Theory
of
Radio Communication
by
John T. Filgate

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THEORY OF RADIO COMMUNICATION

By

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PREFACE

THIS elementary book on "Theory of Radio Communication" has been written as a text for students who are already familiar with the elementary principles of electricity and magnetism.

An effort has been made to present the principles of radio which must be known in order to intelligently operate radio sets and equipment, and also to give the student sufficient information relative to the modern trend of radio development to permit him to keep up with subsequent improvements in the science of radio communication. The use of mathematics has been avoided wherever possible.

The author wishes to acknowledge his indebtedness to Major George Van Deusen, Major Leland Stanford, and Captain Harry Reichelderfer for their criticisms of this text.

J. T. F.

FORT MONMOUTH, N. J.,
DECEMBER 10, 1928.

THEORY OF RADIO COMMUNICATION

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THEORY OF RADIO COMMUNICATION

SECTION I

GENERAL ASPECT OF RADIO COMMUNICATION

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1. **Introduction.**—Radio broadcasting has become a matter of such general interest that most everyone now has some elementary conception of this means of communication. The city dweller and those who live in remote rural districts are able to receive the programs of distant broadcasting stations without any wire connection between their receiving sets and the broadcasting apparatus. Broadcasting stations are authorized to transmit their programs on certain wavelengths, and by the simple expedient of turning a knob on a receiving set, the operator can listen to any one of several stations to the exclusion of others. Ground stations, moving airplanes, surface ships, and underwater submarines may communicate with each other by means of radio, although the stations thus communicating may be separated by thousands of miles.

These things are made possible by relatively new applications of fundamental principles of science. The student of physics and alternating current phenomena will have already acquired considerable information relative to radio communication.

2. Forms of Energy Transferred in Communication Systems.—In all systems of communication, signals are transmitted by the controlled transfer of energy from one station to another and the detection of that energy at the receiving station. For example, in wire telegraphy and telephony, intelligence is transmitted by means of the transfer of energy in the form of electric currents. In optical signalling systems energy is transferred in the form of light, and in acoustical systems energy is transferred in the form of sound. Radio communication is effected by the transfer of energy in the form of electromagnetic waves. This is also true of optical systems, since light is also a form of electromagnetic waves, except that light waves are of much shorter wavelengths than the electromagnetic waves utilized in radio.

3. Elementary Conception of Electromagnetic Waves.—Electromagnetic waves are simply periodic variations in the intensity of the electrostatic and magnetic fields existing at various points in any medium. The exact nature of electromagnetic waves is not agreed upon, but scientists in general have postulated the ether, which is a hypothetical substance said to permeate all matter, and pictured for us the variations in the electrostatic and magnetic fields existing within this substance.

Whatever may be the nature of electromagnetic waves we may form an elementary conception of them by considering their analogy to water waves. Everyone has seen the waves sent out on the surface of a smooth body of water by some disturbance, such as that caused by dropping a pebble into the water. There is, at first, a depression of the surface at the point of impact. This depression deepens until the restoring force exceeds the depressing force, and then it diminishes and the depressed surface moves upward in the direction of its normal level. Due to inertia, the water is carried beyond its normal level, until the restoring force exceeds that due to its momentum, and it then moves down again. This series of events recurs until the resulting up and down motion has been transferred to adjacent surface particles, and the energy imparted to the water by the impact of the pebble has been dissipated.

A large surface of water is soon brought into wave motion and crests and troughs are apparent over the disturbed area. A cross sectional view of the surface of a body of water so disturbed is shown in Fig. 1.

The distance between two successive crests or troughs is said to be the *wavelength* and the height of a crest above the normal surface level or the depth of a trough below the normal level is said to be the *amplitude* of the wave.

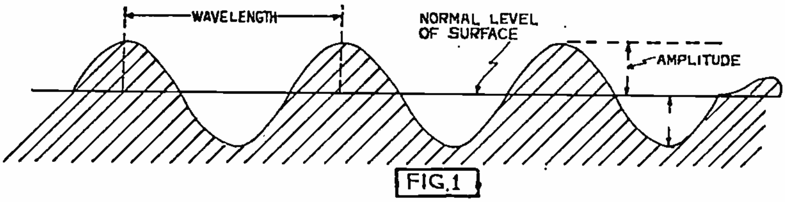

Fig. 1. Water Waves.

Electromagnetic waves might be regarded as similar disturbances in the ether, waves of this nature being deliberately created at the radio transmitting station and propagated in all directions through space.

4. Relationship Between Wavelength and Frequency.—The wavelength of an electromagnetic wave, being the distance between successive points of the same phase, represents the distance which the wave travels in one cycle. If the frequency, or the number of cycles per second, of the wave be multiplied by the wavelength, the product will represent the distance which the wave travels in one second: that is, the velocity of the wave. The wavelengths of electromagnetic waves are measured in meters, and are conventionally represented by the Greek letter lambda (λ). Representing frequency by f and velocity by V, we may write:

$$f\lambda = V \tag{1}$$

The velocity of electromagnetic waves varies from one medium to another, but in air or a vacuum it has been experimentally determined as three hundred million meters per second. These media are the ones with which we are generally concerned, and, therefore, we may substitute 300,000,000 or 3×10^8 for velocity in equation (1). We then have:

$$f\lambda = 3 \times 10^8 \tag{2}$$

An electromagnetic wave having a 300 meter wavelength.

therefore, has a frequency of one million cycles per second; or, since it is customary to express radio frequencies in kilocycles per second, a kilocycle being one thousand cycles, the 300 meter wave has a frequency of 1,000 kilocycles per second.

5. Forms of Electromagnetic Waves Used in Radio.—When a disturbance is created in the ether and an electromagnetic wave is set up, the amplitudes of successive cycles of the wave may all be equal. The wave is then said to be *undamped* or *continuous*. Such a wave is graphically represented in Fig. 2, in which A1 = A2 = A3 = A4 = A5, etc.

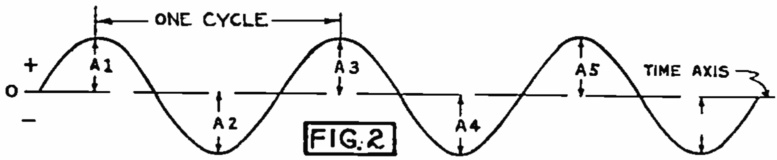

Fig. 2. Undamped or Continuous Wave.

It is also possible for the oscillations created by the disturbance to be gradually damped out, in which case the wave is said to be *damped*. A damped wave is graphically represented by the solid line in Fig. 3, from which it may be seen that each amplitude, beginning with A1, is smaller than the preceding ones.

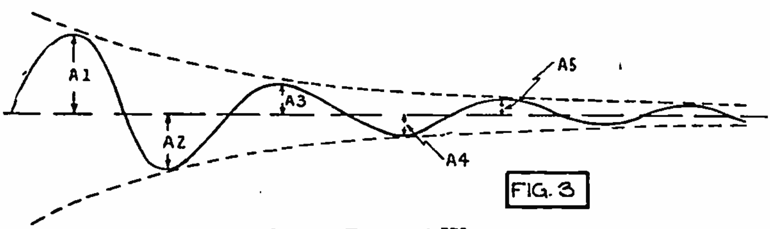

Fig. 3. Damped Wave.

Waves of both of these forms are used in radio telegraphy where signals are controlled by means of a key; and either a continuous wave or a damped wave is radiated from the transmitting station as long as the key is closed.

There is another form of wave which is used in radio telephony and in so-called *tone modulated radio telegraphy.* This wave is called an *audio-frequency modulated wave,* and consists of a high-frequency undamped wave, the successive amplitudes of which have been deliberately varied in accordance with some desired low-frequency wave form. Such a wave is shown in Fig. 4, in which the original undamped high-frequency wave is shown in (1), the audio-frequency wave is shown in (2), and the modulated wave is shown in (3).

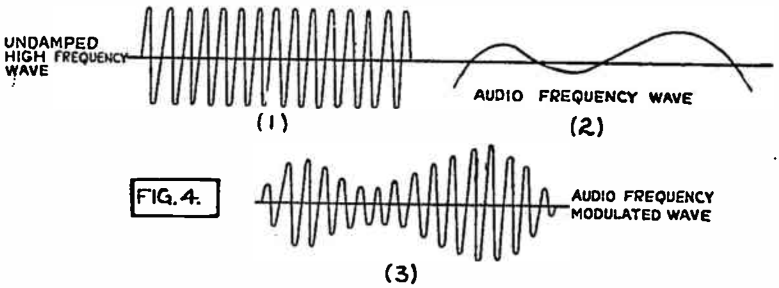

Fig. 4. Modulated Wave.

Under a given set of conditions, communication by means of continuous wave telegraphy can be carried on over greater distances than is possible with damped wave or tone modulated wave telegraphy or telephony; but, as we shall see later, the detection of continuous waves requires some form of high frequency generator at the receiving station, which is not required for the detection of other forms of electromagnetic waves. For purposes of general approximation it may be said that, if the transmitting range with continuous waves is one unit of distance, the transmitting range with damped or tone modulated waves is one-half unit, and with voice modulated waves used in radio telephony it is one-third of a unit.

6. **Decrement.**—There is another term, called *decrement,* which is applied to electromagnetic waves. Its significance can be shown best by the following discussion.

If smooth curves be drawn through successive maxima on the same side of the axis, as shown by the dotted lines in Fig. 3, these curves are said to be the envelopes of the oscillatory curve. These envelopes are logarithmic in form, as may be shown mathematically. It is also true that the ratios of any two successive amplitudes on the same side of the axis are equal, that is:

$$\frac{A1}{A3} = \frac{A2}{A4} = \frac{A3}{A5} = \frac{A4}{A6}, \text{ etc.}$$

The natural logarithm of this ratio is said to be the *decrement* of the wave, and is conventionally represented by the Greek letter small delta (δ).

Therefore:

$$\delta = \log_e \frac{A1}{A3} = \log_e \frac{A2}{A4}, \text{ etc.} = \log_e A_1 - \log_e A_3 \quad (3)$$

In the case of an undamped wave the decrement is zero, since the amplitudes are all equal to each other. That is, for an undamped or continuous wave:

$$A1 = A2 = A3 = A4 = A5, \text{ etc.,}$$

and

$$\delta = \log_e \frac{A1}{A3} = \log_e \frac{A1}{A1} = \log_e 1 = 0.$$

It follows, therefore, that a highly damped wave will have a relatively high decrement, and since such waves are undesirable in radio communication because they create undue interference, decrement is limited by law to a miximum of two-tenths.

Electromagnetic waves will be discussed in considerably more detail in a later section, but with this information and conception of them we may proceed with the consideration of systems of communication in which they are utilized.

7. **General Explanation of Radio Communication.**—In general, radio communication embraces the transmission and reception of signals by means of electromagnetic waves without the use of metallic connections between the transmitting and receiving stations. In all other forms of electrical communication signals are carried over conductors connecting the stations concerned, and to which the transmitting and receiving equipments are connected. In radio communication, however, no such connection is required, the natural non-conducting medium existing between the two stations being utilized for this purpose. This medium might be air, water, the crust of the earth, or the hypothetical ether.

Just as in all other forms of communication, we have in radio a transmitting station and a receiving station. The transmitting station must be capable of radiating energy in the form of electromagnetic waves, and the receiving station must be capable of intercepting this energy and converting it into some other form of energy to which one of the human senses is susceptible.

8. General Component Parts of Radio Transmitting and Receiving Stations.—Let us consider the general requirements of radio transmitting and receiving stations. If we desire to communicate from station A to station B by means of radio, we must have at the transmitting station the following equipment:

(1) A source of energy.
(2) A device for converting this available energy into the form of high-frequency currents.
(3) A device for radiating the energy possessed by these high-frequency currents into space, as electromagnetic waves.

The source of energy might be a storage battery, direct or alternating current mains, or a gas engine or any other source from which energy might be obtained. The device for converting the available energy into the form of high-frequency currents is known as a *high-frequency generator* or an *oscillator,* and the device for radiating the energy of these currents into space is known as an *antenna.*

The transmitting station must also be provided with a device for controlling the radiation, either by means of a key which makes and breaks a circuit, or by means of a *modulator* which varies the amplitudes of a high-frequency continuous current in accordance with some sound wave which it is desired to send out. Both modulator and key are sometimes used in the same transmitting circuit.

Having radiated this energy into space, it will be carried in all directions by the surrounding medium, and among others in the direction of reeciving station B.

At receiving station B we must have:

(1) A device for intercepting energy in space.
(2) A device for converting the intercepted energy into a form which will make its presence known to a receiving operator.

To intercept the energy in space we use an *antenna,* similar to that which is used at the transmitting station, and to convert the intercepted energy into a form which will manifest itself to a receiving operator, use is made of a device known as a *detector*.

The particular human sense normally utilized in radio reception is that of hearing, and while the function of so modifying the radio-frequency currents resulting from the interception of electromagnetic waves as to make them audible is performed by a detector, the signals usually received are too weak to be easily heard without additional energy being added to them at the receiving station. It is customary, therefore, to provide the receiving station with an additional device for making the incoming signals stronger, and this device is known as an *amplifier*.

The receiving station is sometimes provided with an auxiliary device, which in effect breaks up an incoming continuous wave into discontinuous or separately distinct groups of oscillations, or *wave trains*, as they are called. Such a device is known as a *heterodyne*. In the past, mechanical interrupters were sometimes used for this purpose at the receiving station, and for a similar purpose at the transmitting station.[1]

It appears, then, that the general components of a radio transmitting station and of a receiving station are as indicated below:

Transmitting station:
(1) Source of energy.
(2) Oscillator or high-frequency generator.
(3) Controlling device (*e.g.*, key or modulator, or both).
(4) Antenna.

Receiving station:
(1) Antenna.
(2) Detector.
(3) Amplifier.
(4) Heterodyne (in special cases).

Each of these components in their several forms will be covered in detail in later sections, the purpose of this section being to state in a general way what each of these components does, the detailed explanation of how they function being given later.

9. Selection.—Now let us consider the specific means by which a receiving station B may receive the waves emanating from the particular transmitting station A with which it is desired to

[1]Heterodyning and interrupting are similar in their general effects only.

communcate, to the exclusion of waves sent out from other transmitting stations. The antenna of receiving station B will intercept energy from all waves which sweep by it, and each wave will induce an electromotive force (EMF) in the antenna. The antenna is a part of an oscillatory circuit, that is, a circuit containing inductance, capacity and resistance in series. If either the inductance or capacity of this antenna circuit were varied, the opposition which the circuit would offer to currents of particular frequencies would be changed, and likewise, the frequency of resonance of the circuit. Other things being equal, the electromagnetic waves of the same frequency as the resonant frequency of the antenna circuit would cause the greatest current to flow in that circuit. By adjusting the inductance or capacity of the antenna circuit we could, therefore, vary its resonant frequency until it was equal to the frequency of the particular wave which we desired to receive. In other words, if the operator at station B desires to receive a particular wave of frequency f, he may select this wave from a number of others which sweep his antenna by adjusting the inductance or capacity of his antenna circuit until its frequency of resonance is equal to f. This ability of a receiving station to receive the waves of one particular frequency to the exclusion of those of other frequencies is called *selectivity,* and the operation of adjusting the inductance of capacity of an oscillatory circuit so as to change its frequency of resonance to some desired value is called *tuning.* A circuit which can be so adjusted is said to be a *tuned circuit.*

At the transmitting station the operator controls the frequency and wavelength of the energy which his set radiates in an exactly similar manner; that is, he adjusts the constants of his antenna and associated oscillatory circuits. It is by a combination of selective transmitting and receiving that two particular stations are enabled to communicate with each other with a minimum of interference from other stations; however, interference will be experienced from a second station transmitting on the same wavelength, or, from a high-powered transmitting station located near the receiving station and transmitting on a frequency which is anywhere near the fundamental or odd harmonic of the frequency of the transmitted signal that it is desired to receive.

Selection may also be aided by utilizing the directional effects of antennas, as will be explained later.

10. Importance of Alternating Current Phenomena.—It is apparent from the foregoing paragraphs that in radio communication we are particularly concerned with high-frequency currents and the circuits in which they flow. It is important, therefore, that the student of this subject should be thoroughly familiar with the phenomena of high-frequency currents and the characteristics of high-frequency circuits. The next section is accordingly devoted to this subject.

11. Summary:

1. Energy is transferred from the transmitting to the receiving station in all systems of communication.

2. Electromagnetic waves are periodic variations in the intensity of the electrostatic or electromagnetic fields at various points in any medium.

3. The wavelength of an electromagnetic wave is the distance between two successive points of the same phase.

4. The amplitude of a wave is its maximum instantaneous value during one cycle.

5. $f\lambda = 3 \times 10^8$. (λ being in meters.)

6. An undamped or continuous wave is one in which the amplitudes of successive cycles are equal.

7. A damped wave is one in which the successive amplitudes decrease.

8. An audio-frequency modulated wave is a continuous high-frequency wave, the successive amplitudes of which have been varied in accordance with some desired low-frequency wave form.

9. Continuous-wave telegraphy may be operated over greater distances than other forms of radio telegraphy or telephony, but its detection requires the use of a high-frequency generator at the receiving station.

10. The decrement of a wave is the difference between the natural logarithms of successive ordinates, or amplitudes, of corresponding phase; or in other words, decrement is the natural logarithm of the ratio of successive maximum ordinates of corresponding phase.

11. Radio communication embraces the transmission and reception of signals by means of electromagnetic waves of very high frequency without the use of conductors connecting the stations concerned.

12. The general components of a radio transmitting set are:
   1. Source of energy.
   2. Oscillator or high-frequency generator.
   3. Control device (e.g., key or modulator).
   4. Antenna.

13. The general components of a radio receiving set are:
1. Antenna.
2. Detector.
3. Amplifier.
4. Heterodyne (special cases).

14. The antenna radiates energy at the transmitting station and intercepts energy at the receiving station.

15. The oscillator or high-frequency generator converts the available energy into high-frequency currents.

16. The modulator so modifies the output of a high-frequency generator as to effect the transmission of sound waves using high-frequency waves as a carrier medium.

17. The detector is used to convert the intercepted energy into a form which is audible.

18. The amplifier is used to increase the intensity of intercepted signals.

19. Receiving sets which do not have a self-contained oscillator are incapable of receiving continuous waves without the use of an auxiliary high-frequency generator. This auxiliary high-frequency generator is known as a heterodyne.

20. Selective radio transmission is accomplished by adjusting the frequency of reasonance of the antenna and associated circuits by varying the inductance or capacity of these circuits.

21. If the reasonant frequency of a circuit can be adjusted, the circuit is said to be *tuned* and the adjusting operation is called *tuning*.

22. The ability of a receiving set to receive waves of one frequency to the exclusion of those of other frequencies is called *selectivity*.

12. Self-Examination:

1. Is it possible for an airplane to communicate with a submerged submarine by means of radio?

2. In what form is energy transmitted in each of the following systems of signalling:
1. Visual
2. Acoustical
3. Radio
4. Telephony?

3. With regard to electromagnetic waves, what is the significance of the following:
1. Wavelength
2. Amplitude
3. Damped waves
4. Continuous waves
5. Audio-frequency modulated waves?

4. What types of waves are used in the following and what is the relative transmitting distance of each:

1. Radio telegraphy
2. Radio telephony?

5. A 500-meter wave is being radiated from a certain broadcasting station. What is the frequency of the wave?

6. A receiving antenna is tuned to a frequency of 200 kilocycles. What is the wavelength of the wave to which it offers a minimum of opposition?

7. The maximum instantaneous value of an undamped wave during its first cycle is 5 units. What is its maximum instantaneous value during its third cycle?

8. Define decrement of an electromagnetic wave.

9. The decrement of an electromagnetic wave is .2 and the amplitude of its first half cycle is 100. What is the amplitude of its 9th half cycle?

10. Name the general component parts of a radio transmitting and receiving station.

11. What functions are performed by an antenna?

12. What is the general function of each of the following devices at a receiving station:

1. Detector
2. Amplifier
3. Heterodyne?

13. What is the general function of each of the following devices at a transmitting station:

1. Oscillator
2. Modulator?

14. What is meant by tuning an antenna circuit?

15. How is a tuned oscillatory circuit distinguished from an untuned one?

16. What is meant by selectivity of a receiving set?

17. What is the most important means by which selection is accomplished in radio communication?

SECTION II.

PHENOMENA OF HIGH-FREQUENCY CURRENTS AND CHARACTERISTICS OF OSCILLATORY CIRCUITS

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13. Bands of Frequencies.—In electrical power work the currents are of frequencies between twenty-five and sixty cycles per second, although sixty-cycle currents are nearly universal in the United States. Currents of much higher frequencies than these are utilized in communication. For example, the line currents resulting from an ordinary telephone conversation are of frequencies between 100 and 3,000 cycles per second, and those which result from the transmission of orchestral programs over telephone lines vary from 16 to 20,000 cycles per second.

The human ear is susceptible to sound waves which are of frequencies from 16 to 20,000 cycles per second, and, therefore, frequencies lying within this range are called *audio frequencies.*

In radio circuits, currents are employed which are of frequencies above the audio range. These frequencies vary from 20,000 to 300,000,000 cycles per second and are known as *radio frequencies.* Frequencies in the lower part of this band, that is from 20,000 to about 75,000 cycles per second, are sometimes referred to as *intermediate radio frequencies*. In radio communication we are most interested in currents of radio frequencies, although we are also concerned with audio and power frequency currents and with direct currents.

14. Effects of Radio-Frequency Currents.—The effects of radio-frequency currents are the same as those of currents of other kinds, that is, heating, magnetic, chemical, and physiological. However, many electrical devices designed to utilize these effects in direct or low-frequency circuits are either inoperative or inaccurate when high-frequency currents flow through them. The telephone receiver, for example, is capable of effecting a displacement of its diaphragm, which corresponds to variations in the instantaneous value of the current through its windings, provided this current is of audio frequency. When the frequency of the current through the receiver lies within the radio band, the receiver diaphragm is unable to respond to the rapid changes in current, because of the mechanical inertia of the diaphragm, which is relatively inconsequental at low frequencies but renders the device inoperative at high frequencies. Electrical measuring instruments ordinarily used in measuring low-frequency currents are unsuitable for measuring high-frequency currents without recalibration or rearrangement of their component parts. These inaccuracies are due to the increased relative importance of self inductance and capacity and to the fact that resistance, which is practically a constant at low frequencies, is variable at high frequencies. This will be explained later.

In measuring radio-frequency currents, instruments of the hot-wire type are most generally used.

15. Relation Between Current, Voltage and Impedance in Alternating Current Series Circuits.—The well-known fundamental laws of low-frequency alternating-current series circuits hold for similar circuits in which radio-frequency currents flow, and because of the great importance of these laws they will be briefly reviewed.

In a series circuit such as shown in Fig. 5, containing resistance, inductance and capacity, upon which an alternating electromotive force is impressed, the effective value of the current is equal to the effective value of the impressed voltage divided by the impedance of the circuit.

That is: $I = \frac{E}{Z}$ (4)

Where I is expressed in amperes:
E in volts, and
Z in ohms.

The impedance in this case is made up of the three components, resistance (R), inductive reactance (X_L), and capacitive reactance (X_C), which are in the same relative phase relationship for both high and low frequency currents; that is, the two reactive components are 180° out of phase with each other, and each of them is 90° out of phase with the resistance. The total reactance (X) of the circuit is the algebraic sum of the inductive and capacitive reactances, the inductive reactance being considered as positive and the capacitive reactance as negative. That is:

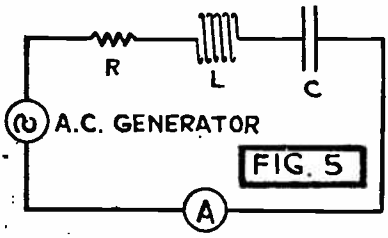

FIG. 5

Fig. 5. Series A.C. Circuit—Fixed C, L, and R.

$$X = X_L - X_C \quad (5)$$

Since the reactance and resistance of the circuit are 90 degrees out of phase with each other, their vector sum may be obtained by application of the geometric theorem which states that the hypotenuse of a right triangle is equal to the square root of the sum of the squares of the other two sides. The vector sum of R and X is the circuit impedance, therefore:

$$Z = \sqrt{R^2 + X^2} \quad (6)$$

The inductive reactance (X_L) of a circuit is expressed in ohms and is equal to the product of the self inductance in henries, the frequency of the impressed voltage and the constant 2π. This expression 2π represents $2 \times \omega$ constant 3.1416, called pi, and represented by the Greek letter symbol π. That is:

$$X_L = 2\pi f L \quad (7)$$

The quantity $2\pi f$ is often represented by the Greek letter omega (ω).

Equation (7) then becomes: $X_L = \omega L$ (7a)

The reactance of a coil having an inductance of 500 microhenries is shown in curve A, Fig. 6, for various frequencies of the impressed voltage ranging from 50 to 300 kilocycles.

The capacitive reactance of a circuit is also expressed in ohms and is equal to the reciprocal of the product of the capacity in farads, the frequency of the impressed voltage, and the constant 2π. That is:

$$X_C = \frac{1}{2\pi f C} \qquad (8)$$

or

$$X_C = \frac{1}{\omega C} \qquad (8a)$$

The capacitive reactance of a condenser having a capacity of .005 microfarads, for various frequencies of the impressed voltage, is shown in curve B, Fig. 6. This curve (B) is shown below, the zero axis to indicate that capacitive reactance is opposite to inductive reactance, the curve (A) of which is shown above the axis.

The algebraic sum of inductive reactance and capacitive reactance in any case is the total reactance of the circuit. With a series circuit consisting of an inductance of 500 microhenries and a condenser of .005 microfarads, the total circuit reactance is graphically represented by curve C, Fig. 6.

In the series circuit shown in Fig. 5 the current and voltage are not necessarily in phase with each other, since the counter electromotive forces (EMF's) of the reactive components of

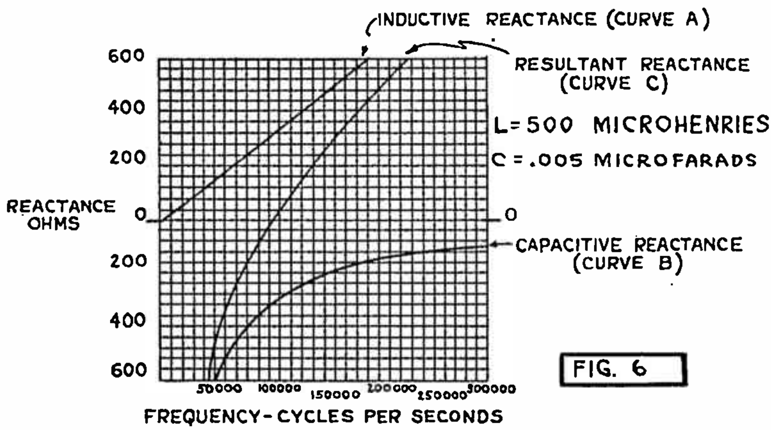

Fig. 6. Variation of Reactance with Frequency.

the circuit are 180° out of phase with each other, and each is 90° out of phase with the counter electromotive forces (EMF's) due to resistance. This angular difference in phase between the current and the impressed voltage in a series circuit is known as the phase angle, or more specifically, as the angle of lead when the capacitive reactance is greater than the inductive reactance, and the angle of the lag when the capacitive reactance is less than the inductive reactance.

If this phase angle be represented by the Greek letter phi (φ), then φ is the angle whose tangent is the ratio of the total circuit reactance to the total resistance. That is:

$$\varphi = \tan^{-1} \frac{X}{R} \qquad (9)$$

If X is zero (that is, when $X_L = X_C$) the angle φ is zero, and the current and impressed voltage are in phase with each other.

16. **Resonance.**—Resonance in any circuit is the condition existing when the supply voltage is in phase with the supply current. Since, in a series circuit this condition obtains when X_L is equal to X_C, the frequency to which a given circuit is resonant may be easily computed. That is:

$$X_L = X_C$$

$$2\pi f L = \frac{1}{2\pi f C}$$

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

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (10)$$

From this we see that increasing either the inductance or capacity of a circuit decreases its frequency of resonance.

It is often desirable to refer to the *wavelength of resonance* of a circuit, by which is meant the wavelength corresponding to the resonant frequency of the circuit, the relationship between *wavelength of resonance* and *frequency of resonance* in a circuit being the same as that which exists between the wavelength and the frequency of electromagnetic waves. (See paragraph 4.)

If a series circuit contains a 500-microhenry coil and a .005-

microfarad condenser (the same constants as were used in the graphs in Fig. 6) the frequency of resonance may be determined as follows:

500 microhenry = .0005 henry = 5×10^{-4} henry.
.005 microfarads = .000,000,005 farad = 5×10^{-9} farad.

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{5 \times 10^{-4} \times 5 \times 10^{-9}}} = \frac{1}{2\pi \times 10^{-6} \times 5\sqrt{10^{-8}}}$$

$$= \frac{10^5\sqrt{10}}{\pi} = \frac{100000 \times 3.16}{3.14} = 100700,$$

or

f = 100,700 cycles, or 100.7 kilocycles.

This is also verified in the curves of Fig. 6, which shows that the total reactance of the circuit having this inductance and capacity is zero at a frequency of 100,700 cycles per second.

The wavelength of resonance in this case may be determined by substitution in formula (1), which expresses the relationship between frequency and wavelength. The wavelength of resonance in this case is:

$$\lambda = \frac{3 \times 10^8}{f} = \frac{3 \times 10^8}{1.007 \times 10^5} = \frac{3 \times 10^3}{1.007} = 2979.1$$

$= 2979.1$ meters.

