic curve. Any direct voltage applied across terminals 1 and 2, 1 being the positive terminal, causes an increase in plate current. A number of readings should be taken applying known voltages and a graph plotted, the abscissas or divisions on the x axis indicating milliammeter readings and the ordinates or divisions on the y axis indicating applied voltage. This graph can be used with the vacuum tube voltmeter in measuring unknown voltages. Taking the readings with known voltages and plotting a graph from these readings is called calibrating the voltmeter. Even without calibrating, the voltmeter can be used for comparing unknown voltages. If an alternating voltage is applied across terminals 1 and 2, the increase in plate current is proportional to the highest voltage in a cycle or the peak voltage. In using the vacuum tube voltmeter, therefore, for measuring alternating voltage, one finds the peak or maximum and not the effective voltage.

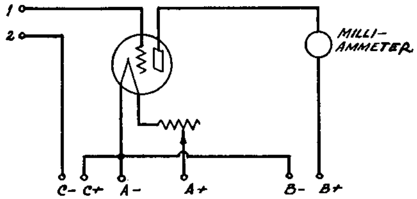


Fig. 229.—A Simple Form of Vacuum Tube Voltmeter

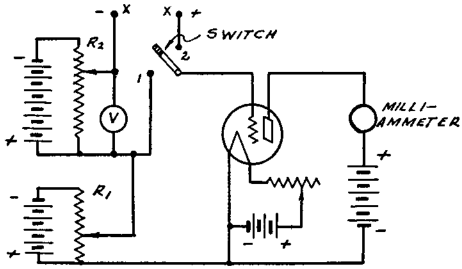


Fig. 230.—A Vacuum Tube Voltmeter for Low Voltages

Some special forms of vacuum tube voltmeter are given in the following figures. Fig. 230 is for low voltages. The unknown voltage is connected across x— and x+ . Switch S is put on point 1 and sliding contact R_1 moved slowly until the milliammeter just drops to zero. The switch is then put on point 2 and sliding contact R_2 moved slowly until the milliammeter again just drops to zero. Then the unknown voltage is equal to that indicated by the voltmeter V. For measuring high voltages it is well to make use of the amplification factor of the tube. A small negative voltage on the grid prevents a much larger voltage on the plate from causing a current to flow through the tube. The amplification factor can be found as explained in Section 39. Then the voltage to be measured is connected across plate and filament. If the voltage is alternating it will not matter which terminal is connected to the plate. If the voltage is direct, of course the positive terminal must be connected to the plate. The plate current is then reduced to zero by applying the necessary negative voltage to the grid. The unknown voltage is then found by multiplying the negative grid voltage by the amplification factor of the tube. The circuit is given in Fig. 231.

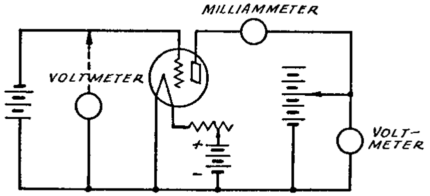


Fig. 231. — A Vacuum Tube Voltmeter for High Voltages

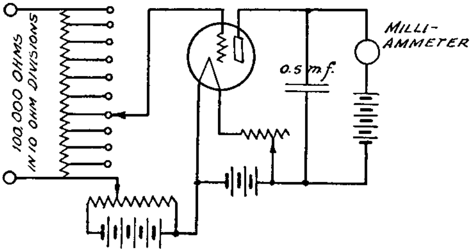


Fig. 232. — Another Form of Vacuum Tube Voltmeter for High Voltages

Another form of vacuum tube voltmeter for high voltages is given in Fig. 232. The unknown voltage is connected across the 100,000 ohm resistance. Call this voltage E. The grid is connected by a clip to one of the taps on the 100,000 ohm resistance. Call the part of this resistance which is in the grid circuit r. Then the voltmeter is operated by adjusting the potentiometer which is connected across the grid battery to reduce the plate current to zero. Then the voltage across r equals the voltage between the movable contact of the potentiometer and the positive terminal of the grid battery. Call this voltage e. Then the unknown voltage, E, can be found from the equation,

$$E = \frac{100{,}000\ e}{r}.$$

APPENDIX

Equations for Resistances in Parallel

If the filaments of three radio tubes are connected in parallel as in Fig. 33, we can find their combined resistance as follows: Let E be the voltage across the bus wires, i_1, i_2, i_3, the currents in the three tubes respectively, r_1, r_2, r_3, the resistances of the three filaments each taken with its rheostat. From Ohm's law we have the equation,

$$i_1 = \frac{E}{r_1},$$

$$i_2 = \frac{E}{r_2},$$

$$i_3 = \frac{E}{r_3},$$

If we let I stand for the total current delivered by the battery and R the combined resistance of all the tubes, we have

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

The total current is the sum of the currents in the three filaments. Therefore,

$$I = i_1 + i_2 + i_3.$$

Substituting the values of the different currents from the equations given above, we have

$$\frac{E}{R} = \frac{E}{r_1} + \frac{E}{r_2} + \frac{E}{r_3}.$$

E is the same in every term of the equation. We may, therefore, divide both sides by E and obtain the equation,

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}.$$

The quantity $\frac{1}{R}$ is called the conductance. It is the reciprocal of the resistance. This gives us the principle that the conductance of a parallel circuit is the sum of the separate conductances. If we have only two conductors in parallel the equation is

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2}.$$

Adding the fractions on the right we get

$$\frac{1}{R} = \frac{r_1 + r_2}{r_1 r_2}.$$

If two fractions are equal their reciprocals are equal, therefore,

$$R = \frac{r_1 r_2}{r_1 + r_2}.$$

Stated in words, if two resistances are connected in parallel, their combined resistance is their product divided by their sum.