If the resistance of a circuit is zero, as is the case when resonance exists, the impedance of the circuit is equal to its direct-current resistance. For this particular condition, therefore, the line current is equal to the impressed voltage divided by the resistance. Since resistance is the lowest possible value of impedance in a series circuit of variable reactance, it is obvious that the impedance is a minimum for a condition of resonance; and, therefore, with a given impressed voltage, the maximum current is obtained when the circuit is resonant to the impressed frequency.

17. **Tuning.**—An oscillatory circuit, that is, a circuit containing inductance, resistance, and capacity in series, may be brought into resonance with the impressed voltage in any one of three ways, as follows:

1. Varying the capacity.
2. Varying the inductance.
3. Varying the frequency of the impressed voltage.

Let us consider these possible methods of tuning a circuit, such as that shown in Fig. 7.

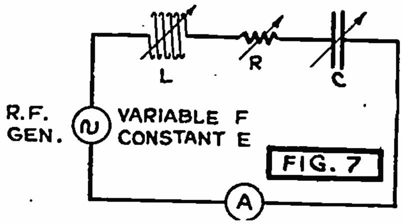

Fig. 7. Series A.C. Circuit: Variable C, L, and R.

Leaving *f*, L and R fixed and varying C progressively from its minimum to its maximum value, it is possible to change the line current, as indicated by the ammeter A, from some low value to a maximum value and back to the low value again. This is graphically represented by any one of the three curves in Fig. 8, which show the current squared for various values of capacity in a circuit containing an inductance of 377 microhenries, a resistance of 4.4 ohms, 9.4 ohms, and 14.4 ohms respectively, and in which the capacity is varied from 2,200 to 2,500 micro-microfarads.

Similar variations in current might have been effected by changing either the inductance of the circuit or the frequency of the impressed voltage, leaving the other variables fixed in either case. Curves could then be plotted showing the relationship between current squared and the variable component.

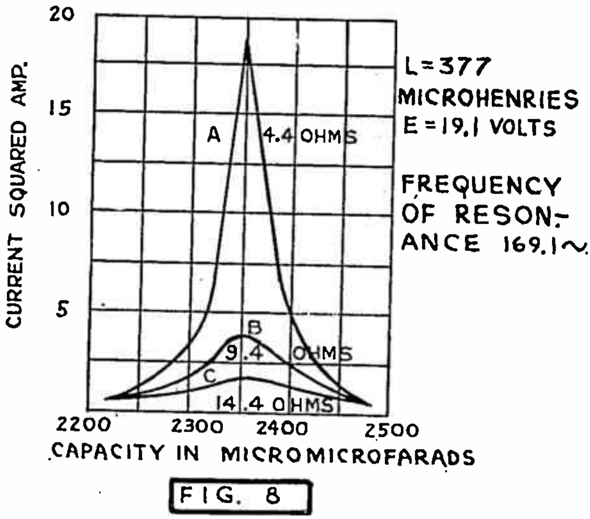

Fig. 8. Resonance Curves for Series Circuit with Different Resistances.

Inspection of these curves and of curves such as those shown in Fig. 8, when plotted to an open scale, indicate clearly that they are symmetrical only when resonance is accomplished by varying the inductance. When resonance is effected by varying the capacity the curve is unsymmetrical, since the current has not the same value for a capacity which is a given amount less than that of resonance as it has for a value of capacity which is the same amount greater than that of resonance. Likewise, the curve is unsymmetrical when resonance is produced by varying the frequency of the impressed voltage. On the other hand, the resonance curve is symmetrical when the inductance only is varied.

Obviously, symmetry of the resonance curve depends upon the existence of a linear relationship between the total circuit reactance and the variable by which resonance is accomplished. Inspection of the reactance curves shown in Fig. 6 indicates that this relationship is linear only when inductance is varied. Symmetrical resonance curves are obtained, therefore, when tuning is accomplished by varying the inductance, but not when either capacity or impressed frequency is varied.

The resonance curves shown in Fig. 8 also indicate two important effects of resistance. These are as follows:

1. The lower the resistance the greater the resonant current.
2. The lower the resistance the sharper the resonant curve, or in other words, the higher the resistance the flatter the resonance curves.

The sharpness of the resonance curve is very important, because it indicates the change in current brought about by a given change in the tuning variable from its value at resonance. For example, with a resistance of 14.4 ohms (curve C, Fig. 8), a change in current squared of about nine-tenths of a unit resulted from a change in capacity from its resonance value to 2,300 mmf. Curve A shows that the same change in capacity results in a change in current squared of about fifteen and four-tenths units when the resistance is 4.4 ohms. Sharper resonance is therefore obtained when the resistance is low.

18. Wavemeters.—We have seen in the preceding paragraphs that the current in a simple oscillatory circuit, which is resonant to the impressed frequency, is equal to the ratio of the impressed voltage to the resistance of the circuit. Obviously, a rather large current might result in a resonant circuit of very low resistance when only a small electromotive force is impressed upon it.

Suppose, for example, that we had a circuit NJKM (Fig. 9) through which a current of frequency *f* was flowing, and that a closed oscillatory circuit, EFGH, was held in such a position that a few of the magnetic lines of force due to alternating current flowing in coil (L_1) interlink with the coil (L_2). There would then be a small electromotive force of frequency *f* induced in circuit L_2.

The current which would flow in the circuit EFGH would depend upon the ratio of this voltage to the circuit impedance. By adjusting the capacity until this circuit is resonant to the impressed voltage, the impedance is reduced until it becomes equal to the resistance R. If R is small, the ratio of E to R might be large; that is, the current in the circuit EFGH might be large. The existence of resonance in the circuit EFGH is manifested by a maximum reading of the ammeter, as the condenser is varied through its possible settings. This ammeter might have been replaced by a small lamp, in which case the brilliancy of the filament would be the means of determining the relative values of current. Also it is possible to utilize a rectifying device (which will be explained later) and a telephone receiver to determine the relative current for various condenser settings.

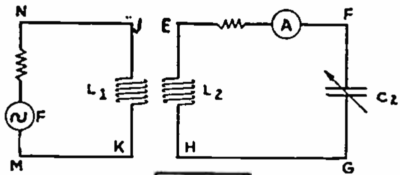

FIG. 9

Fig. 9. Showing Manner of Determining Resonance.

If the inductance of the coil L_2 and the value of the capacity for each of the possible settings be known, it is an easy matter to calibrate the condenser scale directly in frequencies, in which case the frequency of the impressed voltage could be determined by adjusting the condenser until a maximum current was indicated. Such a device would be called a *frequency meter*. If the condenser is calibrated in wavelengths instead of frequencies, the device would be called a *wavemeter*. Modern wavemeters are often calibrated in both wavelength and frequency, present day tendency being to use frequency.

Such a wavemeter could be used to measure the wavelength of an existing current; it could not, however, be used to determine the wavelength of resonance of a circuit in which no current was flowing. Practical forms of wavemeters are usually designed for both purposes.

The wavemeter shown in Fig. 9 could be made to perform both functions by the addition of a small battery, switch, and buzzer as shown in Fig. 10. With the switch open, the circuit is the same as the wavemeter part of Fig. 9 described above, and may be used to measure the wavelength of an existing current. With the switch closed, a circuit for direct current is provided from the positive terminal of the battery through the buzzer, the small resistance R and the inductance L back to the battery. There is also a momentary surge of current through the condenser C, which charges the condenser to the battery voltage.

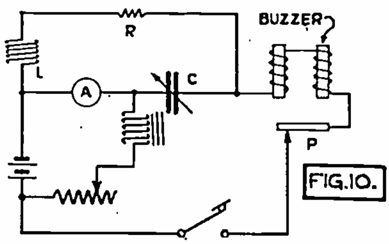

Fig. 10. Simple Wavemeter—Complete.

The direct current flowing through the buzzer windings energizes their cores and attracts the armature, breaking the circuit at the point P, thus de-energizing the buzzer magnets and allowing the armature to fall back and re-make the direct-current circuit. During the time that the direct current is interrupted the condenser C is free to discharge, and it does so, through the resistance R and the coil L. The constants of the circuit RLC are so selected that the discharge of this condenser is oscillatory and the frequency of these oscillations is practically the same as the frequency of resonance of the circuit LCR, which is indicated by the condenser setting. In other words, by associating the battery and buzzer with a simple oscillatory circuit, we have been able to convert the direct-current energy of the battery into energy in the form of alternating currents of any desired radio frequency, dependent on the values of the inductance L and the capacity C.

If now we had a second oscillatory circuit in which no current was flowing, and of which we desire to determine the frequency of resonance, this might be done by inserting in series with the circuit being measured a resonance indicating device (*e.g.*, an ammeter) and holding the wavemeter in such a relative position that an electromotive force will be induced in the circuit under test. By adjusting the wavemeter condenser until the current in the circuit under test is a maximum, the frequency of the circuit under test is then the same as the frequency of resonance of the wavemeter circuit. Thus, we see that a wavemeter may be used to measure either the wavelength of a current or of an oscillatory circuit.

19. **Decrement of Oscillatory Circuits.**—There is another property of oscillatory circuits which depends upon the circuit constants, and that is *decrement*. If the condenser of an oscillatory circuit is charged and then allowed to discharge through resistance and inductance, such as was done in the wavemeter described above, the oscillations will be damped out gradually as the energy originally stored in the condenser is dissipated in heat. The decrement of the current is the logarithmic ratio of instantaneous values of corresponding phases in successive cycles, just as was the case in electromagnetic waves. (See paragraph 6.) It can be shown mathematically that the decrement of this current depends upon the constants R, L, and C of the circuit and, for practical purposes, is given by the following:

$$\delta = \pi R \sqrt{\frac{C}{L}} \qquad (11)$$

where δ (delta) represents decrement.
Since this decrement is expressed in terms of the circuit constants, it is said to be the decrement of the circuit. An instrument designed to measure circuit decrements is known as a *decremeter*. It is a simple wavemeter, the decrement of which is known. Decrementers are not used extensively except in radio communication research laboratories.

20. **Distributed Capacity of Coils.**—A coil of wire wound in a helix, as shown in Fig. 11, is ordinarily regarded as pure inductance with a very small series resistance. However, it has electrostatic capacity between its various turns. The capacity between adjacent turns might be represented by the condensers shown in dotted lines in Fig. 11. Now let us suppose that a low-frequency electromotive force were impressed across this coil between A and J. All of the resulting current will flow through the conductor of this coil, the condensers offering such high op-

position to this current that practically none of it would pass through them. If, however, a high frequency electromotive force be impressed on the coil, the opposition offered by these condensers would be much less and some of the current would flow

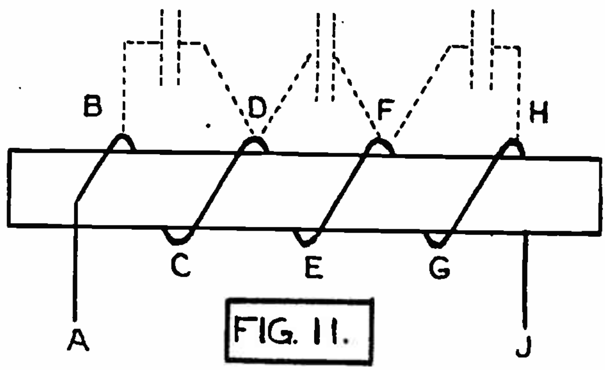

Fig. 11. Inductance Coil, Showing Distributed Capacity.

through them. It would be possible then for current to flow from B to D (Fig. 11) by passing through the conductor BCD or by passing through the condenser from B to D. At high frequencies, then, a coil may be considered as equivalent to inductance and capacity in parallel. This capacity is distributed between the various turns of the coil and is therefore said to be *distributed capacity*. The true inductance of the coil and its distributed capacity are fixed properties of the coil and independent of the current. However, it is obvious that the importance of distributed capacity varies with the frequency of the current. Since this is the case, a coil has a different effect at one frequency than at another. The inductance of a coil, as modified by its distributed capacity, is called the *apparent inductance* of the coil. This apparent inductance (La) depends upon the true inductance (L) the distributed capacity (C_o) and the frequency f. Let us investigate this relationship. Since a coil may be considered as pure inductance (L) and a capacity (C_o) (equal to the distributed capacity of the coil) connected in parallel, we may represent a circuit containing a generator and coil in series by Fig. 12(1). The current through the condenser is as follows:

$$I_C = \frac{E}{X_C} = \frac{E}{\frac{1}{\omega C_o}} = E\omega C_o.$$

The current through the inductance is as follows:

$$I_L = \frac{E}{X_L} = \frac{E}{\omega L}.$$

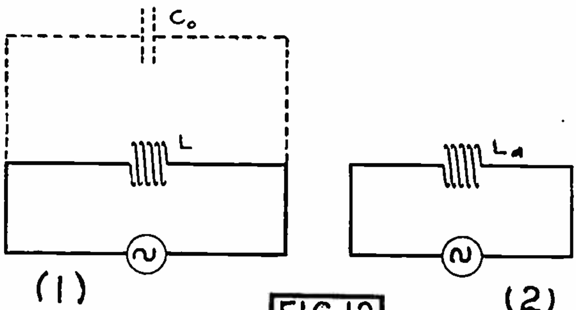

FIG. 12

Fig. 12(1). Series Connection of Generator and Coil Having Distributed Capacity.

Fig. 12(2). Equivalent Circuit with Coil Having Distributed Capacity.

Since C_o and L are in parallel, the total current is their vector sum, and since these currents are 180° out of phase their vector sum is equivalent to their algebraic sum. That is:

$$I = I_L - I_C = \frac{E}{\omega L} - E\omega C_o = E\left(\frac{I}{\omega L} - \omega C_o\right)$$

Obviously, this current is different from what it would have been had the coil with inductance L no distributed capacity. The inductance of the coil has therefore been effectively modified by the distributed capacity.

Let L_a represent the inductance of a coil having no distributed capacity which will allow the same current to flow in the circuit in which it is substituted for the coil just considered. Such a coil is shown in Fig. 12(2).

For this circuit:

$$I = \frac{E}{\omega L_a}$$

Since I and E in this case are the same as the corresponding quantities in the previous case, then:

$$\frac{1}{\frac{1}{\omega L} - \omega C_o} = \omega La$$

or

$$\omega La = \frac{\omega L}{1 - \omega^2 LC_o}$$

$$\therefore La = \frac{L}{I - \omega^2 LC_o} \qquad (12)$$

This expression shows us the way in which the apparent inductance of a coil varies with the true inductance, distributed capacity and frequency.

In the case of a variable inductance coil such as that shown in Fig. 13, only the portion of the coil between M and N is normally considered to be included in the circuit when the variable contact P is in the indicated position. The remaining turns of the coil are said to be *dead turns*. The distributed capacity of these dead turns, however, has the effect of completing the circuit through the condenser C, so that this part of the circuit draws current from the generator and reacts on the other portion of the circuit, effectively changing its impedance at any given frequency.

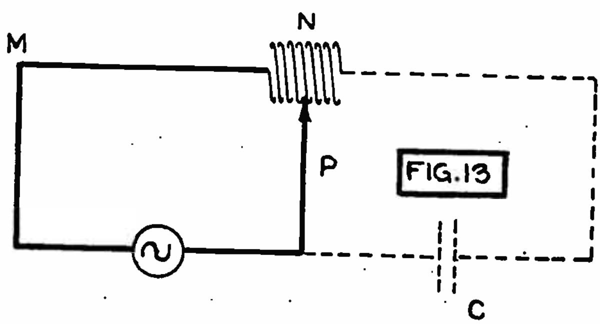

Fig. 13. Showing Effect of Dead Turns of Coil.

It is possible to wind coils in such a way as to minimize this distributed capacity. These constructional details will be covered in a later section.

21. Skin Effect, Apparent Resistance and Effective Resistance.—When a steady current flows through a conductor the distribution of current throughout the cross-section of the conductor is uniform. However, the magnetic flux due to this current is greater at the center portion of the conductor than at its outer regions. With a steady current flowing this fact is inconsequential, since it is only when we try to change a magnetic field that it offers opposition, this opposition being known as inductive reactance. We might reasonably consider a solid conductor, then, as being made up of a number of smaller conductors in parallel, these smaller conductors being of equal resistance but those in the center having greater inductance than those on the periphery. If we pass a steady current through such a conductor, an equal amount will flow through each of the small component conductors; but, if we pass an alternating current through the solid conductor, a greater amount will pass through the peripheral components of low inductance than through the center components of high inductance. Obviously, as the frequency of the alternating current increases, this tendency or the current to flow through the surface portions will increase. This is equivalent to reducing the effective cross sectional area of the conductor, or, to increasing its resistance.

This increase in the resistance of a conductor with the frequency of a current is called *skin effect,* the name suggesting that it is due to the tendency of the alternating current to flow through the surface or *skin* portions of the conductor.

In order to minimize the skin effect in conductors used for radio-frequency currents, these conductors are made with the largest possible surface area for a given volume and length, such as hollow tubing, or they are made of fine stranded wires which are woven together in such a way as to make the inductance uniform throughout the conductor and increase the surface area. The separate strands should be insulated from one another for best results.

In addition to the increase of resistance due to the skin effect of conductors, conductors wound in coils have increased resistance because of the winding. The total resistance of a coil, which consists of its D. C. ohmic resistance plus an increase due to skin effect and an increase due to winding, is called the apparent resistance of the coil. The apparent resistance of a coil depends upon the frequency of the current through the coil, the distributed capacity, the inductance and resistance of the coil, as shown by the following:

$$Ra = \frac{R}{(1 - \omega^2 LC_o)2} \qquad (13)$$

Where R is the true ohmic resistance of the coil and C_o the distributed capacity of the coil.

Since the resistance of a conductor varies with the frequency of the current, it is often convenient to refer to the *effective resistance* of a conductor, which is the ratio of the power dissipated by the conductor to the square of the effective value of the current flowing through it.

22. **Parallel Resonance and Filters.**—If an alternating electromotive force be impressed upon a circuit containing inductance and capacity in parallel, as shown in Fig. 14, we know from

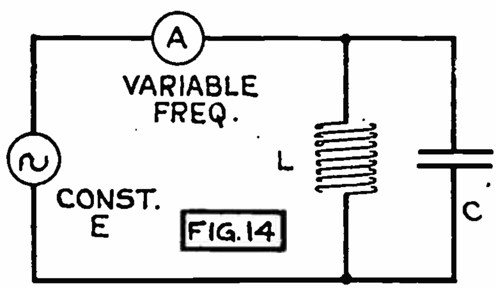

Fig. 14. Simple Parallel Circuit.

previous consideration that the line current, indicated by the ammeter A, will be zero when the circuit LC is resonant to the impressed voltage, and will increase as the frequency of the generator is varied on either side of the value corresponding to the resonant frequency of LC. Let us investigate this change in line current further by considering the changes in the circuit impedance to which the current is inversely proportional.

Obviously, the total impedance of this circuit is equal to the total reactance, since the circuit contains no resistance. We shall, therefore, consider the manner in which the total reactance of this circuit varies with the frequency of the impressed voltages. Remembering that the susceptance of any branch of a parallel circuit is the ratio of the reactance to the square of the impedance of that branch, it is apparent that in this case the susceptance of each branch is the reciprocal of the reactance of that branch. That is, representing susceptance by b:

$$b_L = \frac{1}{\omega L}$$

$$b_C = \frac{1}{\frac{1}{\omega C}} = \omega C \tag{14}$$

The susceptances b_L and b_C would, then, vary as shown in Fig. 15. The total susceptance is the algebraic sum of b_L and b_C.

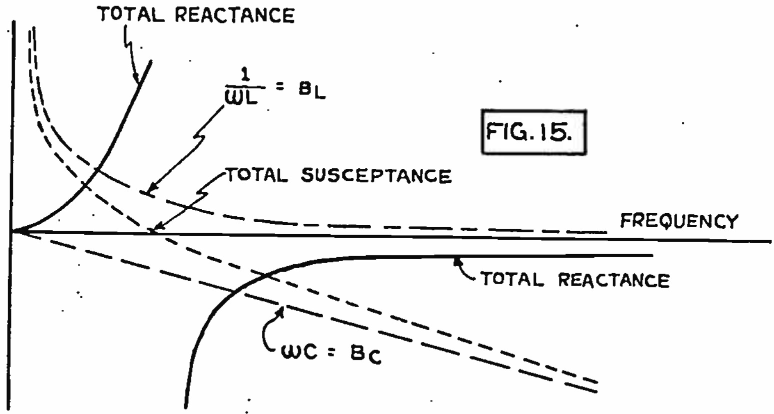

Fig. 15. Reactance and Susceptance Curves for L and C in Parallel.

We see that the total susceptance is infinite at zero frequency and also at infinite frequency, but that it is zero from some frequency between these two. This frequency is the natural frequency of the circuit LC, Fig. 14, that is, the susceptance is zero at a frequency equal to $\frac{1}{2\pi\sqrt{LC}}$. The total reactance of the circuit in this case is the reciprocal of the total susceptance. It therefore is zero when susceptance is infinite, and infinite when the susceptance is zero. The reactance curve of this circuit consequently has two branches, as shown in Fig. 15.

Representing as it does the total circuit impedance in this case, the reactance curve indicates that at a frequency equal to the natural frequency of the circuit LC, Fig. 14, the impedance of the entire circuit is infinite.

If, then, we desire to prevent currents of a certain frequency from flowing in a series circuit, it is only necessary to connect in series with the circuit a coil and condenser in parallel, the inductance and capacity of the coil and condenser being so selected that the natural frequency of the parallel circuit is equal to the frequency of the current which we desire to eliminate.

A combination of inductance and capacity in parallel, which offers infinite series impedance to currents of some particular fre-

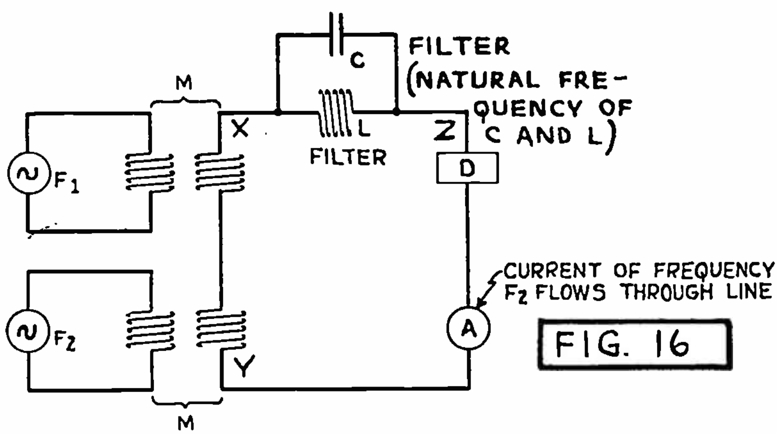

FIG. 16

Fig. 16. Showing Use of Simple Filter.

quency, constitutes a simple filter circuit. If the natural frequency of the filter shown in Fig. 16 is equal to f_1 and electromotive forces of frequencies f_1 and f_2 are induced in the circuit XYZ, only current of frequency f_2 will flow in this circuit. Such a filter serves to prevent currents of frequency f_1 from flowing through the device D, from which it is desired that currents of frequency f_1 be excluded.

In radio communication many different types of filters are used. These may be divided (in accordance with the kinds of current which they pass), into three general classes of: *low pass, high pass,* and *band pass* filters. A simple form of each of these types of filters is schematically shown in Fig. 17.

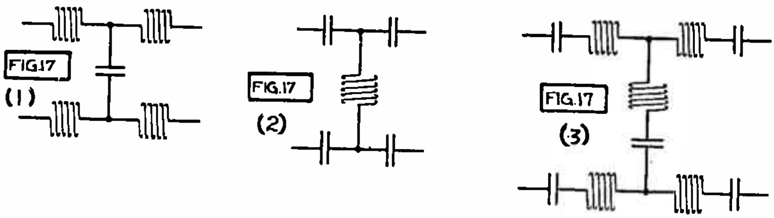

Fig. 17(1). Low Pass Filter. Fig. 17(2). High Pass Filter Fig. 17(3). Band Pass Filter.

The action of these filters is more complicated than that of the simple filter shown in Fig. 16, and depends upon the mutual reaction between coupled circuits.

23. **Free and Forced Oscillations.**—Before taking up coupled circuits, we will study free and forced oscillations. When a condenser is charged and thereafter allowed to discharge through resistance and inductance in series, the resulting current will be alternating if the resistance of the circuit is less than twice the square root of the ratio of the inductance to the capacity.

The frequency of these oscillations is given in terms of the circuit constants by the following expression:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \qquad (15)$$

This frequency is known as the *natural frequency* of the circuit, and may be distinguished from the frequency of resonance by its dependence on the circuit resistance. If the resistance of the circuit is low, resistance squared is negligible and the term $\frac{R^2}{4L^2}$ may be dropped from equation (15), which then becomes:

$$f_n = \frac{1}{2\pi\sqrt{LC}} \qquad (15a)$$

which is the same as the expression for frequency of resonance. In most practical cases in radio circuits the resistance is so small that *natural frequency* and *resonant frequency* are considered equal to each other.

When an oscillatory current is caused to flow through a series circuit by reason of the discharge of a condenser through resistance and inductance, as described above, the oscillations are said to be *free oscillations*. The frequency and decrement of these oscillations are the same as the natural frequency and decrement, respectively, of the circuit.

It is possible to impress on or induce in a series circuit an electromotive force of some frequency different from the natural frequency of the circuit. In such a case, the frequency and decrement of the resulting oscillations would be independent of the corresponding properties of the circuit, and the oscillations would be called *forced oscillations*.

24. **Coupled Circuits.**—In radio we are more frequently concerned with coupled circuits than simple oscillatory circuits. Coupled circuits will, therefore, be considered in detail. Two circuits are said to be coupled when they are so arranged that a change in current in one circuit produces a change in current in the other circuit. In other words, circuits are coupled when there is a transfer of energy from one circuit to the other. There are several ways in which circuits may be coupled, but in any of these there is always some component common to each circuit, or else each circuit is placed in the magnetic field of the other.

The three most important types of coupled circuits are shown in Fig. 18.

In Fig. 18(1) the first circuit consists of C_A, L_A, L_C, and R_A; and the second circuit consists of C_B, L_B, L_D, and R_B. The two

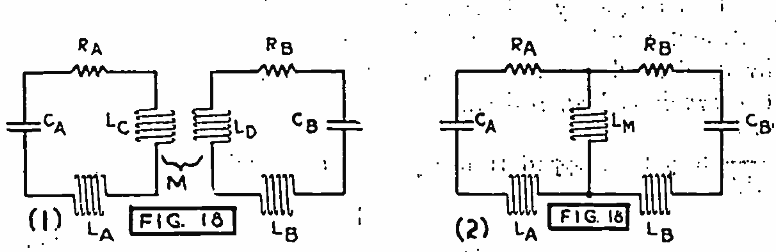

Fig. 18(1). Inductive or Transformer Coupling.
Fig. 18(2). Direct or Impedance Coupling.

circuits are so placed with reference to each other that energy is transferred from one to the other, by reason of the mutual inductance between the coils L_C and L_D. This type of coupling is, therefore, called *inductive* or *transformer* coupling.

In Fig. 18(2) the coil L_m is common to both circuits and the voltage variations due to the change in current through one circuit are impressed on the other circuit. This type of coupling was originally known as *direct inductive* coupling but now it is usually referred to as *direct* or *impedance* coupling.

In Fig. 18(3) the condenser C_m is common to the two circuits, and the variations in voltage across C_m, due to the changing current in one of the circuits, are impressed on the other circuit. This is known as *capacitive coupling.*

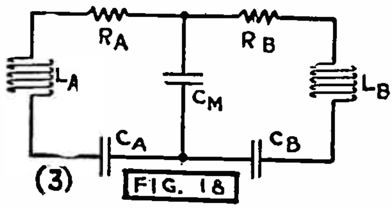

Fig. 18(3). Capacitive Coupling.

In all of these cases the amount of energy transferred from one circuit to another depends on the closeness of the coupling. For example, the energy transferred from one circuit to the other, in the case of transformer coupling (1) would be increased by bringing the circuits closer together. In (2) this increase in energy transferred from one circuit to the other would be accomplished by making the inductance L_m a *larger* part of the total inductance of each circuit. In the case of capacitive coupling (3), the energy transfer may be increased by making the coupling capacity a *smaller* part of the total capacity of each of the two circuits.

Coupling between the two circuits is said to be close when a relatively large amount of energy is transferred from one circuit to the other, and loose when a relatively small amount of energy is so transferred.

In order to compare the closeness of coupling between two circuits, this coupling is rated in numerical values, which are known as *coefficients of coupling,* and which depend upon the factors pertinent to the transfer of energy between circuits in each case. This coefficient of coupling is conventionally represented by *k,* and is defined as the ratio of the reactance common to the two circuits to the square root of the product of the total reactances (of the same kind as that which is mutual) of the primary and secondary circuits taken separately. Because of its generality, this definition is rather cumbersome. However, the following expressions for coefficient of coupling, which are based on this definition, are extremely simple.

Case 18(1)—Transformer coupling:

$$k = \frac{M\omega}{\sqrt{\omega(L_a + L_c)\omega(L_B + L_D)}} = \frac{M}{\sqrt{L_1 L_2}} \qquad (16)$$

Where L_1 represents $L_a + L_c$ and L_2 represents $L_B + L_D$.

Case 18(2)—Direct or impedance coupling:

$$k = \frac{\omega L_m}{\sqrt{\omega(L_a + L_m)\omega(L_b + L_m)}} = \frac{L_m}{\sqrt{L_1 L_2}} \qquad (17)$$

Where L_1 represents $L_a + L_m$ and L_2 represents $L_B + L_m$.

Case 18(3)—Capacitive coupling:

$$k = \frac{\sqrt{C_1 C_2}}{C_m} \qquad (18)$$

Where C_1 represents the equivalent capacity of C_a and C_m in series, and C_2 represents the equivalent capacity of C_B and C_m in series.

These expressions for "coefficient of coupling" are useful because they show the manner in which the coupling between two circuits may be varied. The coupling between circuits is very important, not only because of its influence on the amount of energy transferred from one circuit to the other, but because two coupled circuits react on each other to such an extent that they must be regarded as a unit. As such, they have two frequencies of resonance instead of one, and these two resonant frequencies are separated by an amount which is dependent upon the degree (that is, the coefficient) of coupling between the two circuits.

The significance of this double frequency of resonance in coupled circuits may be explained by consideration of a simple coupled circuit, as shown in Fig. 19. A generator of constant voltage, but adjustable frequency, is used to impress an electromotive force on circuit (1) which is inductively coupled to cir-

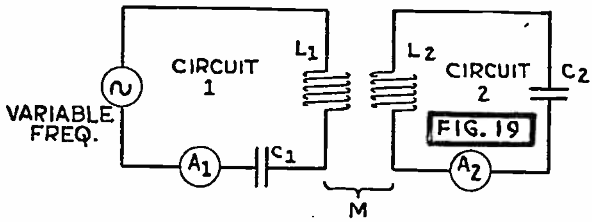

Fig. 19. Inductively Coupled Circuits.

cuit (2). If the coupling between the two circuits is not *loose,* the current in *each circuit* will vary with the generator frequency. This is shown in Fig. 20.

It should be noticed that there are two frequencies (f'_1 and f'_2) at which a maximum current is obtained. These frequencies f'_1 and f'_2 will be closer together if the coupling between the circuits is decreased. By making this coupling very loose, the two frequencies become coincident.

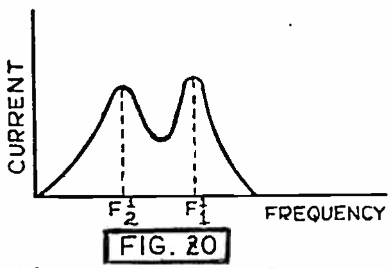

Fig. 20. Variation in Secondary Current with Frequency

If the resonant frequencies of the two separate circuits shown in Fig. 19 are equal, it can be shown mathematically that:

$$f'_1 = \frac{f}{\sqrt{1-k}} \tag{19}$$

$$f'_2 = \frac{f}{\sqrt{1+k}} \tag{20}$$

in which

f is the resonant frequency of each separate circuit;
k is the coefficient of coupling;
f'_1 and f'_2 are the two frequencies of resonance for the complete coupled circuit.

The formulas (19) and (20), above, hold for either direct or inductively coupled circuits, provided the natural frequencies of the primary and secondary circuits, taken separately, are the same. In the case of the capacitive coupling the corresponding formulas for the two resonant frequencies are as follows:

$$f'_1 = f\sqrt{1-k} \qquad (21)$$

$$f'_2 = f\sqrt{1+k} \qquad (21a)$$

If the separate natural frequencies are not the same, there will still be two resonant frequencies for two complete coupled circuits, but the expressions for their value will be considerably more complicated than those given in (19, 20, 21, and 21a).

Let us analyze this mutual reaction between two coupled circuits, which gives rise to the existence of two different frequencies at which the reactance of the circuit is zero. Considering the coupled circuit shown in Fig. 21, which is composed of one circuit consisting of C_1 and L_m, and another circuit composed of L_2, C_2 and L_m, we see that these circuits are directly coupled by the mutual Coil L_m. This complete coupled circuit might be regarded as equivalent to a series circuit containing the condenser C_1, and some other unit, the reactance of which was equivalent at any frequency to the reactance of L_m and the series combination L_2C_2 in parallel.

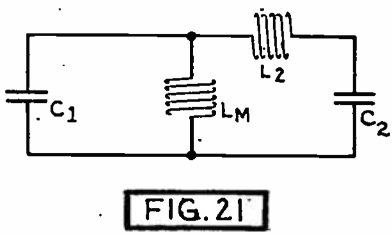

Fig. 21. Direct Coupled Circuits.

By the same means as that explained in paragraph 22 on parallel resonance, we might determine the manner in which the reactance of L_m and the series combination L_2C_2 in parallel varies with frequency. This could be graphically represented by the dotted curves X′ in Fig. 22. It should be noticed that there are two such reactance curves, just as in the previous case in parallel resonance, but one of these curves now crosses the zero axis because of the coil L_2.

We could also plot on the same axis the reactance curve of the condenser C_1. This is shown by the dot and dash curve marked X_{C_1} in Fig. 22. The total reactance of the circuit would then be equal to the algebraic sum of the reactances X' and X_{C1}, and this total reactance is represented by the curve so marked in Fig. 22. Obviously, there are two frequencies, f'_1 and f'_2,

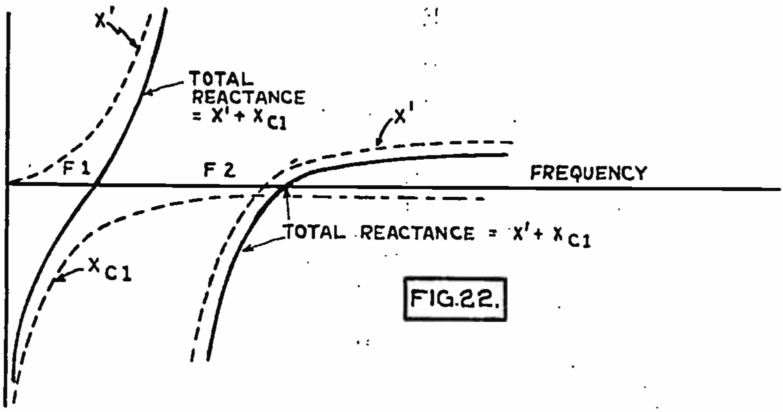

FIG.22.

Fig. 22. Reactance Diagrams for Fig. 21, Showing Two Frequencies at Which Reactance is Zero.

for which the reactance is zero. These are the two frequencies of resonance for the complete coupled circuit shown in Fig. 21.

The reactance diagrams of more complicated coupled circuits might be investigated in a similar manner, and it would be found in each case that there were two frequencies at which the reactance was zero, and that these frequencies would be separated by a lesser amount if the coupling between the circuits were made looser.

These phenomena of coupled circuits are extremely important in radio communication because coupled circuits are found in all modern radio transmitting and receiving sets.

25. Summary:

1. The following bands of frequencies are used in communication:

	Cycles Per Second
Power frequencies	25–60
Audio frequencies	16–20,000
Intermediate radio frequencies	20,000–75,000
Radio frequencies	20,000–300,000,000

2. The effects of radio-frequency currents are the same as those of low-frequency currents, but measuring instruments and

devices in which mechanical motion results from these currents are often inoperative or inaccurate at radio frequencies.

3. For all A.C. series circuits, whether they are low or high frequency, the following equation is true:

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

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

$$X = X_L - X_C$$

$$X_L = 2\pi f L = \omega L$$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{\omega C}$$

$$\varphi = \tan^{-1} \frac{X}{R}$$

Resonance exists when $X_L = X_C$.

Frequency of resonance is given by:

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

Wavelength of resonance in meters is given by:

$$\lambda_R = \frac{3 \times 10^8}{f_R}$$

Maximum current exists at resonance.

4. Tuning to resonance with the impressed voltage may be accomplished by:

1. Varying the inductance;
2. Varying the capacity;
3. Varying the impressed frequency.

5. A symmetrical resonance curve is obtained only when resonance is accomplished by adjusting inductance.

6. Sharper resonance and higher resonant current is obtained with lower resistance.

7. Wavemeters are used to measure the wavelengths of a current or an oscillatory circuit in which no current flows.

8. $\delta = \pi R \sqrt{\frac{C}{L}}$

9 Distributed capacity of a coil is the total capacity between its component turns of wire.

10. The apparent inductance of a coil is the true inductance as effectively modified by the distributed capacity.

11. Skin effect is the tendency of high-frequency currents to flow along the surface of a conductor, thereby resulting in an increased resistance at high frequencies.

12. Line current is a minimum when a coil and condenser in parallel are connected across the line so that the impressed frequency is the same as the resonant frequency of the circuit LC. Simple filter circuits depend on this phenomenon.

13. Free oscillations occur in a circuit when the frequency and decrement of the current are the same as the natural frequency and decrement, respectively, of the circuit; otherwise, any oscillations existing in the circuit are *forced oscillations.*

14. The natural frequency of a circuit is given by the following:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

If R is small:

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

15. Circuits are said to be coupled when a change in current in one circuit produces a change in current in the other.

16. There are three important types of coupled circuits, the names of which indicate the type of coupling unit between the two circuits. These are as follows:

1. Inductive or transformer coupled.
2. Direct or impedance coupled.
3. Capacitive coupled.

17. Coupling between circuits is indicated by a numerical value ranging from zero to one, and called the *coefficient of coupling.*

18. Coupled circuits react on each other to such an extent that they must be regarded as a unit. As such they have two frequencies of resonance, which are separated from each other by a greater amount when the coupling is *close* than when the coupling is *loose.*

19. If the resonant frequencies of two separate circuits are the same and are represented by f, then the two resonant frequencies f_1' and f_2' of the coupled circuits are given by the following:

For capacitive coupling:

$$f_1' = f\sqrt{1-k}$$
$$f_2' = f\sqrt{1+k}$$

For direct and inductive coupling:

$$f_1' = \frac{f}{\sqrt{1-k}}$$
$$f_2' = \frac{f}{\sqrt{1+k}}$$

where k is coefficient of coupling.

20. The circuit reactance of coupled circuits is zero at the two resonant frequencies.

26. Self-Examination:

1. What are the limiting values of each of the following:
   1. Power frequencies;
   2. Audio frequencies;
   3. Intermediate radio frequencies;
   4. Radio frequencies?

2. Why is a telephone receiver unable to respond to the instantaneous radio-frequency current through its windings?

3. What is the resonant frequency of a series circuit containing a 10-ohm resistance, an inductance of one millihenry, and a capacity of 400 micro-microfarads?

4. What is the resonant wavelength of a series circuit having an inductance of 600 microhenries, a capacity of .006 microfarads, and a resistance of 2 ohms?

5. How much current would flow in the circuit referred to in Problem 4, if the impressed voltage were 10 volts at 100,000 cycles?

6. Show graphically and explain the relationship between f, X_L, X_C, and X.

7. How might resonance be accomplished in a series circuit? Which method gives a symmetrical resonance curve?

8. State two important effects of resistance on resonance in a series circuit.

9. Draw a diagram and explain the operation of a complete wavemeter.

10. State three ways in which the existence of resonance might be determined in a series circuit.

11. What is the decrement of the circuit referred to in Problem 4?

12. What is meant by *distributed capacity of a coil?*

13. What is meant by *apparent inductance of a coil?*

14. What is the significance of *skin effect?*

15. Why is stranded wire used in high-frequency conductors?

16. Draw a diagram and explain the operation of a simple filter.

17. Draw a schematic diagram of three types of coupled circuits and name each.

18. State the effect of close coupling on the separation of the two resonant frequencies in coupled circuits.

SECTION III.

GENERATORS OF HIGH-FREQUENCY ELECTROMOTIVE FORCES (OTHER THAN VACUUM TUBES) AND CRYSTAL DETECTORS

	Paragraph
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SPARK GAPS	28
SIMPLE SPARK TRANSMITTER	29
CHARACTERISTICS OF THE ELECTRIC ARC	30
ARC TRANSMITTING SET	31
THE ALEXANDERSON ALTERNATOR	32
DETECTION	33
CONTACT RECTIFIERS	34
CRYSTAL DETECTORS	35
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27. **General.**—In any radio transmitting system we must have some type of generator of high-frequency electromotive force, which is associated with an antenna circuit in such a way that an oscillatory current will flow in the antenna circuit, resulting in the radiation of electromagnetic waves. In modern radio transmitting sets the vacuum tube oscillator is used as a high-frequency generator. However, the *spark transmitter,* the *arc transmitter* and the *Alexanderson alternator,* none of which utilize vacuum tubes, are still in use in maritime and commercial radio service. The theory of these sets is of interest, not only because it gives us information relative to the particular equipment used, but also because these sets exemplify some of the fundamental principles of the most modern radio equipment. These obsolete types of radio transmitting sets, and the crystal detector receiving set, which comes in the same category, will also be considered in some detail for this same reason.

28. Spark Gaps.—In order to discuss the spark transmitting set, consideration must first be given to the characteristics of the spark gap, which consists of two electrodes separated by a gaseous dielectric, as shown in Fig. 23, and across which there is impressed an alternating electromotive force of sufficient voltage to cause electrons to travel from one electrode to the other. The voltage required to break down the gap (allow the passage of electrons) between the electrodes is directly proportional to the distance between the electrodes, the pressure of the intervening gas (within certain limits) and the sharpness of the electrodes. At low voltages, the gap is a good insulator, but as the voltage is increased, the dielectric between the electrodes is increasingly strained and ultimately becomes conducting, permitting the electrons to pass with relatively little opposition from one electrode to the other. This change in resistance of the gap from its high value to a low value occurs rather suddenly as the voltage is increased beyond some critical point, at which the gap breaks down. The conductivity of the gap depends upon the ionization of the gas intervening between the electrodes, which in turn depends upon the heat produced by the electric strain due to the electromotive force impressed across the gap. A spark gap is, therefore, a relatively good conductor when hot and a poor conductor when cold, and it is this property of the spark gap which makes its utilization possible in radio transmitting sets, where it serves as a sort of automatic switch.

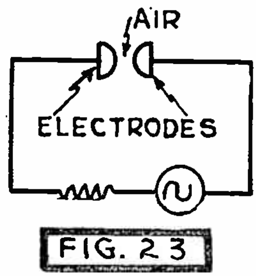

Fig. 23. Simple Spark Gap.

The spark gap performs its function more satisfactorily when the rapidity with which it changes from a good conductor to a good insulator (after once breaking down) is increased. For this reason gaps are designed to be rapidly cooled after breaking down, so that the de-ionization of the gaseous dielectric will be rapid. If a gap of some certain length is required, it is customary to arrange a number of shorter gaps in series, the total length of these gaps being equal to the desired length, and to form the gap with rather large metallic plates which will radiate the heat. Such a gap is known as a *quenched gap,* and is schematically represented in Fig. 24.

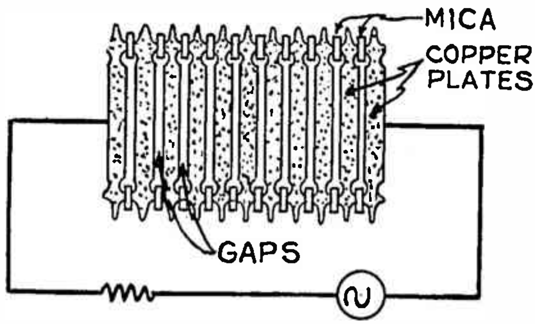

FIG. 24

Fig. 24. Quenched Spark Gap.

There is another type of gap called a *rotary gap,* consisting of a stationary electrode and a rotating plate having several projecting electrodes so arranged that each passes the stationary electrode during one complete revolution of the rotating plate. The fanning action of this rotating plate cools the gap and the time interval during which a rotating electrode is directly opposite the stationary electrode is so short that this type of gap is some-

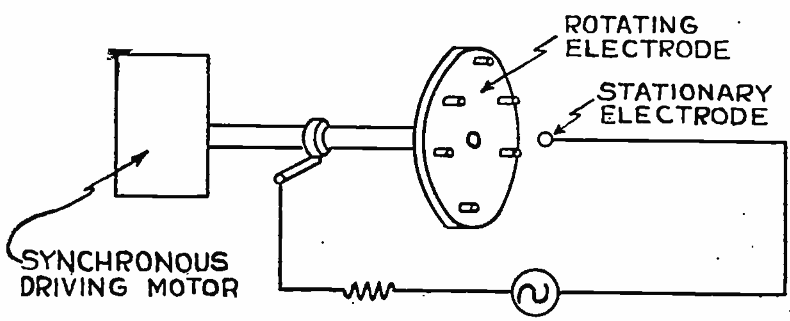

FIG. 25

Fig. 25. Rotary Spark Gap.

what quenched. This gap also permits control of the number of wave trains radiated per second, as will be explained later. The rotary gap is usually driven by a synchronous motor, and is often referred to as a *synchronous rotary gap*. Such a gap is schematically represented in Fig. 25.

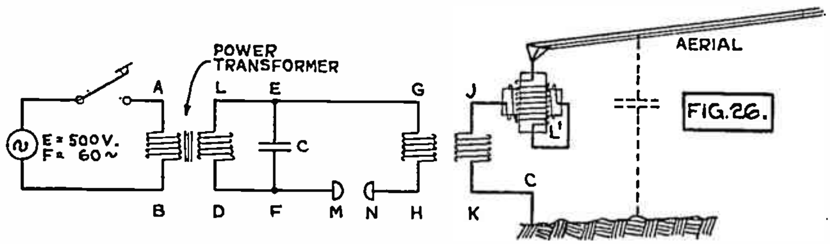

Fig. 26. **Simple Spark Transmitting Set.**

Let us now consider a simple spark transmitting set such as that shown in Fig. 26. When the key is closed, an alternating electromotive force of 500 volts is impressed on the primary AB of a power transformer, and a 3,000-volt alternating electromotive force is induced in the secondary LD. During each half cycle this voltage causes a current to flow in the circuit LECFD, thereby charging the condenser C and building up a potential from E to F. When this voltage has increased to approximately 3,000, it is sufficient to break down the gap MN, thus causing the gap to become a good conductor. The momentary effect of this is the same as if a switch had been closed, completing the circuit from M to N. The condenser C is then free to discharge through the coil GH, this discharge being oscillatory and of a frequency determined by the natural frequency of the closed oscillatory circuit EGHNMF. The gap MN having broken down, the electric strain on its dielectric is reduced, thereby cooling it and increasing its resistance. This in effect is the same as opening a switch from M to N. Increasing the resistance of the gap increases the decrement of the circuit and, therefore, results in an increasingly damped current through the circuit EGHNMF. The variations in the magnetic field resulting from this high-frequency current flowing through the coil GH induce corresponding voltages in the coil JK, which is connected to an aerial wire, a series variometer and the ground. The far end of the aerial wire is insulated from the ground. The capacity of this wire to ground, however, completes the antenna circuit, as shown by the dotted lines in Fig. 26. The inductance of the variometer L′ may be varied until the antenna circuit is resonant to the frequency of the induced voltage, in which case a maximum current will flow in this circuit. Some of the energy of those currents is radiated into space in the form of damped electromagnetic waves.

Going back to the closed oscillatory circuit EGHNMF, it appears that an oscillatory discharge of the condenser C occurs through this circuit whenever the voltage from E to F is great enough to break down the gap MN. This gap is usually adjusted so that it will break down for voltages equal to the maximum voltage induced in the coil LD of the power transformer. In this case there are two oscillatory discharges of the condenser C during each cycle of the voltage impressed from the generator.

The series of oscillations resulting from each breakdown of the gap is called a *wave train* and the number of such wave trains per second is called the *spark frequency*. Obviously, the spark frequency in this case would be twice the frequency of the impressed voltage. If a rotary spark gap such as that shown in Fig. 25 be used instead of the simple gap MN shown in Fig. 26, the spark frequency would be equal to the number of revolutions per second multiplied by the number of electrodes on the rotating plate. The spark frequency of a transmitting set is important because it determines the pitch of the note heard at the receiving station, as will be explained later.

The importance of the rate at which the gap in a spark transmitter cools after its breakdown can now be explained. The ultimate purpose of a set such as that shown in Fig. 26 is to radiate electromagnetic waves of a constant frequency. If the antenna circuit could once be set into oscillation at its own natural frequency, the waves sent out during each wave train would be of this frequency, provided there was no reaction from another oscillatory circuit. In the circuit shown in Fig. 26, the closed oscillatory circuit EGHNMF is coupled to the antenna circuit, and thereby reacts on it and results in the radiation of waves of more tha none frequency. The frequencies of these radiated waves might be brought closer together by decreasing the coupling between the two circuits, but this also decreases the energy transferred from one circuit to the other, which reduces the radiated energy. If, at the instant of maximum transfer of energy to the antenna circuit, the circuit EGHNMF could be opened, it would no longer react on the antenna circuit, which would then be free to oscillate at its own natural period. Rapidly cooling the gap MN quickly increases its resistance and is equivalent to opening the circuit EGHNMF. Quenching the gap, therefore, results in the antenna circuit oscillating at its own natural frequency and in the consequent radiation of electromagnetic waves of one frequency. This is a distinct advantage and the spark gaps used in transmitting sets are almost invariably quenched in some manner.

Spark transmitting sets, in general, radiate damped waves, but a so-called *timed spark set,* designed by Marconi, radiates practically continuous waves. This set contains a number of spark gaps, the breakdown of which are synchronized so that the electromotive forces induced in the antenna are of approximately constant amplitude. A timed spark set is schematically represented in Fig. 27.

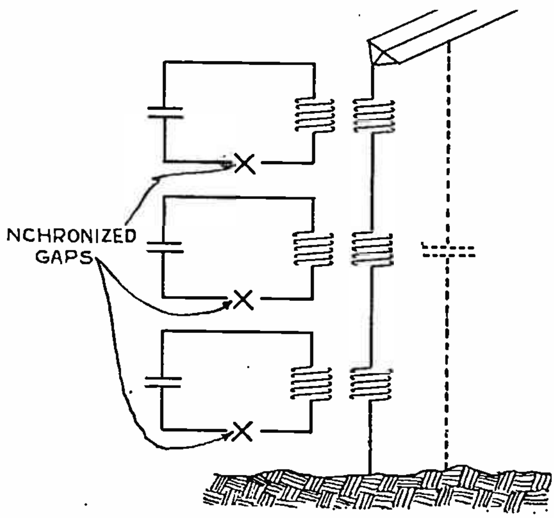

FIG. 27

Fig. 27. Schematic of Timed Spark Set.

30. Characteristics of the Electric Arc.—The electric arc consists of two electrodes across which an electromotive force is impressed and through which current flows when they are brought in contact and continues to flow after they have been separated. The electric arc differs from the spark in the manner in which electricity is carried across the gap which separates the electrodes. In the spark gap the transfer of electricity across the gap is mainly by means of electrons, while in the arc most of the electricity is transferred by means of ions and charged particles of the electrode materials, which are actually consumed in the process of arcing.

The peculiar property of an electric arc which makes its use possible in radio communication is its so-called *falling characteristic,* which may be explained from a consideration of the simple arc shown in Fig. 28.

With the switch S closed the electrodes C and C′ are touched together and a current will flow in the circuit DABE. This current will arc across the gap between C and C′ when the electrodes are separated, and current will continueto flow in this circuit. The resistance offered by the gap varies inversely with the current, so that the smaller the current the larger the gap resistance. If, while the arc is burning steadily, some change is made in the circuit which causes the current through the arc to increase, this increase in current will result in a decrease in the resistance of the arc, and the decrease in resistance will be proportionately greater than the increase in current to which it is due. The voltage across the arc, of course, is the product of the current and resistance and the relative change in these quantities is such that their product decreases as the current increases. It follows, therefore, that as the current through the arc increases, the voltage across the arc decreases and vice versa. This is known as the *falling characteristic* of the arc.

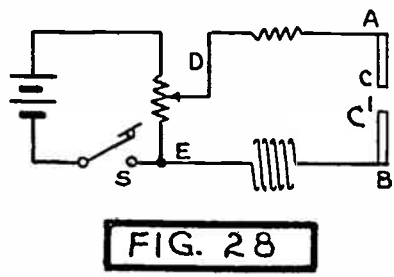

Fig. 28. Simple Arc.

31. Arc Transmitting Set.—A schematic diagram of a simple arc transmitting set is shown in Fig. 29.

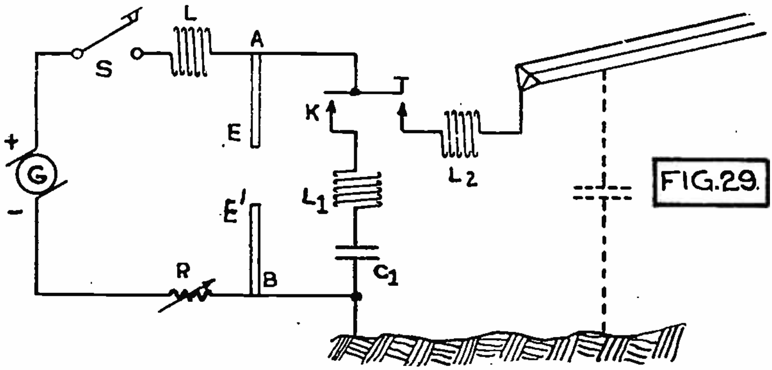

Fig. 29. Simple Arc Transmitter.

With electrodes E and E′ in contact, the switch S is closed, and a direct current flows through the circuit LABRG. The electrodes are then separated and the current continues to arc across the gap. With the arc burning steadily in this manner, the back contact of the key K is closed and there is a surge of current through C_1 and L_1, thus charging the condenser C_1. The current delivered by the generator G to the entire circuit cannot change quickly, because of the opposition offered by the inductance L, which is in series with the generator. As a consequence of this condition, the current which is suddenly demanded by the circuit C_1L_1 must be absorbed from the arc circuit AEE′B. This decrease in current through the arc results in an increase in voltage across the arc from A to B. The condenser C_1 is, therefore, further charged until the potential across its terminals is nearly equal to this increased voltage from A to B. As the potential across the condenser approaches this limiting value, the current through the condenser circuit is diminishing toward zero, and the current through the arc is increasing with the consequent decrease in voltage from A to B. At this instant the condenser voltage is higher than that across the arc from A to B and the condenser discharges through the arc, thereby increasing the arc current and decreasing the voltage AB still further. Current through the circuit C_1L_1 is now flowing up, while previously it was flowing down. This current continues to flow until the condenser is charged in the opposite direction, to a higher voltage, than that which exists from A to B, at which time it discharges again through the arc circuit, current flowing down through the coil L_1. This series of events is periodically repeated with the natural frequency of the circuit C_1L_1, and a sinusoidal alternating current is thus caused to flow through this circuit. By closing the forward contact of the key the antenna circuit is substituted for circuit L_1C_1 and the high frequency currents flowing through the antenna result in the radiation of electromagnetic waves of corresponding form, that is, undamped waves.

In practice, the maximum value of the current due to the discharge of the condenser is about equal to the direct current through the arc, so that the pulsating current through the arc is periodically reduced to zero, and the arc is extinguished for an instant during each cycle. Such an arc is known as a *Poulson Arc,* and in past years has been extensively used in the military and naval communication services.

The constructional details of arc transmitters will not be covered here because of their very limited use in modern radio stations. It will suffice to say that the arc is usually enclosed in a hydrogen-filled chamber and provided with a magnetic blow-out, and its electrodes are cooled by circulating water; also that there are three principal methods of controlling the dots and dashes sent out. They are known as the compensation wave, ignition, and absorption methods, respectively. Fig. 29 represents the absorption method.

32. **The Alexanderson Alternator.**—The generation of high-frequency electromotive forces by the same mechanical means as those employed in the generation of low-frequency electromotive force is prohibited by the limitations of space and force. To illustrate this, let us consider the following: The frequency developed by an ordinary generator is equal to the product of the number of pairs of field poles and the number of armature revolutions per second. In order to generate a high-frequency electromotive force, therefore, we must either have a very large number of poles, which would require considerable space, or else have a very high armature speed, with the consequent enormous centrifugal forces of destructive magnitude acting on the component masses of the armature.

To obviate these difficulties, Alexanderson designed an alternator consisting of a reasonably high speed rotor having a number of slots alternately filled with magnetic and non-magnetic materials, as shown in Fig. 30(2), and which rotor is arranged to vary the magnetic reluctance of the path between the poles of a magnet N and S, Fig. 30(1).

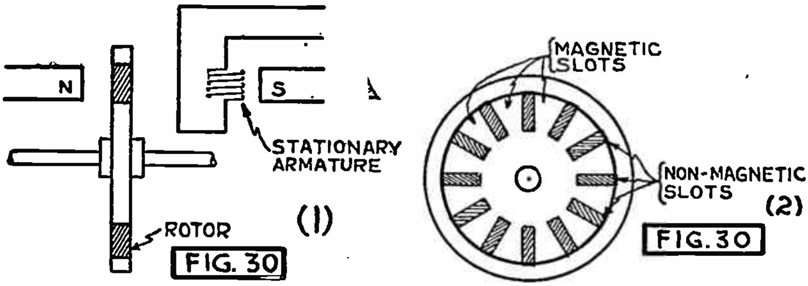

Fig. 30(1). Showing Principles of Alexanderson Alternator.

Fig. 30(2). Rotor.

The magnetic flux interlinking with the stationary armature shown in Fig. 30(1) is thus varied with high frequency, as the rotor varies the reluctance of the path in which the armature is included. A high-frequency electromotive force is, accordingly, induced in the armature and is available to radiate energy into space in the form of continuous electromagnetic waves.