Condenser Equations

The capacity of a condenser in farads equals the charge in coulombs divided by the e.m.f. in volts,

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

From this we get $$E = \frac{Q}{C}.$$

If we have two condensers in series (Fig. 85) the voltage across the line equals the sum of the voltages across the condensers.

$$E = E_1 + E_2.$$

If Q is the charge that flows into the two condensers when the voltage rises from zero to the value E then Q is also the charge that flows into each condenser just as in any series circuit the current that flows through any one conductor is the same as the current through the whole circuit.

For the first condenser we have

$$E_1 = \frac{Q}{C_1}.$$

For the second we have

$$E_2 = \frac{Q}{C_2}.$$

For the two condensers together we have

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

C being the combined capacity of the two condensers.

Adding the values of E_1 and E_2 we get,

$$E = \frac{Q}{C} = \frac{Q}{C_1} + \frac{Q}{C_2}.$$

Dividing by Q we get

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

Solving for C we get

$$C = \frac{C_1 C_2}{C_1 + C_2}.$$

This is an equation of the same form as that for resistances in parallel.

Useful Formulas

I. *Ohm's Law*

$$I = \frac{E}{R}, \qquad E = IR, \qquad R = \frac{E}{I}.$$

II. *Resistance of a Conductor*

$$R = K\frac{l}{d^2}.$$

R = resistance in ohms, l = length in feet, d = diameter in mils, K = the resistance of one mil-foot of the wire or other conductor. One mil is one thousandth of an inch. One mil-foot of wire is one thousandth of an inch in diameter and one foot in length. d^2 is the area in circular mils. A circular mil is a circle having a diameter of one mil.

III. *Series Resistances*

$$R = r_1 + r_2 + r_3.$$

IV. *Parallel Resistances*

$$R = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}}.$$

V. *Inductive Reactance*

$$X_L = 2\pi fL.$$

X = reactance in ohms; f = frequency in cycles per second; L = inductance in henrys.

VI. *Capacitive Reactance*

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

X_C = reactance on ohms; C = capacity in farads; f = frequency.

VII. *Total Reactance*

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

VIII. *Impedance*

$$Z^2 = X^2 + R^2 \text{ or } Z = \sqrt{X^2 + R^2}.$$

Z = impedance in ohms; X = total reactance; R = resistance;

IX. *Ohm's Law for Alternating Currents*

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

I = effective current in amperes; E = effective e.m.f. in volts; Z = impedance.

X. *Power in an a.c. Circuit*

$$P = EI \text{ cosine } \theta$$

P = power in watts; E = volts; I = amperes; θ = angle of lag

$$\text{Cosine } \theta = \frac{\text{resistance}}{\text{impedance}}.$$

XI. *Impedance of a Circuit having Resistance, Inductance and Capacity.*

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

XII. *Wave Length at Resonance*

$$\lambda = 1884\sqrt{LC}$$

λ = wave length in meters; L = inductance in microhenrys C = capacity in microfarads.

XIII. *Frequency at Resonance*

$$f = \frac{159{,}200}{\sqrt{LC}}$$

f = frequency. L = inductance in microhenrys;
C = capacity in microfarads.

XIV. *To Reduce Wave Length to Frequency or Frequency to Wave Length*

$$\lambda = \frac{300{,}000{,}000}{f}.$$

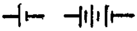
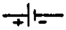
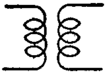
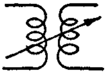
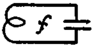
$$f = \frac{300{,}000{,}000}{\lambda}.$$

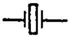
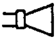
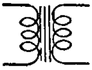
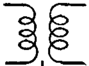
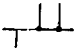
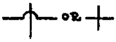
λ = wave length in meters. f = frequency in cycles per second.
300,000,000 = velocity of radio waves in meters per second.

To reduce to kilocycles divide frequency in cycles by 1,000.

For formulas for computing the inductance of coils of different forms, capacity of condensers with different dielectrics, and other formulas for radio circuits see Bureau of Standards Circular 74 which can be obtained from the Superintendent of Documents, Washington, D. C.