The Alexanderson alternator can be used for relatively long wavelengths only, because it is impractical to develop extremely high-frequency currents with this type of equipment. Alexander-

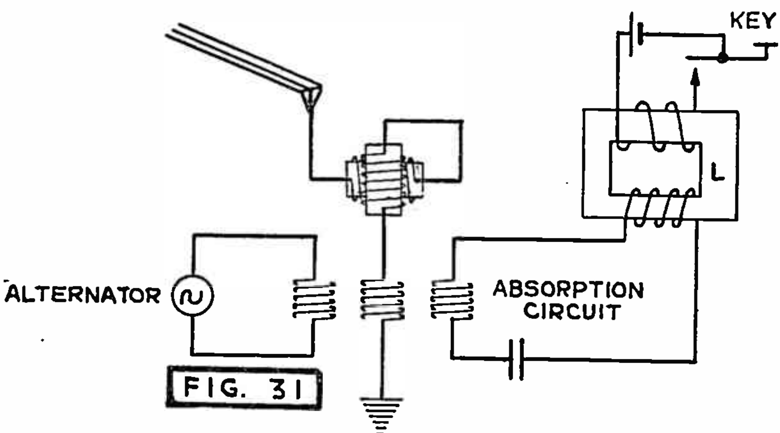

Fig. 31. Schematic of Keying System in Alexanderson Alternator.

son controls the radiation from this set by causing the sending key to change the inductance of an absorption circuit coupled to the antenna, as shown schematically in Fig. 31.

The inductance of the coil L in the absorption circuit is changed by varying the magnetic saturation of the core on which it is wound.

33. **Detection.**—Next, let us consider the requirements of detecting electromagnetic waves at a receiving station.

The first operation is to intercept the energy in space, which is accomplished by so placing a stationary aerial wire that an electromotive force will be induced in it due to the relative motion between this wire and the magnetic field of the wave which we are trying to intercept. The circuit of which the aerial is a part may be adjusted to resonance at the frequency of this induced electromotive force and an alternating current of radio frequency will then flow in the antenna circuit. A detector is arranged with respect to the antenna so as to convert the energy of this antenna current into the form of sound waves.

There are three steps in the performance of this general function of detectors as follows:

1. The rectification of the radio-frequency current.
2. The conversion of the rectified radio-frequency currents into audio-frequency currents having a wave form similar to the envelope of the incoming radio-frequency wave.
3. The conversion of the audio-frequency current into sound waves.

The rectification of radio-frequency currents may be accomplished either by means of a vacuum tube or a combination of dissimilar substances, which combination possesses unilateral (one-way) conductivity.

The conversion of the rectified radio-frequency currents into audio-frequency currents is accomplished by means of the discharging of a condenser through inductance and resistance in accordance with the laws of transient alternating current phenomena. The conversion of the audio-frequency currents into sound waves is performed by a telephone receiver or loud speaker.

Some types of detectors are suitable for detecting damped waves or audio-frequency modulated waves only and therefore are not suitable for reception from continuous wave transmitting stations. The so-called *crystal detector* falls in this category and we shall first consider it.

34. Contact Rectifiers.—It has been found that certain combinations of dissimilar metals, practically in contact, offer greater opposition to the passage of current between them in one direction than in the other. These combinations, therefore, serve to rectify effectively an alternating current. Suppose, for example, that an alternating electromotive force is impressed on a series circuit containing such a combination of two dissimilar metals, A and B, as shown in Fig. 32.

If the form of the impressed electromotive force is represented by curve X of Fig. 33, then the resulting current through this circuit will be of the form shown in curve Y, Fig. 33.

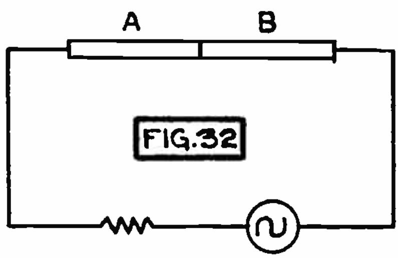

Fig. 32. Simple Contact Rectifier.

These curves indicate that although the amplitudes of positive and negative half cycles of the impressed electromotive force are equal, the amplitudes of the positive half cycles of the resulting current are much greater than the negative half cycles, as illustrated by the different heights of the curves. This is due to the fact that electrons can pass from B to A (in the circuit shown in Fig. 32) with greater ease than from A to B, or in other

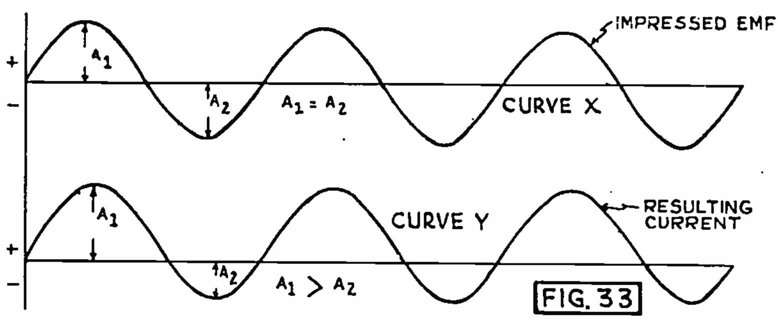

Fig. 33. Rectified Current.

words, this combination of metals has practically unilateral conductivity. An alternating wave is said to be rectified when the amplitude of either its positive or its negative half cycle has been diminished practically to zero, without appreciably reducing the amplitude of the other half cycle. A combination of metals having unilateral conductivity is, therefore, capable of rectifying an alternating current.

There are many combinations of metals in use for this purpose, most of which consist of some mineral crystal in contact with a steel point. The crystals most frequently used are of galena, iron pyrites, silicon, and molybdenite. Recently a combination of copper and an oxide of copper has been found to form an especially good rectifier. Contact rectifiers will be discussed in a later section.

35. **Crystal Detectors.**—Suppose we have a contact rectifier connected as shown in Fig. 34. An electromotive force is

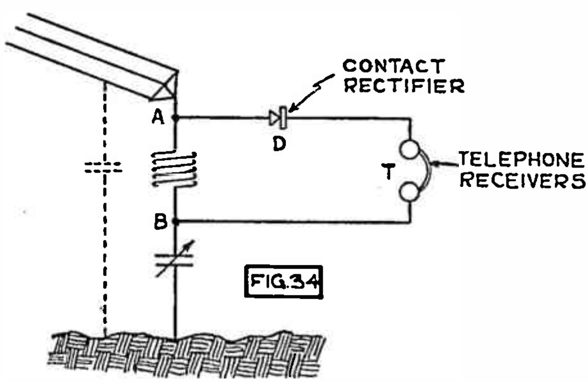

Fig. 34. Simple Crystal Detector.

induced in this circuit by an electromagnetic wave, and after the antenna circuit had been adjusted to resonance, at the frequency of this wave, a maximum current flows through the coil AB. The variations in potential across this coil are impressed on the circuit DT and result in a rectified alternating current of radio frequency flowing through the crystal (D) and the telephone receiver (T). Because the inertia of the telephone receiver diaphragm prevents its displacement in accordance with the instantaneous values of this current, the movement of the telephone diaphragm follows the audio-frequency variations in amplitude of the incoming wave. For example, if the incoming wave is of the form shown in curve A, Fig. 35, a rectified current of the form shown in curve B would flow through the telephone receiver, due to the rectifying action of the crystal. The telephone dia-

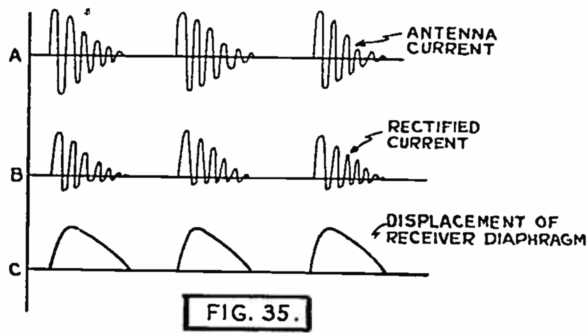

Fig. 35. Wave Forms in Circuit Fig. 34.

phragm would then receive a number of relatively strong radio-frequency impulses tending to displace it in one direction and an equal number of very weak impulses tending to displace it in the opposite direction. Because of its mechanical inertia, the telephone diaphragm would be displaced only once for each wave train, the direction of this displacement being that of the stronger impulses. The form of this displacement is represented by curve C of Fig. 35.

The telephone receiver has considerable inductance and, therefore, offers high opposition to radio-frequency currents. Consequently, the displacement of the telephone diaphragm is very small. A much greater displacement of the receiver diaphragm would be effected with the same variations in potential across the coil AB (Fig. 34), by connecting a small condenser across the telephone receiver, as shown in Fig. 36, the capacity of the condenser and the constants of the telephone receiver being such that the time required for the condenser to discharge through the receiver is of the order of an audio-frequency time period (*i.e.,* more than 1/20,000 of a second).

In this case, the rectified radio-frequency currents which flow through the crystal D also flow through the condenser, thus charging the condenser, which in turn discharges through the telephone receiver in accordance with the audio-frequency varia-

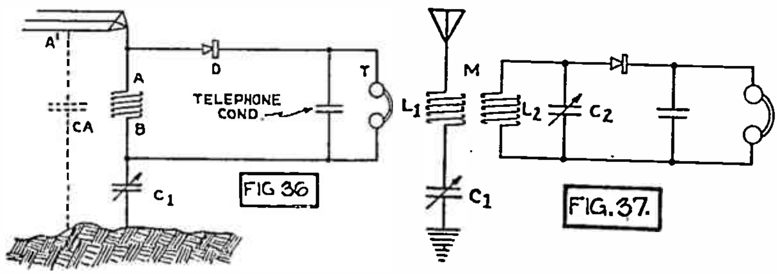

Fig. 36. Simple Crystal Detector with Telephone Condenser.

Fig. 37. Simple Crystal Detector with Two Tuned Circuits.

tion in amplitude of the radio-frequency currents. The complete action of this receiver is then as follows: It selects the particular wave desired by tuning the antenna circuit $A'ABC_1Ca$, rectifies the radio-frequency current by reason of the unilateral conductivity of the crystal D and obtains the envelope of the rectified wave by reason of the discharge of the telephone condenser through the receivers. This circuit is, therefore, suitable for detecting either damped waves or audio-frequency modulated waves, but is not capable of detecting undamped waves, since undamped waves do not have audio-frequency variations in amplitude. If this set were properly tuned to intercept an undamped wave, the receiving operator would hear a click in the receivers each time the transmitting key was closed or opened, but would not be able to distinguish dots and dashes and spaces between characters.*

A set of this type may be improved in selectivity by having two tuned oscillatory circuits, as shown in Fig. 37; that is, the antenna circuit L_1C_1 and the secondary circuit L_2C_2. By providing loose coupling between L_1 and L_2, the selectivity is increased,

*The capacity of the cords leading to the receivers is, in many types of headphones, a satisfactory substitute for the telephone condenser in the circuit.

but the energy obtained in the secondary circuit from the particular wave which we are trying to receive is decreased.

36. **Relation to Modern Radio Sets.**—The basic principles involved in the types of transmitting and receiving equipments described in the foregoing paragraphs are the same as those which pertain to vacuum tube transmitting and receiving sets, which constitute the major portion of modern radio equipment. Before we can discuss these modern sets, however, consideration must be given to the details of vacuum tube characteristics and design.

37. **Summary:**

1. Spark gaps are good insulators when cold and relatively good conductors when hot.

2. Quenched gaps provide auxiliary means of cooling the gap after it has broken down.

3. Spark transmitting sets radiate damped waves, with the exception of the *timed spark,* which radiates continuous waves.

4. In spark transmitters the number of wave trains per second depends upon the number of times per second that an oscillatory breakdown of the gap occurs. This is known as the *spark frequency.*

5. The frequency of the electromagnetic waves radiated from a spark transmitting set depends upon the natural frequency of the antenna circuit and the closed oscillatory circuit.

6. A spark gap acts as a sort of automatic switch which completes an oscillatory circuit, allowing it to oscillate, and then effectively breaks the circuit, causing the oscillations to be damped out rapidly.

7. Quenching a gap is desirable because it permits the antenna circuit to oscillate freely without the reaction of another circuit upon it.

8. The falling characteristic of an electric arc is the property of decreasing its resistance as the current through it is increased, the magnitude of the charge in resistance resulting from a change in current being such that the product of current and resistance decreases as the current increases.

9. An arc transmitting set consists of a direct-current arc across which an oscillatory circuit is connected, so that an alternating current will flow through the oscillatory circuit due to the falling characteristic of the arc, the frequency of the current being determined by the natural frequency of the oscillatory circuit.

10. An arc transmitting set radiates continuous waves of some desired frequency as long as the controlling key is closed.

11. The Alexanderson alternator is a mechanical generator of

high-frequency electromotive forces, in which the flux through stationary conductors is rapidly varied by means of the variations in the magnetic reluctance of a path in which they are included.

12. A detector must rectify an alternating current and then obtain the envelope of the rectified wave.

13. Contact rectifiers consist of a combination of two dissimilar minerals in contact, which combination possesses unilateral conductivity.

14. In simple crystal detector sets, the antenna circuit is adjusted to select the particular wave desired, rectification is accomplished by a crystal contact rectifier, and the envelope of the rectified current is obtained either by reason of the inertia of the receiver diaphragms or preferably by the discharge of the telephone condenser through receivers.

15. Selectivity of a simple receiving circuit may be improved by having two inductively coupled tuned circuits, but the signal strength is decreased by such a system.

38. Self-Examination:

1. Describe a simple spark gap, a quenched gap and a rotary gap.

2. Upon what does the voltage required to break down a gap depend?

3. What is meant by quenching a gap and how is it accomplished?

4. What is meant by *wave trains* radiated from a spark transmitting set?

5. What determines the pitch of the note heard in the receiving set which has detected the waves sent out by a spark transmitter?

6. How might the spark frequency of a rotary spark gap transmitting set be varied?

7. Draw a diagram and explain the operation of a simple spark transmitter.

8. What is the advantage of quenching a spark gap?

9. What part of a spark transmitting set determines the frequency of the radiated wave?

10. Explain the *falling characteristic* of an electric arc.

11. Draw a diagram and explain the operation of a simple arc transmitter.

12. What kind of waves are radiated by the following types of transmitter:

    1. Timed spark;
    2. Arc;
    3. Simple quenched spark?

13. Explain the basic principle used in the Alexanderson alternator for generating high-frequency electromotive forces mechanically.

14. Explain the principle of the keying system used on the Alexanderson alternator.

15. What are the three steps in detecting a damped radio-frequency current or an audio-frequency modulated current?

16. Explain the action of a contact rectifier.

17. Draw a diagram and explain the action of a simple crystal detector set.

18. Why is it that a simple crystal detector set will not detect undamped waves?

19. How might the selectivity of a simple detector set be improved?

20. Would it be possible for a Poulson arc transmitter to communicate with a simple crystal detector receiving set?

21. Would it be possible for a synchronous rotary spark transmitter to communicate with a simple crystal detector receiving set?

22. Can a simple crystal detector receiving set detect the programs radiated by broadcasting stations?

Section IV.

THE THERMIONIC VACUUM TUBE

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39. **Electronic Emission from Solids.**—Scientists have agreed for many years that the forward displacement of electrons through a conductor constitutes an electric current within that conductor, and also that it is relatively more difficult to force electrons out of a conductor into a surrounding dielectric. Some years ago, however, Edison discovered that electrons were thrown out of a wire filament into the gaseous dielectric surrounding it when the filament was heated, and that these electrons were attracted toward a positive plate placed in this dielectric. Subsequently, it has been learned that a similar electronic emission occurs when light of certain wavelengths in the ultraviolet region falls upon a conducting surface, and that this light might either originate in some source of illumination or in fluorescent chemicals which have

been caused to emit the desired light by reason of previous exposure to electromagnetic waves from some other source. It has also been demonstrated that electrons may be thrown out of a conducting surface by the force of other electrons impinging on that surface.

The emission of electrons from wire filaments has become extremely important to the art of communication, this emission being effected by heat in all practical cases. The wire filament is enclosed in an exhausted glass tube which is provided with external contacts through which an electric circuit is established. Current flowing in this circuit heats the filament, with resulting electronic emission. For this reason, such tubes are called *thermionic vacuum tubes.*

A few vacuum tubes have been designed in which a cup containing some fluorescent chemical has been placed under the filament, and as a consequence of the light emanating from the chemical substance and falling upon the filament, electrons are liberated from the surface of the wire. These tubes, however, have not been developed to a state of satisfaction as yet, and we shall, therefore, consider only the thermionic tube.

40. Two-Electrode Vacuum Tubes.—If the thermionic vacuum tube described above also contains a metallic plate to which an external connection may be established, the device is known as a *two-electrode vacuum tube,* the two electrodes being the *filament* and the *plate.* Such a tube was first introduced by Fleming and is, therefore, often referred to as the *Fleming Valve.* The two-electrode tube is schematically represented in Fig. 38.

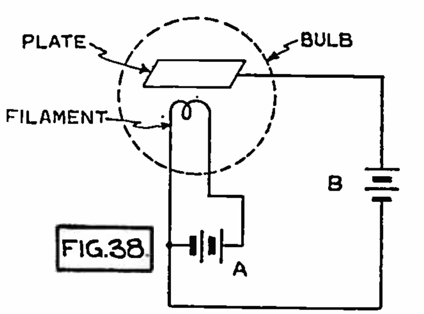


Fig. 38. Two-Electrode Vacuum Tube.

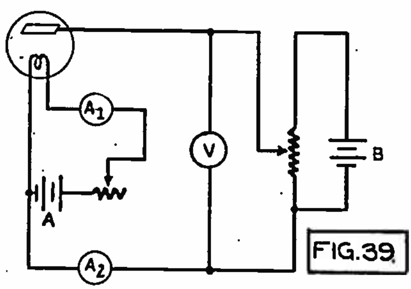
Now let us suppose that a battery is connected across the external filament connections as shown at A in Fig. 38. A current will then flow in the filament circuit and the filament will be heated, thus liberating electrons into the vacuum within the bulb. If a second battery of sufficient electromotive force is connected as shown at B, the plate will be placed at a positive potential with reference to the filament. The electrons or negative charges emitted from the heated filament will then be attracted to the positive plate, in accordance with the fundamental law of electrostatics that unlike charges attract. These electrons, so attracted, will be returned to the filament through the external plate circuit. This electron movement, from the filament to the plate within the tube and through the external plate circuit back to filament, constitutes the so-called *plate current.*

The battery connected across the external filament contacts is conventionally known as an "A" battery and is usually a storage battery. However, for very small tubes dry cells are sometimes used and for very large tubes electric generators are used for this purpose.

The battery connected between the external plate and filament contacts is conventionally known as the "B" battery. It is composed of dry cells. A direct-current generator may be used instead.

Let us consider this two-electrode vacuum tube further, with particular regard to the manner in which the plate current varies and the means by which such variations may be accomplished. Obviously, the number of electrons which pass in a given time across the space between the filament and the plate and then through the external plate circuit back to the filament is limited by the number of electrons emitted from the filament and by the ability of the plate to attract the electrons so emitted. The electron emission depends upon heat, which in turn depends upon the filament current; consequently, one of the factors which influence the plate current is the filament current. The ability of the plate to attract electrons depends upon the difference of potential maintained between the filament and the plate. Due to the IR drop between various points in the filament circuit, these different points within the filament are at different potentials, so that we must decide upon some one point as a reference point from which differences of potential shall be measured. This point is usually the negative terminal of the filament, and in speaking of plate potential we shall mean the difference in potential between the plate and the negative terminal of the filament. It follows that the second factor which limits the plate current is the plate potential. It appears, then, that the plate current of the two-electrode vacuum tube may be varied by changing either the filament current or the plate potential.

Let us next investigate the manner in which the plate current changes with variations in either of these two controlling factors. Suppose we modify the circuit shown in Fig. 38 to that shown in Fig. 39 by inserting a variable resistance and an ammeter (A_1) in series with the filament, and arranging the external plate circuit so that it contains a variable "B" battery, across which a voltmeter (V) is connected, and in series with the circuit an ammeter (A_2). Let us first keep the sliding contact of the "B" battery potential divider in a fixed position so that the plate potential will be constant, and vary the position of the sliding contact on the filament rheostat so as to change the filament current. Starting with the filament resistance all in the circuit, so that the filament current is practically zero, we may adjust this rheostat to include various amounts of its total resistance and read both ammeters while the rheostat sliding contact is in each position.



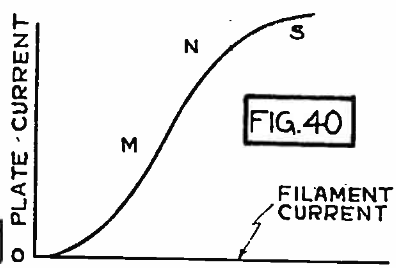


Fig. 39. Circuit for Obtaining Characteristic Curve of the Two-Electrode Vacuum Tube.

Fig. 40. Curve of Two-Electrode Vacuum Tube-Plate Potential Constant.

If, then, we plot a curve with filament current as abscissas and plate current as ordinates, it will be of the general shape shown in Fig. 40. It should be observed that the slope of this curve increases from 0 to M, remains practically constant from M to N, decreases from N to S, and that further increases in filament current beyond the value corresponding to the abscissa for S do not result in increased plate current. The point S is called the *saturation point* and is reached in this case when the plate is attracting all the electrons which it can attract with the given plate potential. The liberation of electrons from the filament at a greater rate does not result in an increased plate current.

Next let us leave the variable contact on the filament rheostat at some central position and adjust the amount of "B" battery included in the circuit, varying it from zero to its maximum value and reading the voltmeter (V) and the plate ammeter (A_2) for each setting. If we now plot a curve with plate potential as abscissas and plate current as ordinates, it will be of the same general shape as that shown in Fig. 40. In this case saturation will be reached when practically all of the electrons emitted by the filament are attracted to the plate. Further increase in plate potential will not then result in an increased flow of electrons.

These curves, obtained as described above, are known as the *characteristic curves* of the two-electrode tube. Because of their shape the tubes to which they pertain may be caused to rectify, amplify, and modulate alternating currents, and to produce sustained oscillations, when properly connected to the necessary auxiliary equipment. However, the two-electrode tube is obsolete except as a rectifier and this consideration of it serves only as an introduction to the three-electrode tube.

41. General Structure and Characteristic Curves of Three-Electrode Vacuum Tubes.—The three-electrode tube, which is so very important in radio communication, is similar to the two-electrode tube, but it has an additional electrode known as a grid, which consists of a mesh of fine wire interposed between the filament and plate and provided with an external contact. A tube of this type was first designed by DeForest, who called it the *audion*. The tube was rapidly developed by the efforts of several scientists. Such a tube is schematically represented in Fig. 41. The introduction of the grid into the tube provides a third means by which the plate current may be varied and one which is much more effective than either of the other two (variation of plate circuit voltage or filament circuit current); that

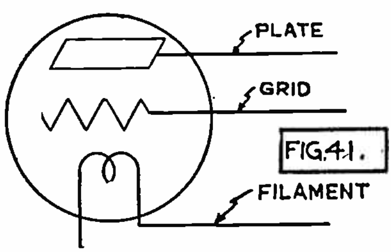


Fig. 41. Three-Electrode Vacuum Tube.

is, the plate current may now be controlled by means of the *grid potential,* by which we mean the difference in potential between the grid and the negative terminal of the filament.

When a stream of electrons is passing from the filament to the plate within the tube, as is the case when a plate current exists, there are many electrons constantly present in the space between these two electrodes. This accumulation of negative charges reacts on the electrons just emitted from the filament with a tendency to oppose their movement toward the plate. Since this electron accumulation occupies the space between the electrodes, it is known as a *space charge.* It is into the middle of this space charge that the grid of the three-electrode tube is introduced. If, by external means, the grid is made positive with reference to the filament, it will partially neutralize the space charge, thus aiding the flow of electrons from the filament to the plate; but if, on the contrary, the grid is made negative with reference to the filament, the grid will augment the effect of the space charge, thereby opposing the transfer of electrons from filament to plate. With a given filament current and plate potential, therefore, the plate current may be varied from zero to some saturation value by means of variations in the grid potential. Obviously, when the grid is positive with reference to the filament, some of the electrons emitted by the filament are attracted to the grid and are returned to the filament through the external grid circuit, producing a *grid circuit current.* If the grid poten-

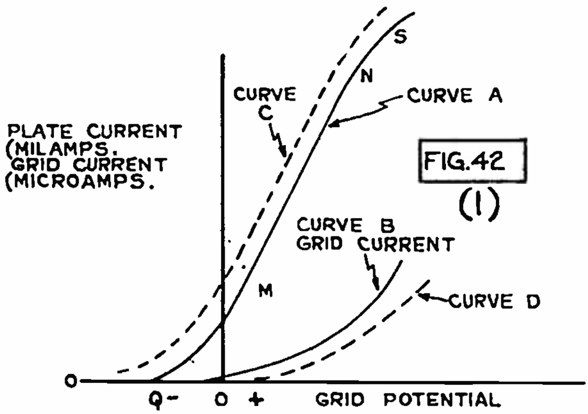


Fig. 42(1). Grid Potential.

tial is increased beyond the point where saturation of the plate current occurs, the grid current is rapidly increased and the plate current is decreased.

In a tube which is free from gas, a positive grid current is obtained for slightly negative values of grid potential. This is due to the fact that the grid is in the path of the rapidly moving electrons, and therefore is constantly bombarded by them. The force of this impact is sufficient to drive these electrons into the metallic surface of the grid and they are conducted from the grid to the filament through the external grid circuit. The grid potential at which the grid current is just zero is called the *free grid potential*. See Fig. 42(2).

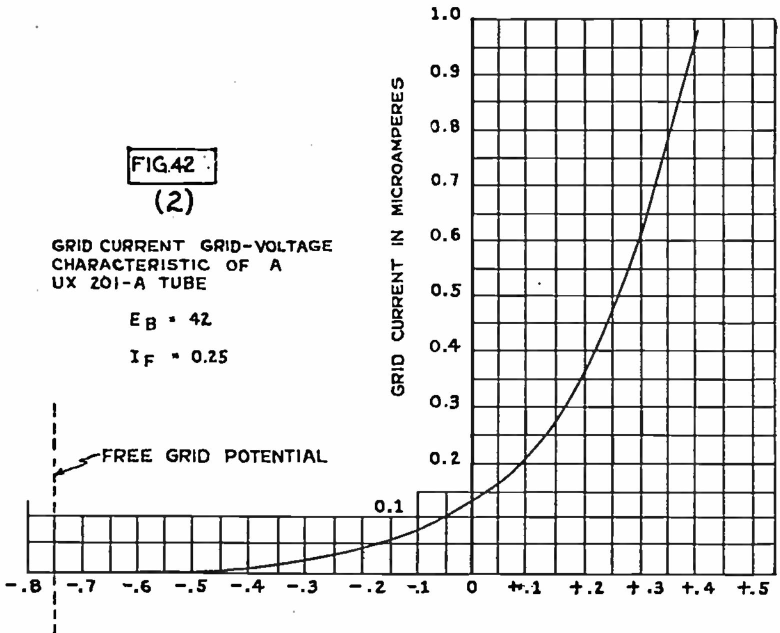


Fig. 42(2). Grid Voltage.

If the tube contains sufficient gas, a negative grid current will exist at low positive or negative potentials. This is due to the ionization of the gas within the tube and the attraction of these ions by the grid. The manner in which the plate current varies with changes in grid potential in a tube with very little gas is shown in curve A, Fig. 42(1), the corresponding variations in grid current being shown in curve B. The plate potential and filament current are kept constant. The general shape of this plate current curve is the same as that of the curves previously discussed as pertaining to the two-electrode tube; that is, the slope of the curve increases from Q to M, is constant from M to N, and decreases from N to S. This curve is very important, for it is by reason of the shape of its various portions that the tube is able to perform its many different functions. The grid current, grid voltage characteristic curve for a UX-201A tube is shown in Fig. 42(2).

The data for these *static characteristic curves,* as they are called, could be experimentally obtained by use of the circuit shown in Fig. 43, in which the filament current and plate potential are kept constant and the grid potential is varied by means of the potential divider connected across the grid circuit battery, which is conventionally styled the "C" battery, and is composed of dry cells. The grid potential is read on the voltmeter V, the plate current on the milliammeter A2, and the grid current on the microammeter A1, a set of readings being taken for each setting of the potential divider (often called a potentiometer).

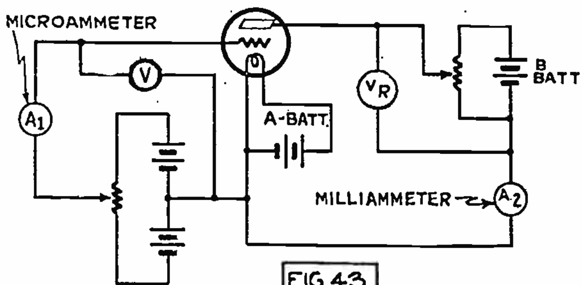


FIG.43.

Fig. 43. Circuit for Obtaining Plate Current Grid Voltage Characteristic Curve of Three-Electrode Vacuum Tube.

If a set of similar data is taken using a higher constant plate potential than that which was used for Fig. 42(1), the plate current curve would have been higher, as shown by the dotted curve C, and the grid current curve would have been lower, as shown by the dotted curve D [Fig. 42(1)].