RADIO SYMBOLS

AMMETER	
ANTENNA OR AERIAL	
BATTERY	
BATTERY (POLARITY INDICATED)	
BUZZER	
COIL ANTENNA	
CONDENSER, FIXED	
CONDENSER, SHIELDED	
CONDENSER, VARIABLE	
CONDENSER, VARIABLE (WITH MOVING PLATE INDICATED)	
COUNTERPOISE	
COUPLER, INDUCTIVE (FIXED MUTUAL INDUCTANCE)	
COUPLER INDUCTIVE (WITH VARIABLE COUPLING)	
CRYSTAL DETECTOR	
FREQUENCY METER (WAVE METER)	
GROUND	
INDUCTOR	
INDUCTOR, IRON CORE	

INDUCTOR, VARIABLE	
INDUCTOR, ADJUSTABLE (BY TAPS OR STEPS)	
JACK	
KEY	
RESISTOR, FIXED	
RESISTOR, VARIABLE	
PIEZOELECTRIC CRYSTAL	
TELEPHONE RECEIVER	
LOUD SPEAKER	
TELEPHONE TRANSMITTER (MICROPHONE)	
THERMOELEMENT	
TRANSFORMER, IRON CORE	
TRANSFORMER, AIR CORE	
VACUUM TUBE, TRIODE	
VACUUM TUBE, DIODE	
VOLTMETER	
WIRES, JOINED	
WIRES, CROSSED NOT JOINED	

MATHEMATICAL RADIO SYMBOLS

Adopted by the Institute of Radio Engineers

Quantity	Symbol
Grid potential	E_g, e_g
Grid current	I_g, i_g
Grid conductance	$g_g = \frac{\text{Change in grid current}}{\text{Change in grid voltage}}$
Grid resistance	$r_g = \frac{1}{g_g}$
Grid bias voltage	E_c
Plate potential	E_p, e_p
Plate current	I_p, i_p
Plate conductance	$g_p = \frac{\text{Change in plate current}}{\text{Change in plate voltage}}$
Plate resistance	$r_p = \frac{1}{g_p}$
Plate supply voltage	E_b
Emission current	I_s
Mutual conductance	$g_m = \frac{\text{Change in plate current}}{\text{Change in grid voltage}}$
Amplification factor	$\mu = \frac{g_m}{g_p}$
Filament terminal voltage	E_f
Filament current	I_f
Filament supply voltage	E_a
Grid-plate capacity	C_{gp}
Grid-filament capacity	C_{gf}
Plate-filament capacity	C_{pf}
Grid capacity	$C_g = C_{gp} + C_{gf}$
Plate capacity	$C_p = C_{gp} + C_{pf}$
Filament capacity	$C_f = C_{gf} + C_{pf}$

THE CONTINENTAL CODE

Letter or Figure Symbol		Phonetic
A	.—	Dit darr
B	—...	Darr dit dit dit
C	—.—.	Darr dit darr dit
D	—..	Darr dit dit
E	.	Dit
F	..—.	Dit dit darr dit
G	——.	Darr darr dit
H	....	Dit dit dit dit
I	..	Dit dit
J	.———	Dit darr darr darr
K	—.—	Darr dit darr
L	.—..	Dit darr dit dit
M	——	Darr darr
N	—.	Darr dit
O	———	Darr darr darr
P	.——.	Dit darr darr dit
Q	——.—	Darr darr dit darr
R	.—.	Dit darr dit
S	...	Dit dit dit
T	—	Darr
U	..—	Dit dit darr
V	...—	Dit dit dit darr
W	.——	Dit darr darr
X	—..—	Darr dit dit darr
Y	—.——	Darr dit darr darr
Z	——..	Darr darr dit dit
1	.————	Dit darr darr darr darr
2	..———	Dit dit darr darr darr
3	...——	Dit dit dit darr darr
4	....—	Dit dit dit dit darr

5	.....	Dit dit dit dit dit
6	—....	Darr dit dit dit dit
7	——...	Darr darr dit dit dit
8	———..	Darr darr darr dit dit
9	————.	Darr darr darr darr dit
0	—————	Darr darr darr darr darr
Period (.)	.. .. ..	Dit dit dit dit dit dit
Question (?)	..——..	Dit dit darr darr dit dit
Break (double dash) (=)	—...—	Darr dit dit dit darr
Exclamation (!)	——..——	Darr darr dit dit darr darr
Received (O.K.)	.—.	Dit darr dit
Bar Indicating Fraction (Oblique stroke)	—..—.	Darr dit dit darr dit
Wait	.—...	Dit darr dit dit dit
Comma (,)	.—.—.—	Dit darr dit darr dit darr
Colon (:)	———...	Darr darr darr dit dit dit
Semicolon (;)	—.—.—.	Darr dit darr dit darr dit
Quotes (" ")	.—..—.	Dit darr dit dit darr dit
Parenthesis ( )	—.——.—	Darr dit darr darr dit darr
Attention Call to precede every transmission	—.—.—	Darr dit darr dit darr

End of each message (cross)	. — . — .	Dit darr dit darr dit
Transmission finished (end of work)	. . . — . —	Dit dit dit darr dit darr
Invitation to transmit (go ahead)	— . —	Darr dit darr

* * *

A dash is equal to three dots.

The space between parts of the same letter is equal to one dot.

The space between two letters is equal to three dots.

The space between two words is equal to five dots.

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