Fig. 44(1) shows a series of plate current grid voltage characteristic curves, each curve representing the characteristic for the value of plate potential indicated by the number on the curve.

This family of curves pertains to a tube containing a greater amount of gas than is contained in the best modern tubes. The corresponding curves of a more perfectly exhausted tube would not reach saturation as quickly. This is shown in Fig. 44(2), in which the plate current grid voltage curves of three UX-201A tubes are shown.

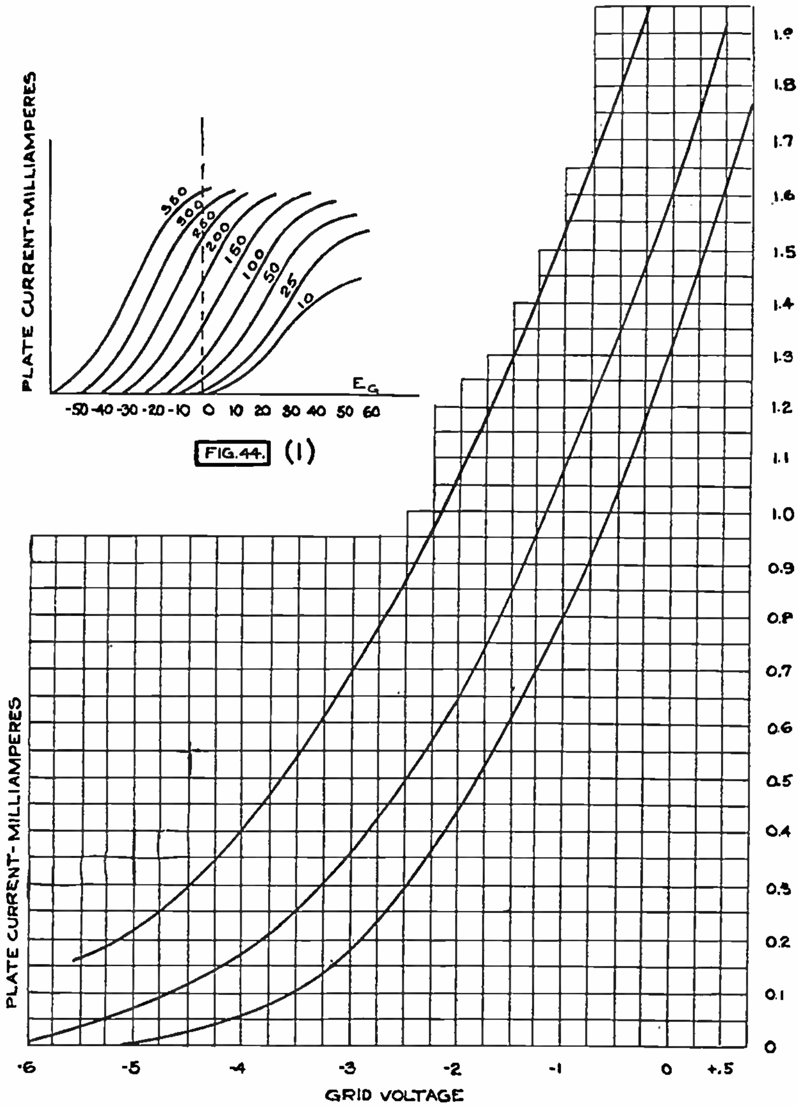


FIG.44 (2)

42. Grid Bias and Operating Point on Characteristic Curve.—The three-electrode vacuum tube is used to perform four major functions; that is, it is used as detector, amplifier, oscillator, and modulator. In all of these cases, however, we are concerned with accomplishing changes in a steady plate current by variations in grid potential. The plate current grid voltage characteristic curve of the tube is therefore the one in which we are most interested.

Whenever the tube is connected with its associated circuits to perform any one of its several functions, there is some initial steady value of plate potential, plate current, filament current, and grid potential. The initial value of grid potential is called the *grid bias*. Variations in grid potential will add to or subtract from the grid bias, depending on their direction. If Fig. 45 represents the characteristic curve of a vacuum tube for some particular value of plate potential, then a negative grid bias equal to 0A would result in a steady plate current equal to I_1. A zero grid bias would result in a steady plate current, I_2, and a positive grid bias 0B would result in a steady plate current I_3.

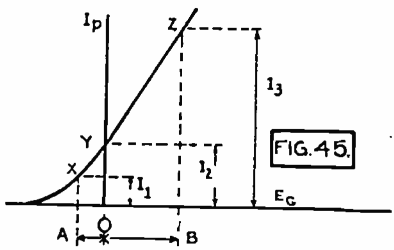


Fig. 45. Showing Grid Bias and Operating Point.

For a grid bias equal to 0A the point X is referred to as the *operating point* on the characteristic curve. Any variation in grid potential will move the abscissa to the right or left of A, and will produce corresponding changes in the value of plate current. Similarly, with a grid bias equal to zero, the point Y is the operating point on the characteristic curve, and for a grid bias represented by 0B the point Z is the operating point.

From this discussion we see that the operating point on the characteristic curve may be selected so as to fall on any desired part of the curve, since it is determined by the initial grid potential or *grid bias*.

In practice there are three methods of establishing the desired grid bias. They are as follows:

1. Use of a "C" battery in the grid circuit.

2. Use of a resistor in the external circuit between the grid and the filament circuit.
3. Returning the grid to various points in the filament circuit.

Two of these methods are often combined in the same circuit. Fig. 46(1) shows the first of these methods, in which the grid circuit is returned to the negative side of the filament and the difference in potential between the grid and the negative side of the filament is equal to the electromotive force of the "C" battery.

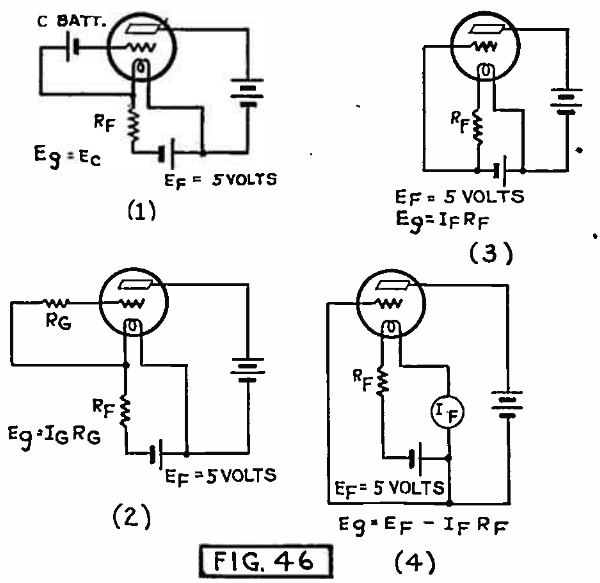


Fig. 46. Four Methods of Establishing Grid Bias.

The second method of establishing grid bias is by means of a series grid resistor and is shown in Fig. 46(2). In this case the grid bias is equal to the product of the steady grid current and the resistance of R_g. With the UX-201A tube referred to in Fig. 42(2), the grid bias would be minus (—) .75 of a volt if the resistance of R_g were infinite, since this is the grid potential at which the grid current just reaches zero. If the resistance of R_g, Fig. 46(2), were zero, the grid would be at the same potential as the negative side of the filament; that is, the grid bias would be zero. Intermediate values of the grid leak R_g would give grid biases between these two limits in this case.

The method of establishing the desired grid bias by returning the grid to some particular point in the filament circuit is shown in Fig. 46(3). In this case the IR drop across the filament resistance R_f is utilized to provide the desired difference in potential between the grid and the negative side of the filament. This method might have been exemplified also by the circuit shown in Fig. 46(4), in which the grid is returned to the positive side of the "A" battery.

43. Voltage Amplification Coefficient.—It was stated in a preceding paragraph that there are three ways of varying the plate current in a three-electrode vacuum tube: that is, by variation of either the grid potential, the plate potential, or the filament current. Suppose, now, that we desired to compare the effectiveness of two of these means of varying the plate current, such as the grid potential and the plate potential method. This might be done with a circuit such as that shown in Fig. 43, which could be set up and adjusted until the plate and grid potentials were of some desired value, let us say 50 volts plate potential and one volt positive grid potential. Suppose that we read the milliammeter in the plate circuit at this time and find it to indicate 1.0 milliampere. Now we could decrease the plate potential until the plate current has decreased to, say, 0.9 milliampere, and then read the voltmeter E_p, which now reads 47.5 volts. This would indicate that a change of two and one-half volts in plate potential is required to decrease the plate current 0.1 milliampere. Our next step is to find the change in grid potential which will effect the same change of plate current. To do this we should first increase the plate potential to its original value of 50 volts in order to restore the current to 1.0 milliampere. Next, the grid potential should be adjusted until the plate current again reads 0.9 milliampere, and the grid voltage should then be read on the voltmeter E_g. If this new value of grid voltage is found to be 0.5 volt, it has required a change of one-half volt in grid potential to change the plate current 0.1 milliampere. We see that a one-half volt change in grid potential produces the same change in plate current as is produced by a change of 2.5 volts in plate potential; therefore, variations in grid potential are five times as effective as variations in plate potential under these circumstances. This measure of the relative effectiveness of variations in grid potential to variations in plate potential in producing a given small change in plate current is called the *voltage amplification coefficient* of the tube. This coefficient is conventionally represented by the Greek letter Mu (μ), and is defined as the ratio of the change in plate potential to the change in grid potential necessary to produce a given small change in plate current. If, then, we represent by $\triangle Ep$ the change in plate potential required to give a certain small change in plate current, $\triangle Ip$, and by $\triangle Eg$ the change in grid potential required to effect the same change in plate current,

$$\mu = \frac{\triangle Ep}{\triangle Eg}.$$

The voltage amplification coefficient of vacuum tubes is extremely important, particularly if the tube is to be used as an amplifier or as an oscillator, in which case the voltage amplification coefficient should be high. This coefficient depends upon certain structural dimensions of the tube, as indicated by the following empirical formula given by Van Der Bijl:

$$\mu = Cpn^2r + 1;$$

where C is a constant which depends upon the shape of electrodes and the conditions under which the tube is operated, p is the distance between plate and grid in centimeters, r is the diameter of the grid wires in centimeters, and n is the number of grid wires per centimeter. It should be observed from this equation that the voltage amplification coefficient is independent of the area of the electrodes, the distance between the plate and filament, and the distance between the grid and filament.

44. Plate Impedance.—The transfer of electricity across the space between the filament and plate within a vacuum tube is almost entirely by means of electron flow, and the opposition which this space offers to an electric current is therefore practically all resistance. However, there is a certain amount of capacity between these two electrodes and, consequently, a small displacement current might flow across the space between them, thus introducing a slight reactive component to the total impedance offered to a changing current by the space between filament and plate. For practical purposes this impedance is regarded as being composed of resistance only, and it is customary to refer to it as the *plate resistance*. If the plate current is changing by reason of variations in the plate potential, the product of this internal plate resistance and the instantaneous change in current must be equal to the instantaneous change in plate potential. If, then, we represent a small change in plate potential by $\triangle E_p$, the resulting change in plate current by $\triangle I_p$, and the internal plate resistance by R_p, the grid potential and filament current being constant, we may say that:

$$R_p \triangle I_p = \triangle E_p, \text{ or } R_p = \frac{\triangle E_p}{\triangle I_p}.$$

It is apparent from inspection of the plate current-plate voltage characteristic curve shown in Fig. 47 that the ratio $\frac{\triangle E_p}{\triangle I_p}$ is simply the reciprocal of the slope of this curve, and that this slope is different from one part of the curve to another. It follows, therefore, that the plate resistance R_p, which is equal to this ratio, is in reality the internal resistance offered by the space between filament and plate to the flow of a changing current, and that it is only constant over the linear portion of the characteristic curve. This resistance which the tube offers to a changing current is referred to as the A.C. resistance. It should be observed that this A.C. resistance is different from the resistance offered to a steady direct current, which in the case shown in Fig. 47 is the ratio of E_p to I_p, as marked in the figure.

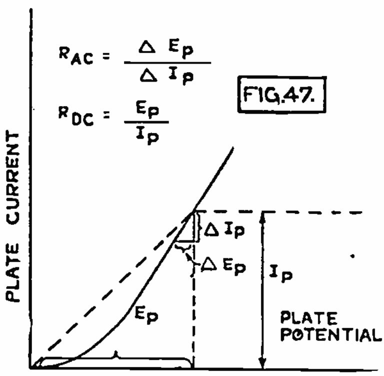


Fig. 47. Showing Difference Between A.C. and D.C. Resistance of Tube.

It is customary to refer to the plate circuit of a vacuum tube as the *output circuit,* and to the grid circuit as the *input circuit;* consequently, the internal plate resistance is often spoken of as the *internal output resistance.* The internal output resistance is then defined as the ratio of the change in plate potential to the resulting change in plate current, when the grid potential and filament current are kept constant. This resistance depends upon the length of the electron path from filament to plate, that is, the distance between these two electrodes, and also upon the area of the filament and plate. It is desirable that this resistance be low, which could be accomplished by placing the plate and filament close together, but this would decrease the voltage amplification coefficient, since the grid is between the filament and plate and this coefficient depends on the distance between the grid and plate. It is, therefore, customary to place the grid as close as possible to the filament, but maintain the distance between grid and plate such as to provide a satisfactory voltage amplification coefficient.

45. Mutual Conductance.—Because of the fact that variations in grid potential are most effective in producing changes in plate current, it is customary to impress upon the grid circuit the signal electromotive forces, with which we are concerned. We are naturally interested, then, in ascertaining the change in plate current which results from a given change in grid potential. In order that the performance of two tubes in this respect may be compared, the name *mutual conductance* has been given to the ratio of the change in plate current to the change in grid potential to which the current change is due, the plate potential and filament current being kept constant. This ratio is called *mutual* because it expresses a relationship between a quantity pertaining to the plate circuit and a quantity pertaining to the grid circuit, and it is called *conductance* because it is the ratio of a current to a voltage. In all types of tubes this ratio should be high.

If we represent mutual conductance by G_m, the change in grid voltage by $\triangle E_g$ and the resulting change in plate current by $\triangle I_p$, the plate voltage and filament current being constant,

then $$G_m = \frac{\triangle I_p}{\triangle E_g}.$$

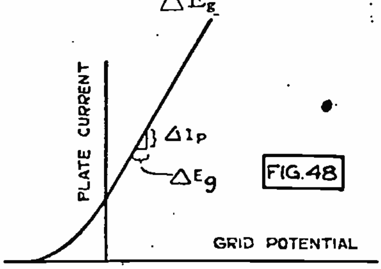
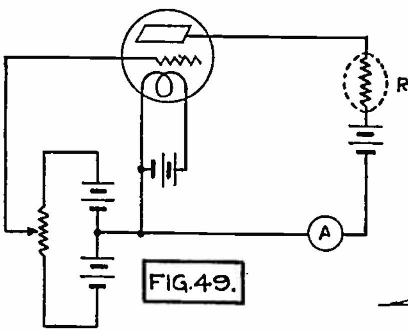


Fig. 48. Showing Relationship Between G_m and Slope.

From this and an inspection of the plate current grid voltage curve in Fig. 48, it is apparent that the mutual conductance is the slope of this curve and is different over the various portions of the curve, being greatest for the linear portion of the curve.

46. Relationship Between Tube Constants.—From the equations stated above for voltage amplification coefficient, internal output resistance, and mutual conductance, the relationship between these various tube constants for a given set of conditions may be shown as follows: Since $\mu = \frac{\Delta E_p}{\Delta E_g}$ and $R_p = \frac{\Delta E_p}{\Delta I_p}$ and $G_m = \frac{\Delta I_p}{\Delta E_g}$, we see that $\mu = R_p G_m$. These three quantities pertaining to vacuum tubes are very important and are frequently referred to in radio literature.

47. **Static Characteristics of Vacuum Tubes When the External Plate Circuit Contains Resistance.**—So far we have discussed the characteristic curves of vacuum tubes, assuming that the resistance of the external plate circuit was zero. Now, let us consider what happens in the circuit shown in Fig. 49, in which



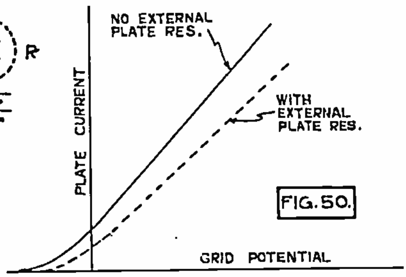


Fig. 49. Circuit for Study of Effects of Resistance in Plate Circuit.

Fig. 50. Showing Relation Between Curves obtained With and Without External Plate Resistance.

a resistor (R) is connected in the external plate circuit. An increase in grid voltage now causes an increase in plate current as before, but this increased plate current now results in increased drop in potential across the resistance R with consequent reduction in potential from plate to filament. This reduced plate potential tends to reduce the plate current, and therefore partially compensates the increase in grid potential. As a result of this condition the characteristic plate current grid voltage curve of a vacuum tube which is obtained with an external plate resistance in the circuit is lower than the corresponding characteristic curve obtained with no external plate resistance, as shown in Fig. 50.

The lower curve shown in this figure represents the characteristic for some particular value of external plate resistance, and would be still lower, relatively, if the external plate resistance were increased. We see, therefore, that the characteristic plate current grid voltage curve pertaining to a tube with no external plate resistance is higher and has a greater slope than the corresponding curve pertaining to the tube when its circuit contains resistance.

48. Dynamic Characteristic.—All of the characteristic curves previously considered have been *static curves;* that is, they have been based on steady potentials and currents. However, as the vacuum tube is used in practice, an alternating or a pulsating electromotive force is impressed on the grid and results in a pulsating plate current. As a consequence of this alternating component of the plate current, the current between plate and filament within the tube due to the electron movement is supplemented by the displacement current due to the inter-electrode capacity, so that the characteristic curve of the tube itself (*i.e.*, without external plate impedance) is slightly different when we consider direct potentials applied to the grid than when we consider alternating potentials applied to the grid. A characteristic curve obtained with alternating potentials applied to the grid is called a *dynamic* characteristic curve. For most practical purposes, the static and dynamic characteristic curves of a particular tube are coincident when the external plate circuit contains no reactance. However, if the external plate circuit includes inductance, changes in plate current when an alternating electromotive force is impressed on the grid produce an IZ drop in potential across the inductance which is not present when a steady electromotive force is impressed on the grid. In such cases the static and the dynamic curves are different. The dynamic curves also differ for different frequencies of the grid electromotive force. The general shape of the static and dynamic curves is the same, however, in all cases.

49. Power Amplification Coefficient.—When the tube is considered with its associated external circuits, there is another important relation, called the *power amplification coefficient.*

In the circuit shown in Fig. 51, a certain amount of alternating-current power is supplied to the grid circuit by the generator G. This will result in a corresponding variation in current through the resistance R in the plate circuit. The amount of alternating-current power dissipated in this external plate resistance will be equal to the product of the square of the effective value of the alternating component of the pulsating plate current and the resistance R. The power amplification coefficient in this case is the ratio of the alternating-current power dissipated in the external plate resistance to the alternating-current power supplied to the grid. This coefficient may be very high and in practical forms of tubes is sometimes as great as ten thousand. Of course, the alternating-current power supplied to the grid circuit is the product of the square of the grid current and the resistance of the complete grid circuit. If the grid is positive with reference to the filament, there is an electron current across the space between the grid and filament, and the total grid circuit resistance is then the sum of the external grid resistance and the resistance of the space between the grid and filament inside the tube. On the other hand, if the grid potential is highly negative, only a small displacement current will flow between the grid and filament inside the tube and this will be due to the small capacity between these two electrodes. In this case the total grid resistance is that of the external grid circuit. When the grid is slightly negative, there will be a small current flowing from grid to filament. due to the bombardment of the grid by the rapidly moving electrons. In any case, the current between grid and filament inside the tube also flows through the external grid circuit, and when an alternating electromotive force is impressed on the grid there will always be some small alternating grid current, even though the grid potential is continuously negative. Therefore, the power amplification coefficient cannot be infinite, as it would be if the grid current were zero.

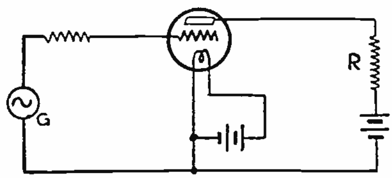


FIG. 51

Fig. 51. Representative Circuit to Illustrate Power Amplification Coefficient.

There is another interesting thing about the power amplification coefficient, and that is that it is greater than unity. On first consideration this seems to indicate that we get more power from the tube than we put into it. This, however, is not the case, because the additional energy in the output circuit is supplied from the plate battery, so that the over-all efficiency of the tube with its associated circuits does not exceed one hundred per cent.

In operating a loud speaker or other vacuum-tube power devices used at a receiving station, or in power amplifiers used at transmitting stations, the tube should have a high power amplification coefficient.

50. Effects of Gas in Vacuum Tubes.—The presence of even slight amounts of gas in vacuum tubes has two important effects on the tube's operation:

1. The number of electrons emitted by the filament at a given temperature is varied by the contact of the gas with the surface of the filament.
2. Ionization currents flow between the electrodes. If sufficient gas is present, these ionization currents will result in negative currents flowing when the grid potential is negative.

These two effects of gas on the operation of vacuum tubes are such that tubes in which gas is contained are erratic, and do not have a smooth characteristic curve such as those previously discussed. Two vacuum tubes which are identical in every construction feature have very different characteristics if they are not equally exhausted. Carefully selected tubes with a small amount of gas are sometimes used as detectors, such tubes being referred to as *soft* tubes, to distinguish them from *hard* tubes, which are more perfectly exhausted.

51. Constructional Forms of Vacuum Tubes.—In practice, tubes are designed with electrodes of various shapes, arranged in different manners. The plates of these tubes are usually plane or approximately cylindrical and the shape of the grid corresponds to that of the plate. The arrangement of wires within the grid meshes also varies from one design to another. Some tubes are provided with one filament, two grids in parallel, and two plates in parallel. Some tubes are provided with filaments coated with the oxides of barium, calcium, or thorium, which increase the electron emission for a given degree of heat.

The oxides used on the filaments of such tubes usually work toward the inside of the filament wire as the tube is used. This greatly impairs the usefulness of the tube, which must then be rejuvenated by heating the filament excessively for a short time, thereby driving the oxides back to the surface of the filament.

TYPES OF VACUUM TUBE CONSTRUCTION

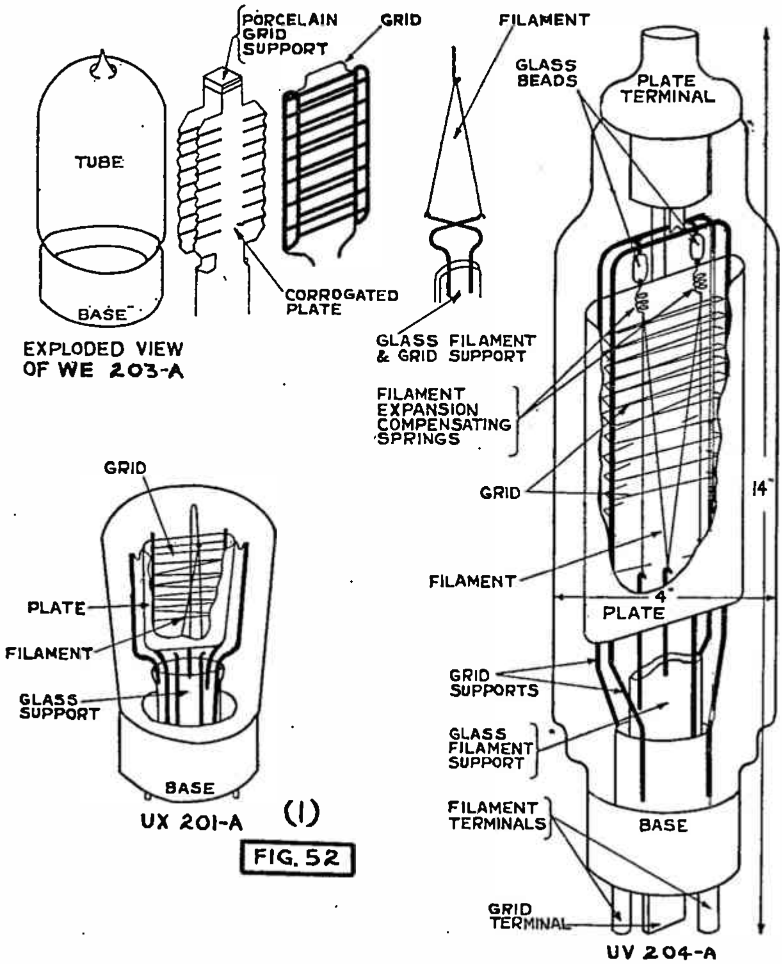


Fig. 52(1). Showing Constructional Forms of Several Vacuum Tubes.

Three practical forms of vacuum tubes are shown in Fig. 52(1).

Some idea of the current and voltage requirements of vacuum tubes and of their characteristics and uses may be obtained from following table:—

CHARACTERISTICS OF VACUUM TUBES.

Manufacturer's Code No.	Manufacturer	Filament — Term Volts	Filament — Current Amps.	Plate Voltage — As Detector	Plate Voltage — As Amplifier	Plate Voltage — As Trans.	Normal Plate Current (M.A.)	"C" Bat. As Amp.	Plate Impedance Ohms	Amplification Constant	Rated Power Watts	Socket Used	Action as Detector	Action as Amplifier	Remarks
UX-12 CX-12	West.	1.1	.25	20-45	40-100	...	.3-3.9	3	19,000	6.5	..	UX	.....	.....	....
U.V.199 C-299	Various	3	.06	20-45	40-100	...	.25-3.9	.5-.7.5	16,000 18,000	6.5	..	Spec.	Good	Good	Excellent r.f.amp.
CX-299 UX-199	Various	3	.06	20-45	40-100	... .	.25-3.9	.5-.7.5 O1A	16,000 18,000	6.5	..	UX	.....	.....	....
CX-200 UX-120	G. E. Co.	3	1.25	....	135	...	6.5	22.5	6,600	3.3	..	UX	.....	Exc.	Power amp., last stage
—O1A	Various	5	.25	20-45	40-120	...	1-7.5	.5-9	12,500 16,500	8	..	Stand.	Good	Exc.	Stand. receiving tube
200A	Various	5	.25	22	...	...	.25-1	...	9,000	..	..	Stand.	Exc.	.....	Detector only
112	Various	5	.5	....	90-157.5	...	2.4-7.9	6-10.5	4,800 5,800	8	..	UX	Exc.	Exc.	Last stage power amp.
171	Various	5	.5	....	90-180	...	...	16.5-40.5	....	3	..	UX	.....	.....	Last stage power amp.
210	Various	7.5	1.25	....	90-425	425	3-22	4.5-35	5,000 9,700	7.75	7.5	UX	.....	Exc.	Last stage power amp.
M.U.20	Various	6	.25	....	90-150	...	1.1	6	40,000	20	..	Stand.	.....	.....	R. and imp. amplifier
A.C.	McCull	3-A.C.	1.0	....	67.5-90	...	10	6-10	9,000	10	..	Stand.	.....	Exc.	A.C. tube
Raytheon	......	..	..	....	none	...	60	..	....	..	..	......	.....	.....	Rectifier
		3.3	.132	....	135	...	...	-1.5S.G. 45 scr.	800,000	350	..	UX	.....	Exc.	R.F. amp. must be shielded
UX-26	Various	1.5	1.05	....	90-180	...	3.7—7.5	6—13.5	9,400 7,000	8.2	..	UX	.....	Exc.	Direct heater A.C. tube
UY-27	Various	2.5	1.75	45	90-180	...	3—6	6—13.5	10,000 9,000	9	..	UY	Good	Exc.	Indirect heater A.C. tube
UY-24	Various	2.5	1.75	....	180	...	4	—1.5 +75 Scr.	400,000	400	..	UY	Good	Exc.	Indirect heater must be shielded
UX-40	Various	5.0	.25	....	135—180		.20	—1.5 to —3.0	150,000	30	..	UX	.....	Good	Use with resistance coupled amplifier
UX-245	Various	2.5	1.5	....	250	...	26 to 32	—33. to —50	1,950	3.5	..	UX	.....	Good	Power amplifier only
UX-250	Various	7.5	1.25	....	250 to 450	...	28 to 55	45 to —84	2,100 to 1,800	3.8	..	UX	.....	Good	Power amplifier only

52. Tubes Using Alternating Current for Heating Filament.—A substitute for the batteries used in broadcast receivers has been sought for some time. A large number of homes throughout the United States are lighted by alternating current, and the availability of such a source of energy at once suggests the possibility of eliminating the "A" battery used with vacuum tubes, by heating the filaments of these tubes with alternating current.

If an alternating electromotive force of suitable potential were impressed on the filament of an ordinary tube, as it is employed in receiving sets, it would result in a periodic variation of the potential of the grid and plate with reference to the center of the filament. This variation of the plate and grid potential would cause a corresponding variation in plate current, which would produce a disturbing noise in the headphones or loud speaker. To obviate this, a fourth element is introduced in the tube, this element being a device for heating the cathode (ordinary filament) by radiation. The arrangement of the elements in such a tube is shown in Fig. 52(2). The alternating current flowing through the heater element radiates sufficient heat to raise the temperature of the cathode to a point where it emits electrons. These electrons are then attracted by the plate, and influenced by the grid, in the same manner as in a three-electrode tube. The external plate and grid circuits, of course, are returned to the cathode in this case. Such tubes are usually referred to as alternating-current tubes of the heater cathode type. These types are extensively used in broadcast receivers, and they require a five-prong socket, known as a UY socket.

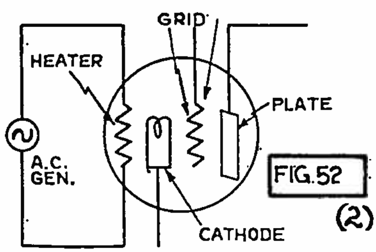


Fig. 52(2). Schematic of A.C. Tube.

Alternating-current tubes are also manufactured without this indirect heater. Such tubes have a relatively large filament and are used in circuits in which a center-tapped resistor is connected across the external filament circuit. The plate and grid circuits are then returned to the center tap of this resistor. These tubes are used extensively in output stages and to a lesser extent in radio- and intermediate audio-frequency amplifiers. They require the standard four-prong, or UX, base.

53. Shield Grid or Screen Grid Tubes.—Subsequent to the first success of the three-electrode tube, experimenters have tried consistently to improve the operation of the tube by the introduction of a second grid. As a consequence, tubes having two grids have come into somewhat general use in Europe and recently several manufacturers have introduced them in the American market. These tubes are known as either *shield grid* or *screen grid* tubes. They consist of a filament, grid, and plate of the usual type, with an additional grid of finely meshed wire surrounding the plate. The grid nearest the filament in this type of tube is brought out to a contact at the top of the tube and the additional grid is connected to the usual grid contact in the base. The screen grid tube is schematically shown in Fig. 52(3). This tube may be used in two ways. The first way is to use grid No. 2 as the grid of an ordinary three-electrode tube and to bias No. 1 positively to an extent which will just compensate the space charge due to the presence of electrons in the space between the filament and plate. When so connected, this tube is employed as a low or intermediate frequency amplifier or detector, and is claimed to be somewhat better than the ordinary three-electrode tube for this purpose. This tube is also manufactured with an indirect heater or cathode for use with alternating current.

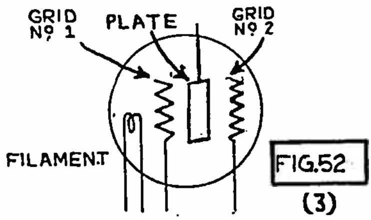


Fig. 52(3). Schematic Diagram of Screen Grid Tube.

When this four-electrode tube is to be employed as a radio-frequency amplifier, it is best to connect grid No. 1 as the ordinary or signal grid and to bias grid No. 2 so as to neutralize the electrostatic field within the ordinary grid and the plate. In the three-electrode tube this internal capacity is the cause of disturbing oscillations, which must be prevented by either losser or neutralizing methods, as we shall see later. These oscillations may be prevented by properly biasing grid No. 2, which is between the ordinary grid and the plate.

This four-electrode tube has a higher voltage amplification coefficient and higher internal plate impedance than the corresponding three-electrode tube.

54. **Circuits Employing Vacuum Tubes.**—In this section we have considered only the characteristics of the various types of vacuum tubes. The following sections will be devoted to circuits in which vacuum tubes are employed. The student should observe that to all circuits employing the three-electrode vacuum tube, the following fundamental principles pertain:

1. The input circuit is the grid circuit and the output circuit is the plate circuit.
2. There must be a conducting path for both direct and alternating current from the grid to the filament and from the plate to the filament.
3. Choke coils are used to prevent radio- and audio-frequency currents, or radio-frequency currents only, from flowing in any particular branch of a circuit.
4. Stopping condensers are used to stop the flow of direct current in any particular branch of a circuit and to prevent the "B" battery of one tube from biasing the grid of another tube.

55. **Summary:**

1. Electrons are emitted from solids due to:
   1. Heat.
   2. Ultraviolet light.
   3. Impact of other electrons moving with high velocity.

2. An exhausted glass bulb containing (1) a filament which can be heated by a current from an external source and (2) a separate plate provided with an external contact is called a *two-electrode thermionic vacuum tube.*

3. The battery which supplies the filament current is known as the "A" battery and is usually a storage battery.

4. The battery which supplies the plate potential is known as the "B" battery. In receiving sets, it is usually composed of dry cells. A small generator is normally used for this purpose in transmitting sets.

5. The plate current of a two-electrode tube may be varied by changing either the filament current or the plate potential.

6. The three-electrode tube is equivalent to a two-electrode tube with an additional electrode, called the *grid,* placed between the plate and filament.

7. The grid of the three-electrode tube increases the space charge effect when negative and decreases the space charge effect when positive.

8. The plate current of a three-electrode vacuum tube can be varied in three ways, as follows:

1. Changing the filament current.
2. Changing the plate potential.
3. Changing the grid potential.

Of these three ways, the last is the most effective.

9. The characteristic plate current grid voltage curve of a vacuum tube has a lower bend of changing slope, a linear portion of constant slope and an upper bend of changing slope. This curve also shows that a saturation point exists beyond which no increase in current will be caused by a further increase in grid potential.

10. When the grid is positive with reference to the filament, electrons are attracted by the grid and returned to the filament through the external grid circuit. Small grid currents also flow for low negative values of grid potential. This is due either to the presence of gas or to electron bombardment of the grid.

11. The initial steady grid potential is called *grid bias,* and the point on the plate current grid potential curve which has an abscissa equal to the grid bias is called the *operating point.* By adjusting the grid bias, the operating point may be brought to any desired part of the characteristic curve.

12. The voltage amplification coefficient of a vacuum tube is the ratio of the change in plate potential to the corresponding change in grid potential required to produce a certain minute change in plate current. This coefficient depends upon certain structural characteristics of the tube and, to a lesser extent, upon the conditions under which it is operated.

13. The internal output resistance of a tube is the ratio of a small change in plate potential to the resulting small change in plate current, everything else being constant.

14. The mutual conductance of a tube is the ratio of a small change in plate current to the change in grid potential which produced the current change, everything else being constant.

15. $$\mu = R_p G_m.$$

16. The power amplification coefficient is the ratio of the A.C. power dissipated in the plate circuit to the A.C. power supplied to the grid circuit.

17. The static characteristic curve of a vacuum tube is lower and its slope is less when there is appreciable resistance in the external plate circuit.

18. The dynamic curve of a tube is obtained with an alternating electromotive force impressed on the grid. It is somewhat different from the static curve, particularly when the external plate circuit contains a reactive component.

19. Gas makes a tube erratic and is in general undesirable.

However, carefully selected tubes containing a small amount of gas (known as soft tubes) are often very satisfactory for detectors.

20. In practical forms of tubes:
    1. Some have oxide coated filaments to increase electron emission at a given temperature;
    2. Some have one filament, two parallel grids, and two parallel plates;
    3. Some have plane plates and grids;
    4. Some have practically cylindrical plates and grids.

21. The so-called A.C. tube has an additional electrode in the form of a heater operated by alternating current and radiating heat to a cathode, from which electrons are emitted.

22. The *screen grid* tube has a second grid placed between the filament and plate. This tube may be connected so that one grid simply compensates for the space charge and the other grid is used as signal grid. This tube is normally used as a radio-frequency amplifier, in which case the additional grid is so biased as to neutralize the internal capacity between the signal grid and the plate.

23. The four fundamentals pertaining to circuits using the three-electrode vacuum tube are:
    1. The input circuit is the grid circuit and the output circuit is the plate circuit.
    2. There must be a conducting path for both direct and alternating current from the grid to the filament and from the plate to the filament.
    3. Choke coils are used to prevent radio- and audio-frequency currents, or radio-frequency currents only, from flowing in any particular branch of a circuit.
    4. Stopping condensers are used to stop the flow of direct current in any particular branch of a circuit, and to prevent the "B" battery of one tube from biasing the grid of another tube.

56. Self-Examination:

1. Name three ways in which electrons may be liberated from a solid conductor.

2. Explain the action of a two-electrode vacuum tube.

3. Explain the action of the three-electrode vacuum tube.

4. Explain how a series of plate current grid potential curves might be obtained with various values of plate potential.

5. Describe the typical characteristic curve of a vacuum tube.

6. State three ways of varying the plate current of a three-electrode vacuum tube and indicate which is the most effective.

7. What is the significance of the following:
   1. Grid bias;
   2. Operating point?

8. How might the operating point be placed on any desired portion of the characteristic curve?

9. What is meant by the slope of a characteristic curve at any point?

10. In what general part of the characteristic curve is the slope greatest?

11. What is meant by *space charge* and how is it influenced by the grid?

12. Explain the significance of the *voltage amplification coefficient* of a vacuum tube

13. Explain the significance of the internal output resistance of a tube as distinguished from the D.C. internal plate resistance.

14. Explain the signficance of the *mutual conductance* of a tube.

15. Develop the relationship between the quantities referred to in 13, 14, 15 above for any given change in plate current.

16. Explain the relation between a static curve of a vacuum tube obtained with external plate resistance and a corresponding curve obtained without external plate resistance.

17. What is the difference between static and dynamic curves of vacuum tubes?

18. What is the signficance of *power amplification coefficient* of a vacuum tube?

19. State the effect of gas on the operation of vacuum tubes.

20. Describe some of the constructional features of practical forms of vacuum tubes.

21. Describe the A.C. tube.

22. Describe the screen grid tube.

23. What are the four fundamentals pertaining to circuits employing the three-electrode vacuum tube?

Section V.

THE VACUUM TUBE DETECTOR

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57. **General.**—In Section III, the manner in which an electromagnetic wave was intercepted and detected by a crystal detector set was explained, rectification being accomplished in this case by reason of the unilateral conductivity of a combination of dissimilar minerals in contact. The vacuum tube detector is very similar to this except that rectification is accomplished by reason of the characteristics of the thermionic vacuum tube. There are two general types of vacuum tube detectors, which we shall call the *"C" bias detector* and the *grid condenser-grid leak detector.* These detectors rectify the radio-frequency currents in somewhat different ways. They are described below.

58. **"C" Bias Detector.**—In using a three-electrode vacuum tube to rectify signal currents, the tube is invariably connected so that potentials due to variations in the signal current are impressed on the grid circuit of the tube. This is exemplified in the circuit of the *"C" bias detector* shown in Fig. 53. The portion

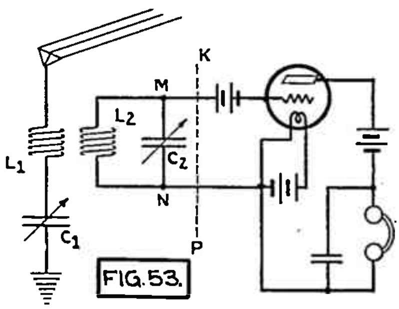


Fig. 53. Simple "C" Bias Detector.

of this circuit to the left of the line KP is exactly the same as that shown in Fig. 37 for the crystal detector circuit, and the intercepted electromagnetic wave produces variations in potential across terminals M and N in exactly the same manner as previously described for the crystal detector circuit. The only difference between the two circuits is that a vacuum tube, with its associated "A," "B" and "C" batteries, is substituted for the contact rectifier used in the crystal detector circuit.

Let us investigate the manner in which the vacuum tube rectifies the signal current. In the first place, it should be observed that the grid bias, the plate potential, and filament current used in this detector are constant. Fig. 54 represents the characteristic plate current-grid voltage curve of such a tube, for the particular plate voltage and filament current used. The grid bias is represented by the abscissa G_B, and the constant plate current is represented by the ordinate I_{dc}. This, of course, refers to the stable condition of the tube with no current flowing in the antenna circuit.

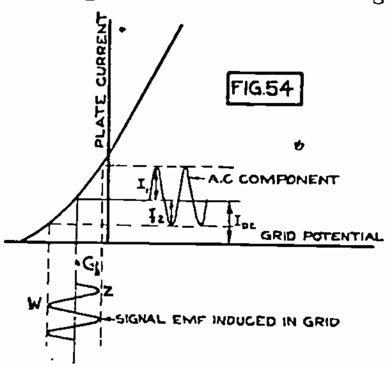


Fig. 54. Showing Rectification of Signal Current by Curvature of Plate Current Characteristic.

Now let us assume that an electromagnetic wave is intercepted by the antenna and that a signal electromotive force, one cycle of which is shown in Fig. 54, is induced in the grid circuit. Because of the curvature or changing slope of the characteristic curve, the half cycle marked Z of this signal electromotive force produces a change in plate current marked I_1, and the half cycle marked W produces a much smaller change in plate current, marked I_2. It appears, then, that even though the amplitudes Z and W of the two half cycles of the signal electromotive force are nearly equal to each other, the amplitudes I_1 and I_2 of the resulting plate current are very different in magnitude. The plate current, therefore, is rectified because of the changing slope of the characteristic curve of the tube. This rectified plate current flows through the telephone condenser, thereby charging it.

Because of the constants (resistance and inductance) of the receiver and the capacity of the telephone condenser, the condenser discharges through the receiver in accordance with the audio-frequency variations in amplitude of the signal electromotive force. If, then, the signal electromotive force is of the form shown in curve A, Fig. 55, the resulting plate current will be of the form shown in curve B and the displacement of the telephone diaphragm will be as shown in curve C. This type of detector is better than a crystal detector, because it produces a much greater relative change in the amplitudes of positive and negative half cycles of the signal current, by reason of increasing one and decreasing the other, rather than simply decreasing one more than the other, as is the case in the crystal detector.

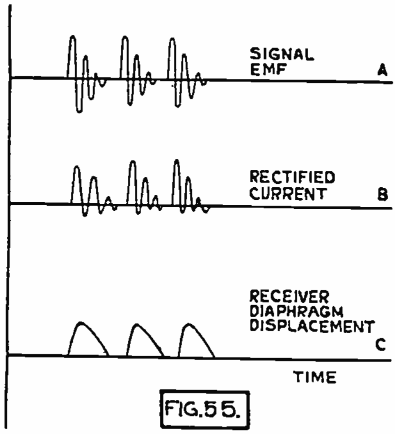


Fig. 55. Detector Action of the Vacuum Tube.

This detector (that is, circuit shown in Fig. 53) does not accomplish the detection of continuous waves, because there are no audio-frequency variations in the amplitudes of such waves; and it is, therefore, similar to the crystal detector in that it is capable of receiving only damped or audio-frequency modulated waves; that is, it is capable of receiving either damped wave telegraph signals, tone modulated telegraph signals, or radiotelephone signals, but not continuous-wave telegraph signals.

In order to rectify the signal current by reason of the curvature of the characteristic curve, it is only necessary to adjust the grid bias so that the operating point will be on the bend of the characteristic curve. In the case of tubes designed for relatively low plate potentials, a grid bias of zero volts will place the operating point on the bend of the characteristic curve, as shown in Fig. 56 by the solid curve. If a higher plate potential were used, the characteristic curve would be displaced to the position shown by the dotted line. A zero grid bias would then cause the operating point to fall on the linear portion of the curve, which would be unsatisfactory for rectification with this type of detector.

When this system of detection (the "C" bias type) is used, the detector tube is usually operated on a low plate potential and a grid bias established by the IR drop across a filament resistor. The circuit of this detector is shown in Fig. 57.

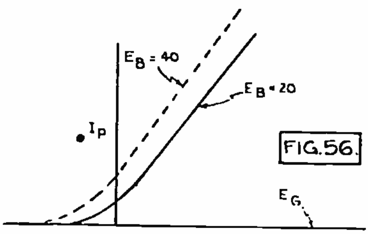


Fig. 56. Plate Rectification Detection with Zero Grid Bias.

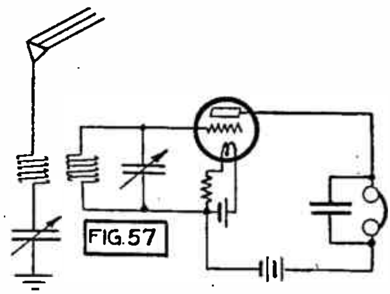


Fig. 57. Obtaining Grid Bias from Filament Resistor.

The "C" bias detector, often referred to as the plate current detector, is used in several modern broadcasting sets as a so-called "power detector." In these cases a relatively high plate potential is used on the detector, and the detector is preceded by sufficient radio-frequency amplification to cause a relatively large voltage to be impressed on the grid circuit of the detector. This voltage is such that the envelope of the radio-frequency grid voltage curve falls on the linear portion of the plate current-grid voltage characteristic of the tube. The power detector is capable of supplying a relatively large amount of undistorted power from its output circuit.

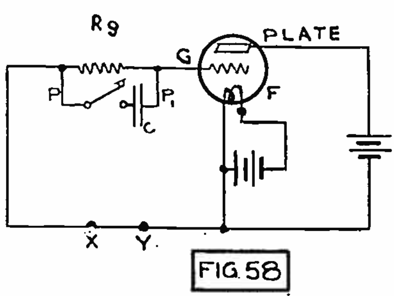


Fig. 58. Grid Condenser-Grid Leak Detector.

59. Action of Vacuum Tube with Grid Condenser and Grid Leak.—Before considering the complete circuit of the grid condenser-grid leak type of detector, let us consider the circuit shown in Fig. 58. In this circuit, with fixed plate and filament potentials, the grid will assume a bias determined by the resistance of the grid resistor R_g and the voltage E_f across the filament. If the resistance of R_g be zero, the grid will be at the same potential as the positive terminal of the "A" battery, and the grid potential will be equal to E_f. If the resistance of R_g be infinite, the steady grid current will be zero and the grid bias will be the grid potential at which the grid current just reaches zero. In the case of the 201A tube represented in Fig. 42(2), this grid potential would be —0.75 of a volt. By applying Kirchoff's voltage law to the circuit GFYXR$_g$ (Fig. 58) and remembering that the grid potential is the difference of potential between G and F, we may determine the grid bias for any intermediate value of the grid resistance. In the case where the grid circuit is returned to the positive side of the filament, the value of the grid bias is given by the following expression:

$$E_g = E_f - i_g R_g.$$

This grid bias is independent of the capacity C of the grid condenser; and if this condenser be a perfect one, the grid bias will be the same with the switch S closed as with it opened. With the switch S closed, the condenser will be charged to a potential equal to $i_g R_g$.

Let us close the switch and deliberately make the resistance of R_g such that the resulting grid bias will cause the operating point on the *grid current*-grid voltage curve to fall on a part of the curve which is of changing slope. If we open the grid circuit and connect a source of radio-frequency alternating electromotive force from X to Y, an alternating component will be added to the grid current, and because of the curvature of the $I_g E_g$ curve this grid current will be rectified. The grid condenser is so selected that its impedance to radio-frequency currents is relatively low, so that only a small portion of the voltage impressed from X to Y is lost in overcoming the opposition of the external grid circuit.

The rectified grid current which flows under these conditions might be represented as in Fig. 59. Let us study its effect on the potential from G to F, Fig. 58. As a result of the positive half cycle of this cur-

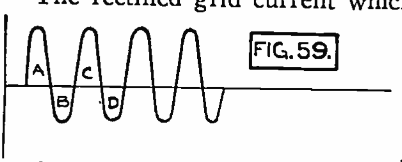


Fig. 59. Rectified Grid Current.

rent as indicated by A, Fig. 59, the plate P of the condenser is charged more positively than before, and thus electrons are attracted from the grid, leaving the grid more positively charged; that is, with a greater deficiency of electrons. This grid, being more positive, will now attract more electrons to itself from the heated filament, and because these electrons are unable to pass through the condenser C and the resistor is unable to pass them in the short time of one-half cycle, they will be trapped in the part of the circuit between the plate P′ of the condenser and the grid G.

During the next half cycle B of the impressed grid electromotive force, the electrons in this part of the circuit P′G will be repelled from the plate P′ to the grid G, but they cannot be forced out of the grid, and therefore they do not escape from the trap between P′ and G.

If the capacity of the condenser C and the resistance of the parallel resistor R be such that the time required for the condenser to discharge through the resistor is of the order of an audio-frequency time period (that is, it will require one twenty-thousandth part of a second for the condenser to discharge through the resistor), then more electrons will be accumulated in the trap between P′ and G during each cycle than can escape, and the grid would consequently be left with an increased negative charge at the end of each cycle. In this manner the grid would become increasingly negative during each cycle, until the variations in impressed grid voltage were unable to charge the condenser more during one-half cycle than it is discharged dur-

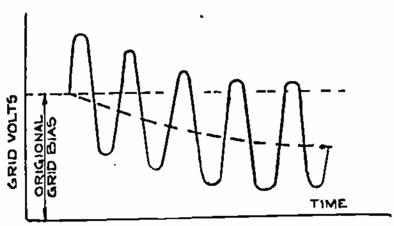


FIG. 60

Fig. 60. Variations in Grid Potential.

ing the next half cycle. The variations in grid potential, therefore, would be of the form shown in Fig. 60, the distortion of the radio-frequency wave form being due to the changing slope of the grid current-grid voltage curve.

Now let us suppose that the electromotive force impressed on the grid is broken up into discontinuous groups or trains of oscillations, as shown in Fig. 61, the groups recurring with audio

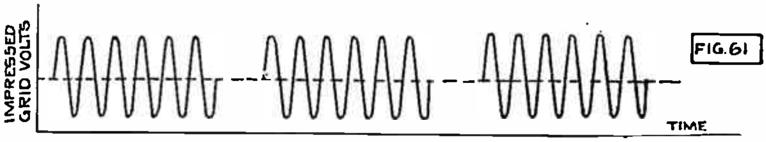


Fig. 61. Discontinuous Groups of Audio Oscillations.

frequency. During the time required for the oscillations within a group the condenser will not have time to discharge through the resistor. However, at the end of each group the condenser will discharge through the parallel resistor or leak, as it is called,

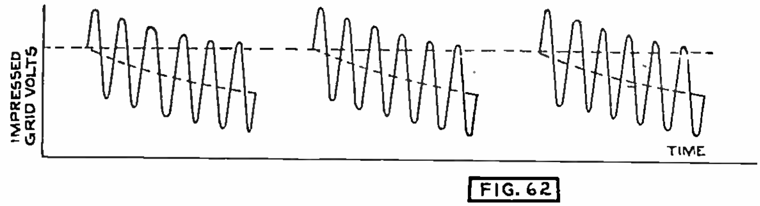


Fig. 62. Potential Variations Inside Tube.

and the actual variations in potential between grid and filament inside the tube will then be as indicated in Fig. 62.

These variations in grid potential would result in exactly

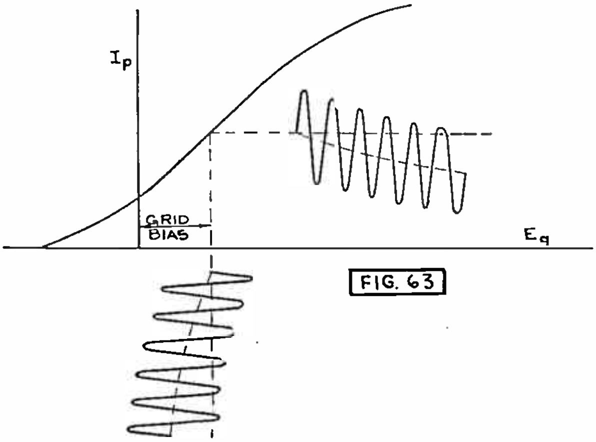


Fig. 63. How the Plate Current Changes with the Grid Potential.

similar variations in plate current, because the grid bias is so adjusted that the operating point falls on the straight line portion of the plate current-grid voltage characteristic. The variations in grid potential and the manner in which the plate current changes with these variations are shown in Fig. 63, from which we see that the resulting plate current is the sum of three components, one of which is the initial steady current, another a rectified radio-frequency current and the third an audio-frequency current. These three components are shown separately in Fig. 64.

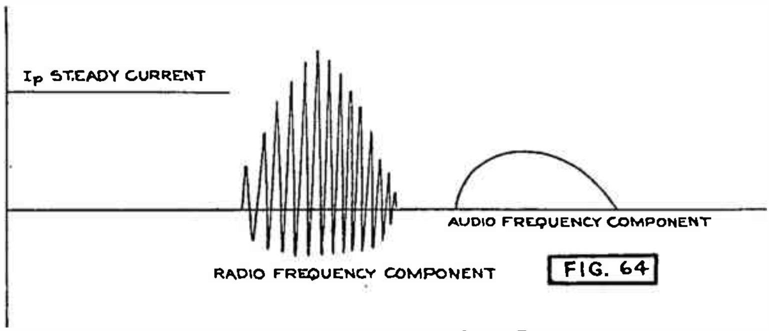
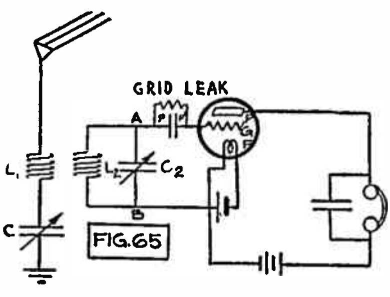


Fig. 64. Components of Plate Current.

60. **Grid Condenser-Grid Leak Detector.**—Next let us consider the so-called *grid condenser-grid leak* detector, which is used in the form shown in Fig. 65 and in a regenerative form (which will be described later) in practically all modern radio receiving sets. With the antenna circuit L_1C and the secondary circuit L_2C_2, Fig. 65, tuned to resonance at the frequency of the wave which we desire to receive, variations in potential across terminals A and B will be produced in accordance with the variations in the signal current in the same manner as previously described



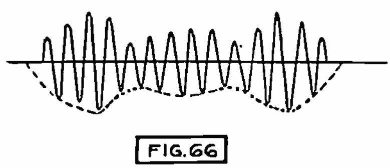


Fig. 66. Wame Form of Typical Signal.

Fig. 65. Circuit of Grid Condenser-Grid Leak Detector.

for other types of detectors. Let us assume that in a particular case the incoming signal is an audio-frequency modulated wave of the form shown in Fig. 66 by the solid lines. The potential between the positive terminal of the "A" battery and the plate P of the series grid condenser is consequently varied in the same manner and as a result of the positive half cycles of this electromotive force electrons are attracted to the grid and are trapped in the space between the plate P′ and the grid G, as explained in the preceding paragraph. These electrons cannot escape through the resistor shunted across the series grid condenser in a radio-frequency time period, but they can escape in an audio-frequency time period, so that the actual grid potential will be the sum of two components, one of which is of the rectified radio-frequency form, and the other of which is due to the discharge of the series grid condenser through its leak, and is of the form shown by the lower dotted curve in Fig. 66. The variations in

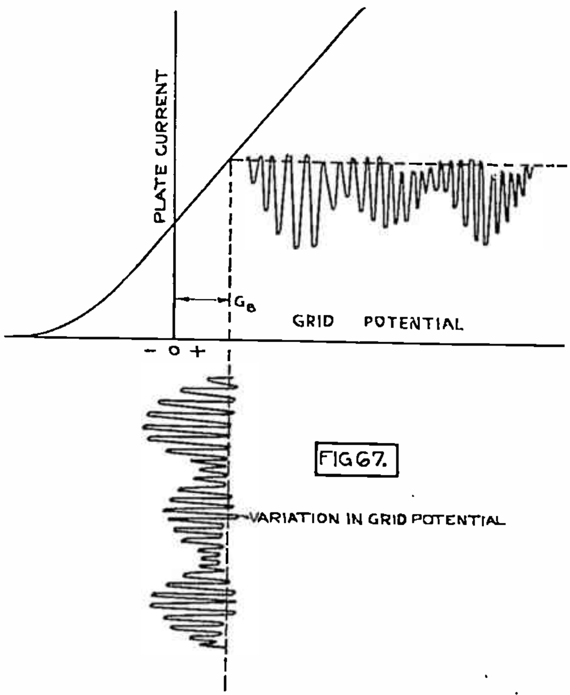


Fig. 67. Operation of Tube on Straight Section of Curve.

grid potential will produce corresponding variations in plate current, since the operating point is on the straight line portion of the characteristic curve, as shown in Fig. 67.

The plate current, therefore, is made up of a steady component, a radio-frequency component of the same form as the incoming wave, and an audio-frequency component of the same form as the lower envelope of the incoming wave. The audio-frequency component of the plate current would flow through the telephone receivers, and the radio-frequency component would flow through the telephone condenser. Consequently, the receiver diaphragm would be displaced in accordance with the audio-frequency envelope of the incoming wave, and the receiving operator would hear a sound wave corresponding to that with which the continuous wave was modulated at the transmitting station, or in the case of damped wave telegraphy, he would hear a note of a frequency corresponding to the number of wave trains per second.

This type of detector, like all others described so far, would not be suitable, in the form shown in Fig. 65, for the reception of continuous waves. However, it is much better than the other types of detectors discussed in the preceding paragraphs, because it amplifies the incoming signals to a greater extent than the others.* This amplifying action of the vacuum tube will be described in the next chapter.

61. Summary:

1. The signal electromotive forces are impressed on the grid of the vacuum tube detector and the rectified current is obtained in the plate circuit.

2. Rectification is accomplished in the "C" bias detector by reason of the curvature of the plate current-grid voltage characteristic curve.

3. The "C" bias detector is better than the crystal detector, because it gives some amplification as well as detection.

4. The simple "C" bias detector will detect damped waves or audio-frequency modulated waves, but not continuous waves.

5. The action of the grid condenser-grid leak detector depends upon the curvature of the I_gE_g characteristic and the discharge of the grid condenser through a high resistance leak in accordance

*Any of the detectors described so far may be used for the detection of continuous waves, if they are associated with a suitable high-frequency generator. This will be explained in the section on OSCILLATORS.

with the audio-frequency variations in amplitude of the impressed electromotive force.

6. The grid condenser-grid leak detector gives a greater amount of amplification and less distortion than the other types, and is, therefore, the most generally used.

7. The simple grid condenser-grid leak detector will detect damped waves or audio-frequency modulated waves, but not continuous waves.

62. **Self-Examination:**

1. Draw a diagram and describe fully the complete action of a "C" bias detector.

2. Under what specific circumstances does a detector, functioning on the principle of "C" bias detector, not require a grid battery?

3. What types of waves is a "C" bias detector capable of detecting?

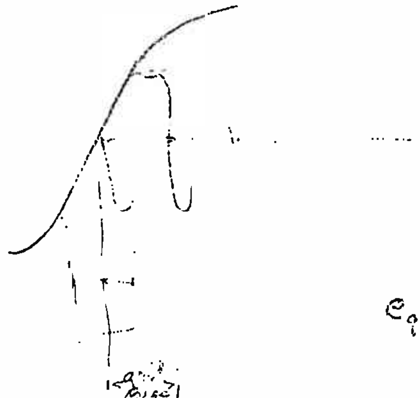
4. What would a receiving operator, whose set was properly tuned to the wave sent out by a C.W. telegraph transmitting station, be able to hear by the interception of this wave, if the receiving detector were of the "C" bias type?

5. Draw a diagram and explain fully the complete action of a grid condenser-grid leak detector.

6. What type of waves is a grid condenser-grid leak detector capable of detecting?

7. Explain why your answer to question 4 would or would not hold for a grid condenser-grid leak detector.

8. Under what circumstances is a "C" bias detector called a "power detector"?



SECTION VI.

THE VACUUM TUBE AMPLIFIER

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TYPES OF VACUUM TUBE AMPLIFIERS	64
CIRCUITS USED IN AMPLIFIERS	65
POWER AMPLIFIERS	66
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63. Elementary Theory of Amplification.—Incident to the consideration of the voltage amplification coefficient of vacuum tubes, it was explained that a given change in grid potential would accomplish several times as great a change in plate current as would be effected by the same change in plate potential, the relationship being that a change e_g in grid potential was equivalent to a change μe_g in plate potential, where μ is the voltage amplification coefficient of the tube. It is because of this fact that we always impress on, or induce in, the grid circuit of a vacuum tube the voltage which we desire to amplify. To illustrate the action of the vacuum tube as a voltage amplifier, let us consider the circuit shown in Fig. 68, in which the voltage e_g, which we desire to amplify, is impressed on the grid circuit of a vacuum tube which has a zero grid bias and a sufficiently large steady plate potential to cause the operating point to fall on the linear portion of the characteristic curve, so that variations in grid potential produce exactly corresponding variations in plate current.

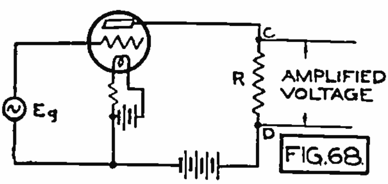


Fig. 68. The Tube Amplifier.

The voltage e_g impressed on the grid circuit is equivalent to a voltage μe_g impressed on the plate circuit, as previously explained, and the alternating component of the plate current is by Ohm's Law equal to the ratio of this equivalent plate voltage μe_g to the total resistance of the plate circuit. The total plate circuit resistance is equal to the sum of the external resistance R and the internal resistance R_p between plate and filament. Representing the alternating component of the plate current by i_p, it follows that:

$$i_p = \frac{\mu e_g}{R_p + R} \qquad (1)$$

Also by Ohm's Law, the alternating voltage across the external resistance R is equal to the product of i_p and R; that is,

$$e_R = \frac{\mu e_g R}{R_p + R} \qquad (2)$$

where e_R represents the voltage from C to D, Fig. 68.

From this we see that

$$e_R = e_g \left(\frac{\mu R}{R_p + R} \right) \qquad (3)$$

and since, in any practical case, the quantity in the parentheses is several times greater than unity, the voltage e_R is several times greater than the voltage e_g. By utilizing the potential from C to D, Fig. 68, therefore, we would obtain an amplified voltage of the same form as the voltage e_g which was originally available.

Equation (2) shows that the amplified voltage is directly proportional to the voltage amplification coefficient μ. Remembering that for a particular value of internal plate resistance, R_p, the coefficient μ is directly proportional to the mutual conductance, that is, the slope of the plate current-grid voltage curve, we see that the slope of this curve is very important in determining the voltage amplification. In using the vacuum tube as a voltage amplifier, therefore, it is desirable to have the slope of the plate current-grid voltage curve as great as possible. For any particular curve, the slope is greatest over the straight-line portion of the curve. For this reason and also because it is necessary that the variations in plate current be of exactly the same form as the variations in grid potential, the operating point on the characteristic curve must be on the linear portion of the curve when the tube is used as a voltage amplifier.

We are sometimes interested in power amplification rather than voltage amplification. However, the same conditions obtain in both cases; that is, the operating point must be on the linear portion of the plate current-grid voltage curve, and the slope of the curve should be as great as possible.

In the case of either voltage amplification or power amplification, the slope of the plate current-grid voltage curve is greater for increased values of plate battery. However, increasing the plate battery requires more cells in series to make up the additional electromotive force and also results in a larger steady current being drawn from the batteries and the consequent rapid consumption of the cells. It is necessary, therefore, that a balance be established between a large plate battery with a curve of very high slope, and a smaller plate battery with a curve of lesser slope but more economical use of the battery.

64. **Types of Vacuum Tube Amplifiers.**—Let us consider the more important types of circuits used in amplifiers. In Fig. 68 the amplified voltage was obtained across the resistor in the external plate circuit; that is, the originally available electromotive force which it was desired to amplify was impressed on the grid circuit of the tube and the IR drop in potential across the external plate resistance was utilized as the amplified electromotive force. This external plate resistance might have been replaced with an inductance coil, as shown in Fig. 69(1), in which case the iZ drop in potential across the coil would have been the amplified electromotive force. Still another and very important method is to substitute the primary of a transformer for the external plate resistor and utilize the voltage induced in the secondary as the amplified voltage, as shown in Fig. 69(2).

Usually more than one amplifier is required to give the neces-

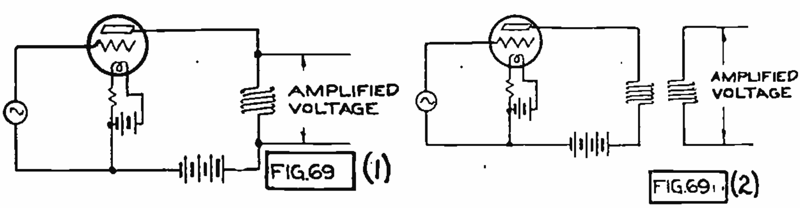


Fig. 69. Two Forms of Vacuum Tube Amplifiers.

sary amplification, and consequently two or more amplifiers are associated, so that the output of one is made the input of another, each amplifier constituting what is called a *stage of amplification*. The complete unit consisting of two or more amplifiers is called a *cascade amplifier*. Amplifiers are further classified in accordance with the type of coupling used between the output circuit of one tube and the input circuit of the next. For example, in the two-stage amplifier shown in Fig. 70, the transformer T is the coupling

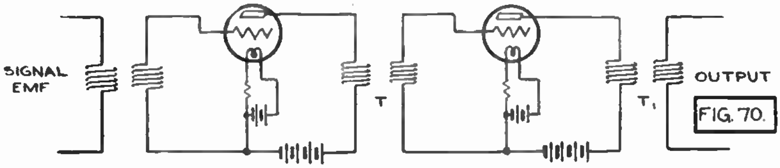


Fig. 70. Two-Stage Transformer Coupled Amplifier.

unit between the output circuit of the first tube and the input circuit of the second tube, and this amplifier is, therefore, called a *transformer coupled* amplifier. Similarly, the amplifier shown schematically in Fig. 71 is called a *resistance coupled* amplifier.

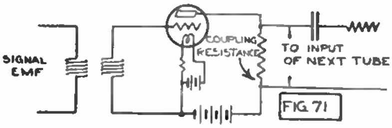


Fig. 71. Schematic Diagram of Resistance Coupled Amplifier.

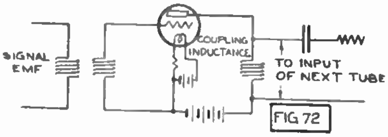
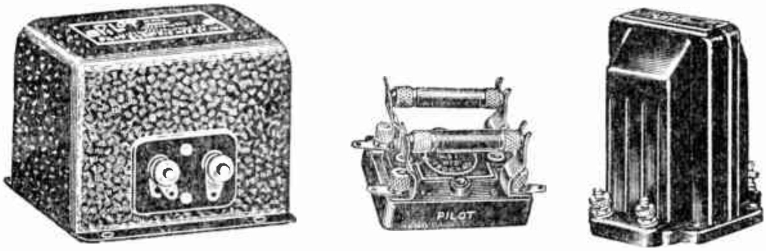


Fig. 72. Schematic Diagram of Impedance Coupled Amplifier.

because the coupling unit between the two stages is a resistor.

Also, the amplifier shown schematically in Fig. 72 would be called an *impedance* or *choke coil coupled* amplifier, since the



Left, Right: Typical Audio Amplifying Transformers. Center: Resistance Coupling Unit.

coupling unit between the plate of one tube and the grid of the other is an inductance coil.

If amplifiers are designed and used to amplify radio-frequency currents, they are called *radio-frequency amplifiers,* and when they are designed and used to amplify audio-frequency currents they are called *audio-frequency amplifiers.*

At radio receiving stations amplifiers are invariably associated with a detector. Radio-frequency amplifiers are used ahead of the detector, where we are concerned with radio-frequency currents; audio-frequency amplifiers are used after the detector, where we are interested in audio-frequency currents. When weak signals are intercepted at a receiving station, it is necessary to have several stages of amplification, and these should be divided between radio and audio frequency in order to prevent distortion. This arrangement is symbolically represented in Fig. 73.

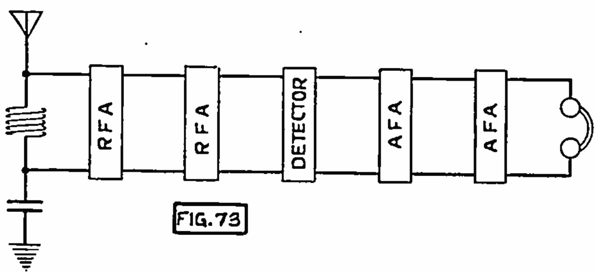


Fig. 73. Symbolical Arrangement of Amplifiers and Detector.

The distortion which results from the use of too many stages of one kind of amplification (*i.e.,* radio or audio frequency) is due to overloading the tubes, which we will consider in a little more detail. Let us assume that the electromotive force input of the first amplifier in a given circuit is represented by curve A, Fig. 74, and that after passing through this amplifier the voltage applied to the second stage is as shown in curve B. Each stage amplifies the voltage more, until after perhaps four stages it is as shown by curve C. The amplitudes of these oscillations are now so great that when they are impressed on the grid of the next tube, they either extend beyond the linear portion of the characteristic curve and therefore introduce distortion of the wave form, or they exceed the grid bias and cause distorting grid currents to flow while the grid is positive. This is shown in Fig. 75, and is true of either radio- or audio-frequency amplification. Obviously, this is the limiting factor as to the number of stages of amplification of one kind (*i.e.,* radio or audio frequency) which may be used.

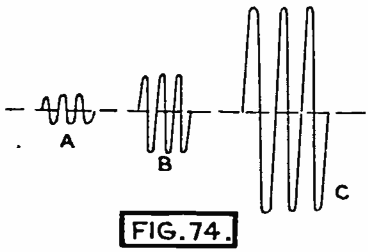


Fig. 74. Amplification of Signal by Tube Amplifiers.

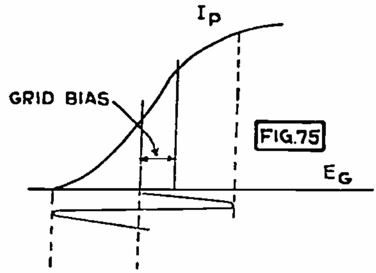


Fig. 75. Distortion Caused by Limitation of Tube.

A larger total number of stages of amplification may be used when part of them are radio frequency and part audio frequency, because we are then able to amplify the incoming signals at radio frequency as much as is possible without distortion, then pass this amplified signal current through the detector, which impresses on the input circuit of the first audio-frequency amplifier a voltage of entirely different form and amplitude which may then be passed through several stages of amplification.

65. Circuits Used in Amplifiers.—In the preceding section the circuits shown are merely schematic representations of the various types of vacuum tube amplifiers, and they do not represent the actual circuits used in practical forms of amplifiers. Now let us consider the factors which influence the manner in which the various components are actually connected together.

The vacuum tubes designed for use as voltage amplifiers require between 40 and 100 volts plate potential, and they are invariably operated with either zero or negative grid bias. The proper grid bias is often obtained by connecting the grid return to the negative terminal of the "A" battery, although a "C" battery is usually used for this purpose.

The voltage of the "B" battery will be determined by the nature of the external plate circuit and the plate potential required for operation of the tube. If the required plate potential of the tube is, say, 40 volts and the external plate circuit contains resistance, the electromotive force of the battery must be equal to the sum of the plate potential and the IR drop in the external plate circuit.

In resistance coupled amplifiers the voltage amplification increases with the external plate resistance, as was previously explained, and with a given value of steady plate current, the plate battery would have to be relatively very large in order to provide the required potential between plate and filament inside the tube. If the amplifier is impedance or transformer coupled, the resistance of the coupling unit may be made small and still the total impedance, which is the important factor in these cases, may be kept large. In such cases it would not be necessary to use such a large plate battery to obtain the required plate potential.

On the other hand, the coupling unit in impedance coupled and transformer coupled amplifiers has a greater impedance to currents of higher frequencies than to those of lower frequencies, and since the amplification depends upon this impedance, electromotive forces of one frequency will be amplified more than those of another and, consequently, distortion would be introduced.

When transformer coupling is used in amplifiers, it is possible to obtain additional amplification by using step-up transformers, so that we would then obtain amplification through the tube and through the transformer. The turn ratio of transformers used in amplifiers differs from a one-to-one ratio to a one-to-eight ratio, audio-frequency transformers, in general, being of a higher turn ratio than those used in radio-frequency amplifiers. Transformer coupled amplifiers also have the advantage that no stopping condensers are required to prevent direct potentials due to the plate battery from reaching the grid of another tube. This may be more readily understood from the consideration given below to the actual wiring diagrams of practical forms of amplifiers.

The use of separate "A," "B" and "C" batteries for each tube in a cascade amplifier is uneconomical, so that one "A" battery is actually used to heat all the filaments, one "B" battery to supply all the plate potentials, and one "C" battery (when necessary) to supply all the grid biases. This is exemplified by the circuit shown in Fig. 76 of a three-stage transformer-coupled, radio-frequency amplifier.

In this circuit no "C" battery is used, the necessary grid bias being obtained by connecting the grid back to the negative terminal of the common "A" battery, which supplies current to the three filaments in parallel through separate filament control

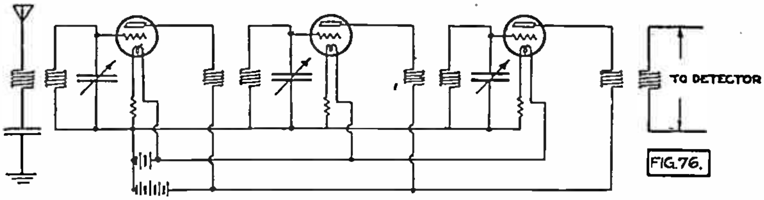
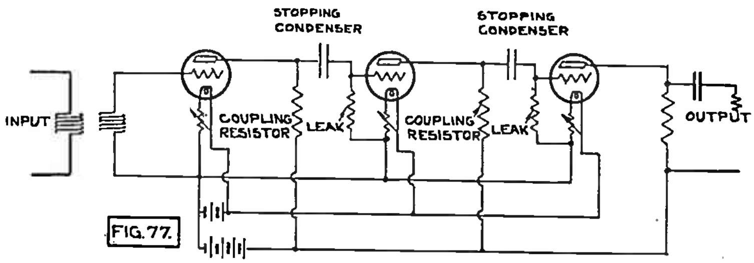


Fig. 76. Three-Stage Transformer Coupled Radio-Frequency Amplifier.

resistors for each tube. The filaments of the three tubes might have been connected in series and one rheostat might have been provided for all tubes. The "B" battery in this case is common to all tubes.

Common batteries might also have been used in a resistance coupled amplifier, as shown in Fig. 77, or in an impedance coupled amplifier as shown in Fig. 78. In both of these cases it is neces-



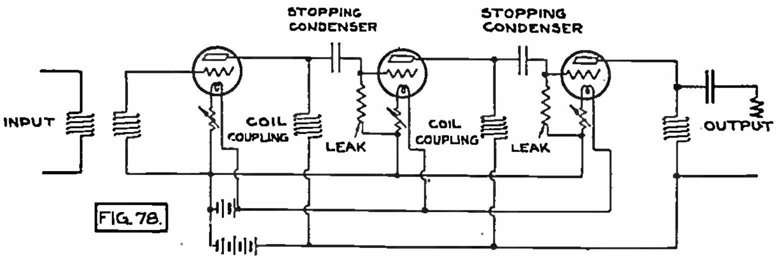


Fig. 77. Resistance Coupled Amplifier.
Fig. 78. Impedance Coupled Amplifier.

sary to provide stopping condensers to prevent the plate potential of one tube being impressed on the grid of the next. These stopping condensers, being series grid condensers, would trap electrons between the grid and the adjacent condenser plate were it not for the high resistance leakage path provided for their return to the filament circuit.

In the actual wiring of most types of radio-frequency amplifiers some provision is made for neutralizing the inter-electrode capacity between the plate and grid inside the tube, in order to prevent the amplifier from generating radio-frequency oscillations within itself. This will be explained in the chapter on Oscillators

Another type of amplifier circuit which is sometimes used in receiving sets is shown in Fig. 79 and is known as the *push-pull amplifier*.

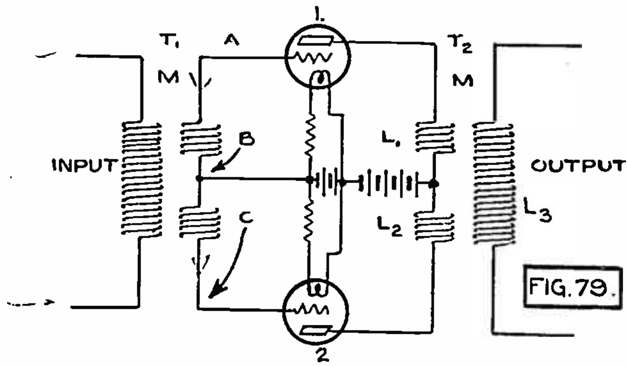


Fig. 79. Push-Pull Amplifier.

The advantage of this circuit is that it surely eliminates any distortion which might exist in ordinary amplifiers due to the non-linear characteristic of the tube, and at the same time gives about twice as much amplification as one stage of amplification.

Suppose that at a certain instant the voltage induced in the secondary of transformer T_1 (Fig. 79) is such that the point A is positive with reference to B, and B is equally positive with reference to C. This will result in an increase in current through the plate circuit of the tube No. 1 and a decrease in plate current through tube No. 2. Coils L_1 and L_2 in the plate circuits of tubes 1 and 2, respectively, are so coupled to coil L_3 that an increasing current through L_1 induces a voltage in L_3 in the same direction as that induced by a decreasing current in L_2. Since this is true, the effect in the output coil L_3 of the two tubes is additive. Now let us assume that each tube has a non-linear characteristic, as shown somewhat exaggerated in Fig. 80. The *a* half cycle of the sinusoidal signal voltage increases the plate current of tube No. 1 more than the *b* half cycle decreases it. However, the *a* half cycle of the signal voltage decreases the plate current of tube No. 2, and due to the non-linear characteristic of tube No. 2, this decrease in plate current during the half cycle *a* will be less than the increase in plate current during the half cycle *b*.

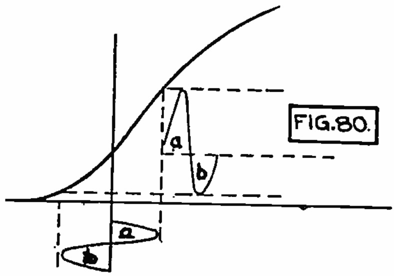


Fig. 80. Action of Tube with Non-Linear Characteristic.

Since an increase through the plate current of tube No. 1 has the same effect as a decrease in plate current through tube No. 2, insofar as the direction of the electromotive force induced in the output coil L_3 is concerned, we may add the increase in current through one tube at a certain instant to the decrease in current through the other tube at that instant. Consequently, the total electromotive force induced in the output coil L_3 is symmetrical in form and the distortion which would have resulted from using these same two tubes as two separate stages of amplification is eliminated.

66. **Power Amplifiers.**—In transmitting sets we are often interested in power amplifiers. For example, we might desire to amplify the output of a high-frequency generator, in which case we would couple the output circuit of the generator to the grid circuit of a vacuum tube amplifier and obtain the amplified power in the plate circuit of the tube. Power amplifiers are no different from voltage amplifiers, except that the tubes are usually larger and require higher plate voltages and filament currents than the smaller tubes used for voltage amplification, and the resistance of such tubes is lower than those of voltage amplifying tubes.

The last stage of audio-frequency amplification used in receiving sets might also be a power amplifier, particularly when a loud speaker is used instead of a headset receiver.

67. **Telephone Repeaters.**—The vacuum tube amplifier is not only used in radio, but in many other divisions of science and engineering. One of the most important uses of the vacuum tube is in the telephone repeater, which is extensively used in long line telephone circuits. It consists of two vacuum tube amplifiers so combined as to give two-way amplification.

In the amplifier circuits considered in the preceding paragraphs it was only possible to amplify one way (in one direction); that is, if the signal voltage to be amplified were impressed at X, Fig. 81, and passed through the several amplifiers, the final amplified voltage would have been obtained at Y. However, it would be impossible to obtain the amplified voltage at X by impressing the available voltage at Y. In wire telephony, we are concerned with two-way transmission over a pair of wires connecting two

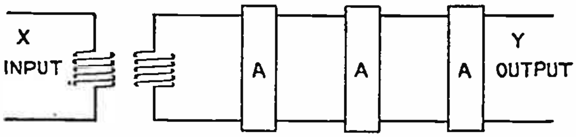


FIG. 81.

Fig. 81. One-Way Amplifier Circuit.

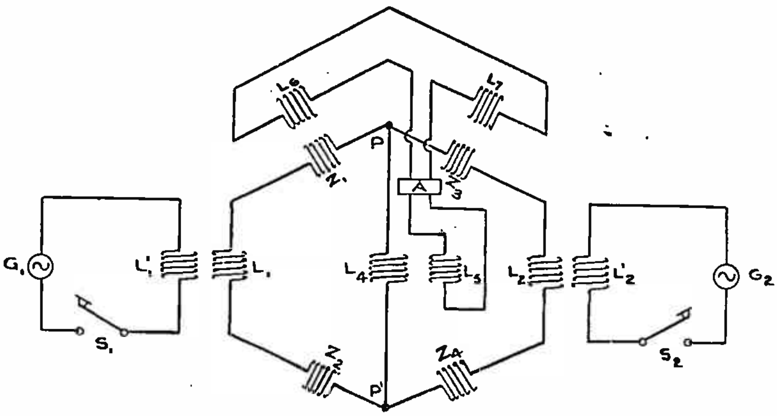


FIG. 82

Fig. 82. Illustrating Principle of Telephone Repeater.

subsets, and a one-way amplifier would be unsuitable for this purpose.

To surmount this difficulty the American Telephone & Telegraph Company has developed two types of vacuum tube repeaters or two-way amplifiers, both of which depend upon a balanced bridge principle, which may be explained as follows:

Referring to Fig. 82, let us assume that the equivalent impedances of Z_1, Z_2 and L_1 equals that of Z_3, Z_4 and L_2. Now if the switch S_1 be closed, the generator G_1 is impressed on the coil L'_1 and an alternating electromotive force is induced in the coil L_1, thus causing a current to flow through Z_1 where it divides, most of it flowing through the circuit L_4, Z_2 and back to L_1, the remainder flowing from Z_1 through Z_3, L_2, Z_4, Z_2 back to L_1. The alternating current flowing through coil L_4 induces a corresponding electromotive force in coil L_5, which electromotive force is amplified by vacuum tube amplifier A, Fig. 82. The output of this amplifier is connected to the circuit containing coils L_6 and L_7, from which coils an amplified electromotive force is induced in Z_1 and Z_3, thus increasing the current in the circuit Z_1, Z_3, L_2, Z_4, Z_2, L_1. The points P and P′ across which the coil L_4 is connected are then at the electrical center of the system, so that there is no difference of potential between these two points and the amplified electromotive force does not result in an amplified current in coil L_4 which would be reamplified by the amplifier and ultimately produce oscillations and distortion. This may be seen from Fig. 83, in which the direction of the two induced electromotive forces at a particular instant is shown by the arrows, these electromotive forces being equal. Because of the direction and equality of these electromotive forces, and since the impedances to the left of PP′ are equal to those on the right, no difference of potential between the points P and P′ results from the electromotive forces induced in the main circuit from the output circuit of the amplifier.

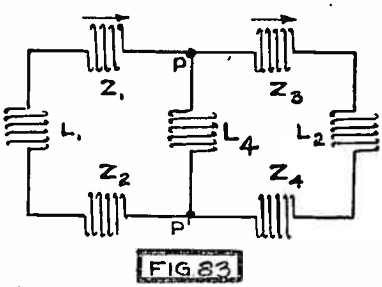


Fig. 83. Repeater Action.

The actual wiring diagram of one type of repeater circuit, known as the 21-type repeater circuit (two-way one-tube repeater), is shown in Fig. 84, in which the components are marked with

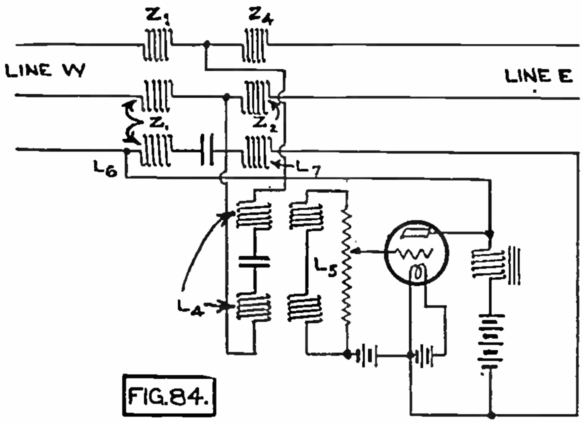


Fig. 84. Telephone Repeater Type 21.

the same letters as those used on corresponding parts in Fig. 82. This type of repeater requires that the two lines (west and east) be balanced, that is, they must have equal impedances, as this is a necessary condition to the operation of the repeater, as explained in connection with Fig. 82.

The other type of repeater developed by the American Telephone & Telegraph Company, and known as the Type 22 Repeater Circuit (two-way two-tube type repeater), is shown in Fig. 85. This type of repeater is provided with two artificial lines, one of which is balanced against each real line, thereby obviating the

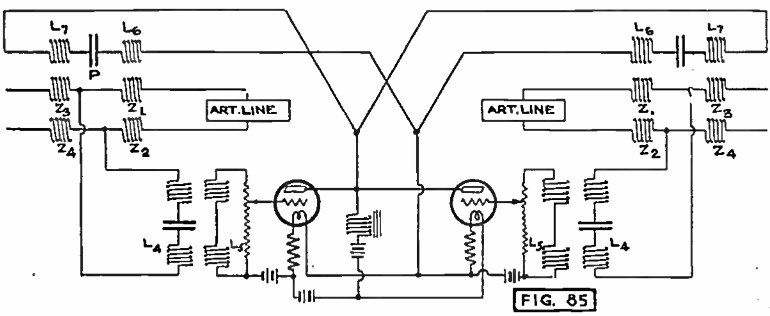


Fig. 85. Telephone Repeater Type 22.

necessity for the real lines being balanced against each other.

The type 22 repeater circuit is often associated with a number of one-way amplifiers in a so-called *four-wire repeater,* which simply consists of a type 22 repeater circuit with one-way amplifiers interposed at X, Y, Z and W (Fig. 85), or as many more one-way amplifiers as may be necessary placed in the same leads. The four-wire repeater is schematically represented in Fig. 86.

We see that while the type 22 repeater circuit used as such is located in its entirety at one place, and requires two wires connecting the east and west stations, the four-wire repeater is equivalent to two type 22 repeaters, with additional one-way amplifiers spread over the entire distance from

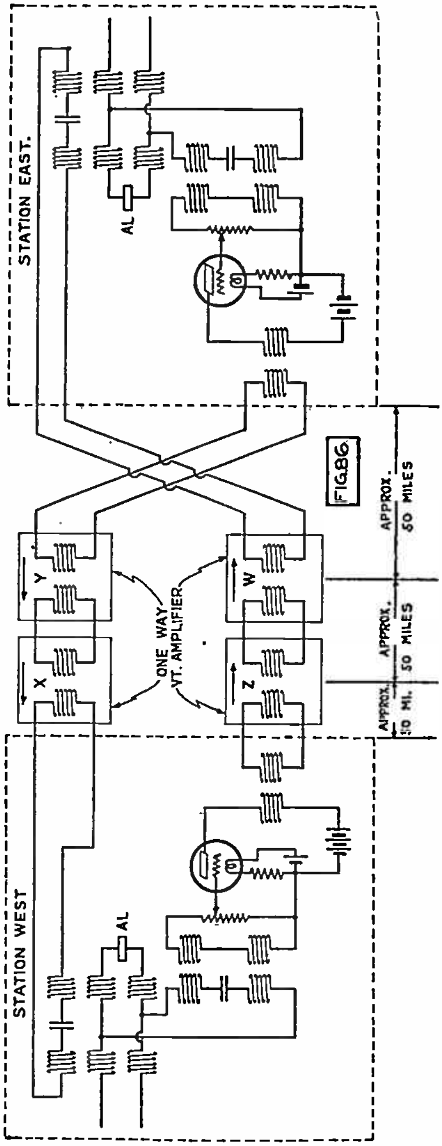


Fig. 86. Four-Wire Telephone Repeater.

*The four-wire repeater may be considered as requiring two communication channels over the entire distance, and while these two channels are provided by two pairs of wire in this case, it is possible to provide the two channels over one pair of wires by means of *carrier frequencies,* as will be explained later.

the west to the east stations and requiring four wires over the entire distance* (see bottom of page 111).

Four-wire repeaters are used on long lines where more than one type 22 repeater would be required, each of which would have to be kept balanced at all times, which is difficult to realize in practice because of the changing conditions along the line due to atmospheric variations. Obviously, the four-wire repeater would have to be balanced at two stations only and for relatively short lines.

68. Summary:

1. An available electromotive force may be amplified by a vacuum tube, due to the fact that a voltage e_g impressed on the grid of the tube will be equivalent to a voltage μe_g in the plate circuit.

2. When it is desired to amplify a certain available voltage, this voltage is impressed on the grid circuit of the amplifier tube, and the amplified voltage is obtained by utilizing the iZ drop across an impedance in the external plate circuit, or the electromotive force induced in the secondary of a transformer, the primary of which is connected in the external plate circuit.

3. A number of amplifiers connected together so that the output of one tube is made the input of the next tube constitutes a *cascade amplifier* and each tube is called a *stage of amplification.*

4. Cascade amplifiers are classified according to the type of coupling between stages as:
   1. Transformer;
   2. Resistance;
   3. Impedance or choke coil.

5. Amplifiers designed to amplify radio-frequency currents are used ahead of the detector at receiving stations, and are called *radio-frequency amplifiers.*

6. Amplifiers designed to amplify audio-frequency currents are used after the detector at receiving stations and are known as *audio-frequency amplifiers.*

7. When a number of stages of amplification are required, they should be distributed between radio- and audio-frequency amplifiers, in order to prevent distortion due to overloading the tubes.

8. The "B" battery voltage must be equal to the required plate potential and the IR drop in the external circuit. For this reason, particularly, high-voltage "B" batteries are required in resistance coupled amplifiers.

9. Due to the variations of reactance with frequency, impedance and transformer coupled amplifiers often amplify electromotive forces of one frequency more than another, and thereby give distortion.

10. Transformer coupled amplifiers may provide amplification through the transformer as well as through the tube.

11. Common "A," "B" and "C" batteries are used in cascade amplifiers for reasons of economy.

12. The push-pull amplifier gives approximately twice the amount of amplification as one separate stage of amplification, and eliminates the distortion caused by the non-linear characteristic of tubes.

13. Telephone repeaters are simply two-way vacuum tube amplifiers.

14. The following types of telephone repeaters are used commercially:

1. Type 21 (two-way, one tube);
2. Type 22 (two-way, two tubes);
3. Four-wire.

69. **Self-Examination:**

1. Describe in detail the amplifying action of a vacuum tube.

2. What is a cascade amplifier?

3. Why is a stopping condenser required in the grid circuit of an amplifier, which is resistance or impedance coupled to a preceding tube?

4. Why is a grid leak required in an amplifier using a stopping condenser?

5. Explain the advantage and disadvantage of each of the types of coupling used in cascade amplifiers.

6. Explain why the use of a greater number of stages of amplification is possible when they are distributed between radio-frequency and audio-frequency amplifiers.

7. Draw a diagram and explain the operation of a push-pull amplifier.

8. Explain the operation of each of the following:

1. Type 21 telephone repeater;
2. Type 22 telephone repeater;
3. Four-wire telephone repeater.

Section VII.

THE VACUUM TUBE OSCILLATOR

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Efficiency of Vacuum Tube Oscillators	72
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70. **General Nature of Oscillator Function.**—It has already been stated that the vacuum tube may be used as a generator of high-frequency electromotive forces, and that when it is so used it is called an *oscillator*. Let us see exactly what the nature of this function is and how the vacuum tube performs it. In the first place, let us assume that we have available a source of energy in the form of a battery capable of delivering direct electrical energy to an external circuit, and that we desire to convert this energy into the form of high-frequency currents. This could be done with the simple apparatus shown in Fig. 87. The condenser C might be charged by throwing the switch S to the left. The condenser would discharge through the inductance L and the resistance R, when the switch S was thrown to the right, and the resulting current in the circuit LRC would be oscillatory. The frequency of this current would depend upon the natural frequency of the circuit; that is, free oscillations would exist in

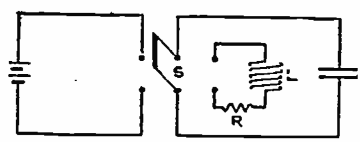


Fig. 87. Simple Oscillator.

the circuit LRC. During each oscillation some of the energy would be dissipated in the resistance, and after a short time all of the energy originally stored in the condenser would have been dissipated in this manner. It would then be necessary to repeat the cycle of charging the condenser by throwing the switch S to the left, and allowing the condenser to discharge by throwing the switch to the right again. By this means we might convert the energy available in the battery into high-frequency currents, but at best, these currents would be damped periodically, reaching zero, and also, to operate the switch S manually with the required rapidity, would be impossible. Our desire, now then, is to associate this source of energy and this oscillatory circuit with a vacuum tube in such a way that continuous oscillations will be produced in the oscillatory circuit. To do this we must provide some means whereby energy will be returned to the oscillatory circuit as fast as it is dissipated.

71. **Requirements for Sustained Oscillations.**—In using the vacuum tube as a generator of high-frequency electromotive forces, the "A," "B" and "C" batteries constitute the sources of energy and the tube is connected to the oscillatory circuit, so that there is coupling between the grid circuit and the oscillatory circuit and also between the plate circuit and the oscillatory circuit.

To illustrate this, let us consider the circuit shown below in Fig. 88. The only sources of energy contained within this circuit

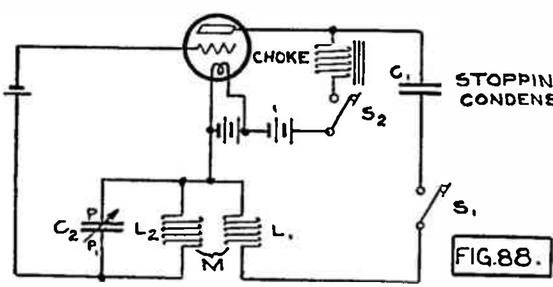


Fig. 88. Simple Oscillator—Modified Hartley Type.

are the "A," "B" and "C" batteries and we propose to obtain high-frequency currents from these sources, by associating them with the vacuum tube and the oscillatory circuit L_2C_2. It should be observed that the grid circuit is *directly coupled* to the oscillatory circuit through the coil L_2, and the plate circuit is *inductively* *coupled* to the oscillatory circuit through the mutual inductance between coils L_2 and L_1.

When the switch S_1 is open and S_2 is closed, a steady current flows from the "B" battery through the choke coil and the internal plate circuit. The condenser C_1 stops this direct current from flowing through the coil L_1 when S_1 is closed, thereby preventing the "B" battery from discharging through the coil L_1, and also makes the reactance of the circuit L_1C_1 to radio-frequency currents low. With S_1 closed, the circuit is completed from plate to filament through the path C_1L_1. This results in a surge in current down through the condenser C_1 and up through coil L_1, this current being absorbed from the internal plate circuit of the tube, since the choke prevents a change in battery current. This changing current through coil L_1 would induce an electromotive force in coil L_2, the direction of which depends upon the manner in which coils L_1 and L_2 are wound. Assuming that this induced electromotive force is such as to cause a surge of current down through coil L_2, the condenser C_2 would be charged with the plate P′ positive. The voltage across this condenser would then be in opposition to the original grid bias, and would, consequently, make the grid less negative than before. This decrease in negative grid potential would effect an increase in the internal plate current. Because of the choke coil in the battery circuit the increased current must flow down through the coil L_1 and up through the condenser C_1, which in turn would induce a voltage in the coil L_2, causing a surge of current up through this coil and charging the condenser C_2 with the plate P positive. Now, the potential across the condenser C_2 aids the original grid bias and results in an increased negative grid potential, and therefore the current from plate to filament is decreased again, with the resulting surge of current down through C_1 and up through L_1, which induces an electromotive force in L_2, and so the cycle is repeated indefinitely.

Because of the amplifying action of the vacuum tube, the alternating electromotive force across the grid condenser C_2 during a given cycle would result in an increased alternating electromotive force across the coil L_1 in the plate circuit, and, consequently, with sufficiently close coupling between L_1 and L_2, the electromotive force induced in coil L_2 would be greater than that which previously existed across the condenser C_2. For this reason the amplitude of each cycle would be greater than that of the preceding cycle, and the oscillations of the plate current would continue to increase until the instantaneous values of plate current varied between some maximum and some minimum determined by the coupling and the constants of the circuit. The form of this oscillating plate current is shown in Fig. 89. As long as the circuit remains unchanged these oscillations would continue indefinitely, and an alternating current of a frequency corresponding to the natural frequency of the oscillator circuit L_2C_2 would be sustained in that circuit.

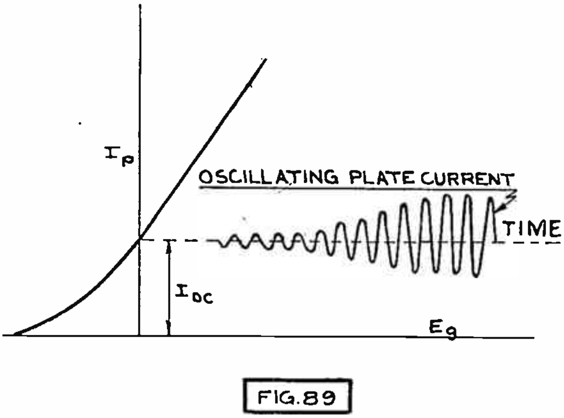


Fig. 89. Build-Up of Oscillation.

Thus we see that by associating the sources of energy (batteries) and the oscillatory circuit with the vacuum tube in such a way as to provide suitable coupling between the plate circuit and the oscillatory circuit, and between the grid circuit and the oscillatory circuit, we have been able to produce sustained oscillations; and therefore we have converted some of the available energy into the form of high frequency currents.

In this type of oscillator the coupling between the grid coil L_2 and the plate coil L_1 is very important. In the first place, this coupling might have been so loose that even though oscillations were sustained they would have been of very small amplitude. Secondly, it should be observed that the electromotive force induced in the coil L_2 might have been in the opposite direction to that necessary to sustain oscillations. This would have been the case had the relative direction of the windings of coils L_1 and L_2 been reversed, and under these circumstances self-sustained oscillations would have been impossible.

For the most part, oscillators are used at transmitting stations, and the tubes utilized for this purpose are power tubes employing relatively large plate potentials. However, any three-electrode vacuum tube may be made to oscillate, and smaller tubes with lower plate potentials are employed as oscillators for several purposes. The following special requirements must be fulfilled in order to sustain oscillation in a three-electrode tube with its associated batteries:

1. There must be an oscillatory circuit, the natural frequency of which determines the frequency of the oscillatory current.
2. There must be a suitable coupling between the plate circuit and the oscillatory circuit.
3. There must be suitable coupling between the grid circuit and the oscillatory circuit.

72. **Efficiency of Vacuum Tube Oscillators.**—It can be shown mathematically that the efficiency of a vacuum tube oscillator cannot exceed fifty per cent., and for practical purposes this may be demonstrated as follows: Let us assume that all of the power of an oscillator is derived from the plate battery. Then the efficiency of the oscillator will be the ratio of the alternating current power in the plate circuit to the direct current power in the plate circuit. Under the condition necessary to make the plate current oscillations of equal amplitude in their positive and negative half cycles, the steady plate current would be equal to the maximum value of the oscillatory current, as it is only under these circumstances that the amplitude of the lower half cycles which reach to zero would be equal to the amplitude of the upper half cycles. Assuming this value of the steady plate current and also that the oscillatory current is sinusoidal in form, as shown in Fig. 90, it follows that the effective value of the oscillatory current is $\dfrac{I_{DC}}{\sqrt{2}}$.

Since the A.C. plate power is equal to the square of the effective value of the oscillatory current multiplied by the plate resistance, and the D.C. plate power is the square of the direct current multiplied by the plate resistance, then:

$$\text{Eff} = \left(\frac{I_{DC}}{\sqrt{2}}\right)^2 R \div (I_{DC})^2 R = \tfrac{1}{2} = 50\%.$$

73. Types of Oscillator Circuits.—The circuit shown in Fig. 88 is only one of a number of circuits which may be used in vacuum tube oscillators. In fact, any circuit which meets the requirements stated above is satisfactory for this purpose.

Possibly the most extensively used circuit is that shown in Fig. 91, which is known as the *Colpitts oscillator.* In this system

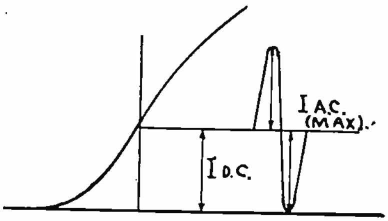


FIG. 90.

Fig. 90. Why Tube Oscillators Are 50% Efficient.

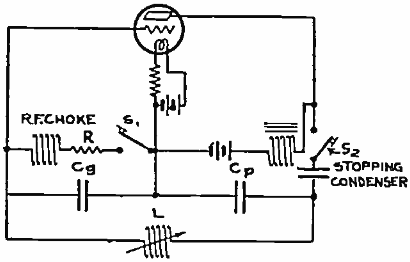


FIG. 91

Fig. 91. Colpitts Oscillator.

the oscillatory circuit LC_pC_g is capacitively coupled to the grid circuit through the condenser C_g, and also is capacitively coupled to the plate circuit through the condenser C_p. With either one of the switches S_1 or S_2 closed, oscillations would be started in this system by closing the other of these two switches. In fact, any change whatsoever in the circuit which effects a change in plate current is sufficient to start the oscillation.

Let us investigate the manner in which oscillations are sustained in this circuit. We may first assume that some change is accomplished in the circuit, such as closing S_2 with S_1 closed. This will suddenly produce a surge of current through the condenser C_p charging its right-hand plate positively. There will also be a surge of current from right to left through the coil L and from left to right through the condenser C_g, thus charging C_g with its left plate positively. This amounts to impressing an additional positive potential between grid and filament, and will result in an increased current from plate to filament inside the tube and through the condenser C_p from left to right, thus charging this condenser with its left plate positive. The condenser C_p would then discharge through the circuit C_gL, charging the condenser C_g with its right plate positive, and consequently reducing the grid potential, with the resulting decrease in plate current through the tube. Since the current through the battery cannot change suddenly because of the choke coil, this decrease in current from plate to filament within the tube is accompanied by a corresponding increase in current from right to left through the condenser C_p, charging its right plate positively again. In this manner the cycle is repeated indefinitely.

Another important type of oscillator circuit is shown in Fig. 92 and is known as the *Hartley oscillator*. The oscillatory

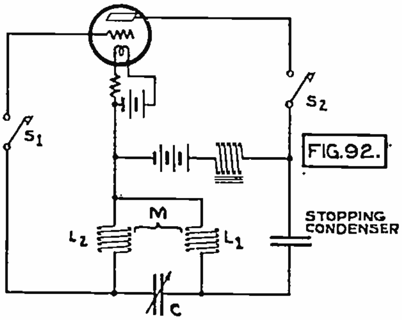


Fig. 92. Hartley Oscillator.

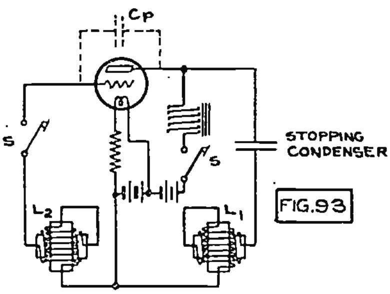


Fig. 93. Variation of Hartley Oscillator.

circuit in this case consists of coils L_2 and L_1 and the condenser C. Direct coupling between the oscillatory circuit and the grid circuit is provided through the coil L_2, and similar coupling is provided between the oscillatory circuit and plate circuit through the coil L_1. Mutual inductance between coils L_2 and L_1 also exists, but is not essential in this case. It will be noticed that this circuit is similar to that shown in Fig. 88, the difference being that the coil L_1 is now a series part of the oscillatory circuit, whereas in Fig. 88 it was not. The circuit shown in Fig. 88 is, therefore, a modified Hartley circuit and it is so called.

A satisfactory oscillator may be obtained by an arrangement, shown in Fig. 93, which is a slight variation of the Hartley circuit shown in Fig. 92. In the circuit shown in Fig. 93 the inter-electrode capacity between the plate and grid within the tube is exclusively utilized to complete the oscillatory circuit, and also no transformer coupling is provided between the plate and grid coils. The type of oscillator as shown in Fig. 93 contains the variometers L_2 and L_1, which are used as grid and plate coils and which provide the coupling between their respective circuits and the oscillatory circuit consisting of L_1, L_2 and C_P. In this system the iZ drops in potential across the coils L_1 and L_2, as the circuit $L_1C_PL_2$ oscillates, are impressed on the grid and plate circuits, respectively.

The so-called *Meisner circuit* is another modification of the Hartley oscillator which is often used. In the Meisner system the oscillatory circuit is inductively coupled to both the plate and grid coils, as shown in Fig. 94.

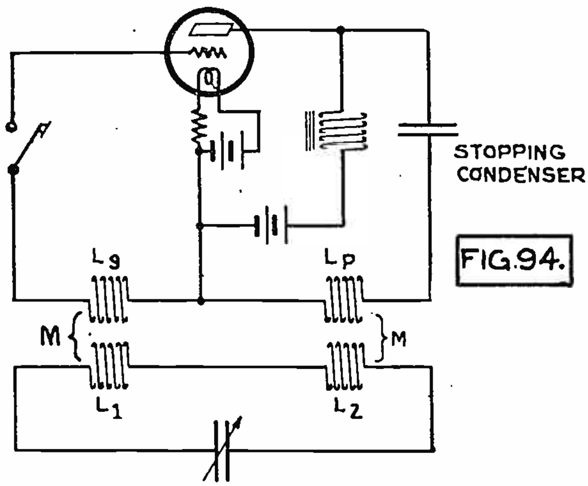


FIG. 94.

Fig. 94. Meisner Oscillator.

Each of these types of oscillators meets the requirements stated in the preceding paragraph as being pertinent to the production of sustained oscillations, and it is also true that oscillations may be started in any of these systems by any change in the circuit which results in a change in plate current through the tube. Furthermore, it should be noted that the frequency of the oscillations in each case depends upon the constants of the oscillatory circuit, and that the oscillations are undamped.

74. Use of Vacuum Tube Oscillators at Transmitting Stations.—Nearly all modern radio transmitting stations employ vacuum tube oscillators, and the circuits described above are extensively used with a variety of minor modifications for this purpose.

In small transmitting stations only one tube might be used, as shown in Fig. 95, which represents a continuous wave radio-telegraph transmitter.

This particular figure happens to show a Meisner oscillator, in which the antenna capacity C_a is a part of the oscillatory cir-

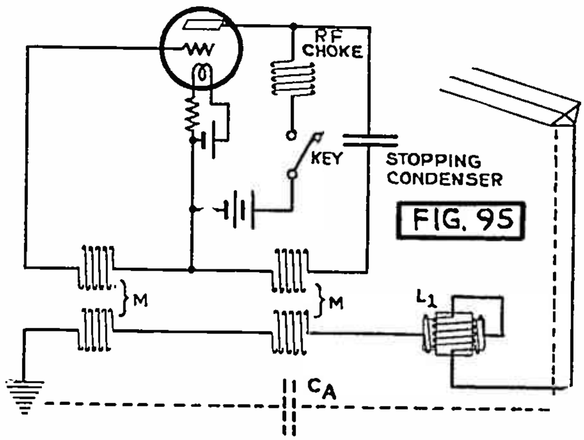


Fig. 95. One-Tube C.W. Telegraph Transmitter Employing Meisner Circuit.

cuit, and is equivalent to the condenser C shown in Fig. 94, except that it is not variable. The variometer L_1 has been added to the oscillatory circuit, so that the frequency of this circuit may be varied as desired. The frequency of the radiated wave, of course, depends upon the frequency of the oscillatory circuit, and as long as the key is held closed a continuous wave of some desired frequency is radiated from the antenna.

Sometimes two or more oscillator tubes are used in parallel. Fig. 96 shows a continuous wave radio-telegraph transmitter utilizing two oscillator tubes in parallel. Tubes are said to be connected in parallel when their corresponding electrodes are directly connected together; that is, when their plates are connected together, their grids are connected together, and their filaments are connected together. The circuit employed in the transmitter shown in Fig. 96 is that of the Colpitts oscillator, in which the antenna capacity C_a has replaced the condenser C_p in Fig. 91.

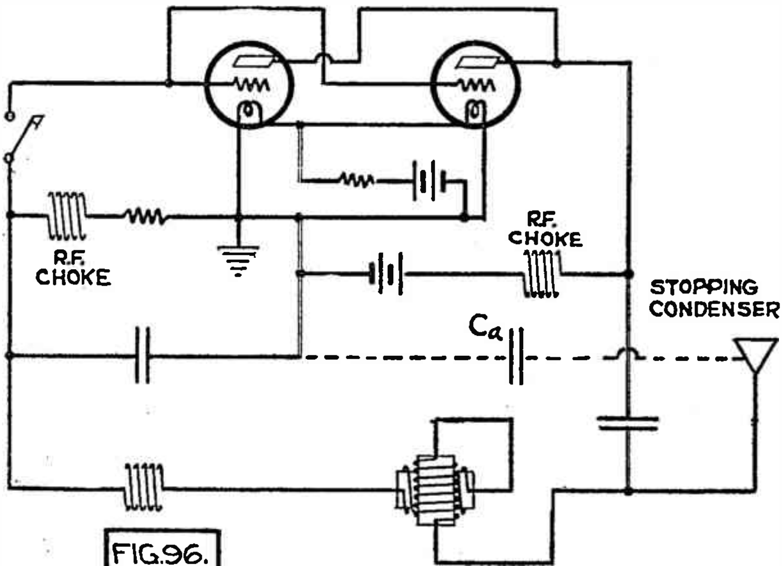


FIG.96.

Fig. 96. C.W. Telegraph Transmitter Employing Two Parallel Tubes in a Colpitts Circuit.

There is another type of circuit which is particularly desirable for sets using portable antenna, and in which an oscillator associated with a power amplifier is utilized. This circuit is shown schematically in Fig. 97.

The oscillatory circuit of the Colpitts oscillator employed in this system is capacitively coupled to the input circuit of the power amplifier through the condenser C_p, and the resulting amplified oscillations occurring in the plate circuit of the power amplifier induce corresponding electromotive forces in the antenna coil L_2. The antenna circuit may then be adjusted to resonance by means of the variometer L_3, resonance being manifested by a maximum reading of the ammeter A.

The frequency of the continuous waves radiated by this set depends upon the constants of the oscillatory circuit LC_gC_p, and is independent of the constants of the antenna circuit. For this reason it is possible to calibrate the tuning unit L (of the oscillatory circuit) directly in frequencies or wavelengths corresponding to those of the radiated waves. This type of circuit is known as a *master oscillator* circuit to distinguish it from other types in which the antenna is a part of the oscillatory circuit which determines the frequency of the radiated waves. When the power amplifier is not used in a transmitting circuit, it is necessary to have the antenna circuit a part of the oscillatory circuit, in order that a reasonable amount of the energy due to the high-frequency currents in the oscillatory circuit may be radiated as electromagnetic waves. If the antenna is a part of the oscillatory circuit, the tuning unit of this circuit might be calibrated in frequencies

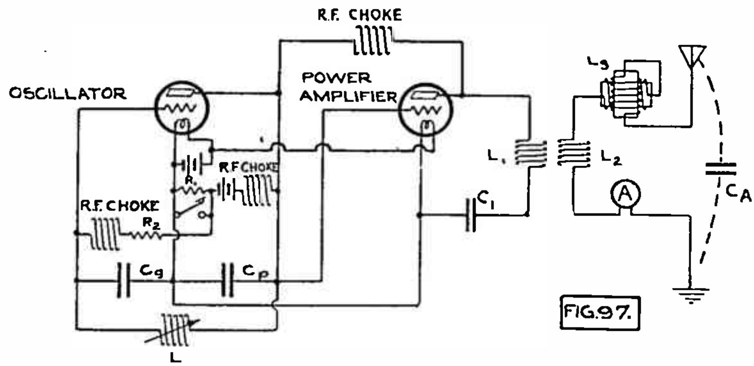


Fig. 97. **Master Oscillator of Colpitts Type with Power Amplifier.**

or wavelengths corresponding to those of the waves radiated by one particular antenna, but if this antenna were taken down and re-erected, as would be necessary with portable types, or if the antenna is changed by reason of expansion or contraction, the constants of the antenna system would in all probability be different and therefore the calibration would be useless. Since the frequency of the master oscillator circuit is independent of the antenna constants and the use of the power amplifier results in a relatively large amount of power being delivered to the antenna circuit, the master oscillator-power amplifier circuit is one of the most useful employed in portable radio transmitters.

The different methods of *keying*, that is, controlling the oscillations in these several circuits discussed in this section, are worthy of consideration. In all cases, the oscillations exist only while the key is closed. In the circuit shown in Fig. 95, the oscillations are started and stopped by making and breaking the direct-current plate circuit, while in the circuit shown in Fig. 96 the grid circuit is made and broken by the key, thus controlling the oscillations. The method of keying employed in the circuit shown in Fig. 97 is different from either of these, in that oscillations are prevented when the key is open by the high negative bias placed on the grid of the oscillator tube, due to the IR (I represents steady plate current) drop across the resistor R_1. When the key in this system is closed, this large bias is removed from the grid by short circuiting the resistor R_1, and oscillations will be sustained as long as the key is closed. Short circuiting the resistor R_1 (Fig. 97) also increases the plate potential of the oscillator tube.

75. Use of Oscillators at Receiving Stations.—It will be remembered that none of the simple detectors (crystal or tube) described so far in this book were capable of detecting continuous waves, because these undamped waves are of constant amplitude. The detection of continuous waves would be possible with any of these detectors, however, if the detector were properly associated with a suitable oscillator.

Before explaining the complete reason for this possibility, let us consider what happens in the circuit shown in Fig. 98. With

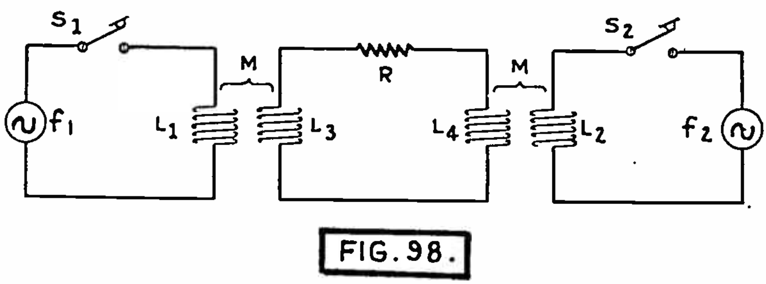


Fig. 98. Circuit Illustrating Heterodyne Action.

the switch S_2 closed (S_1 open), an electromotive force of frequency f_2 cycles per second is induced in the coil L_4 and a corresponding current flows in the circuit L_4RL_3. This current is represented by the dotted curve A in Fig. 99. On the other hand, with switch S_1 closed and S_2 open, an electromotive force of frequency f_1 would be induced in the coil L_3 and a corresponding current would flow in the circuit L_3L_4R. This current is represented by the dashed curve B, Fig. 99. With both switch S_1 and switch S_2 closed, each of these currents would flow simultaneously in the circuit L_3L_4R, and the resulting total current at each instant would be the algebraic sum of the instantaneous values of these two component currents. The total current is represented by the solid curve C in Fig. 99 and, as may be seen, is a current of varying amplitudes, due to the fact that the component currents, being of different frequencies, are alternately in

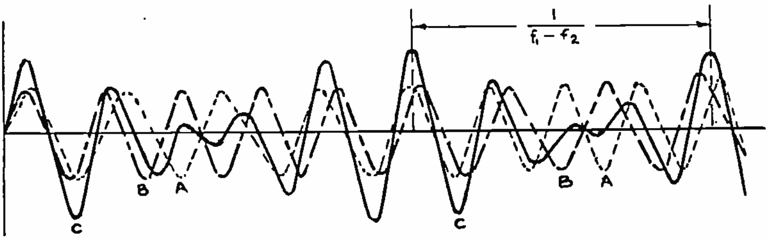


FIG. 99

Fig. 99. How Two Oscillations Heterodyne to Produce a Third.

and out of phase with each other. The frequency with which these component currents are completely in or out of phase with each other is equal to the difference between the frequencies of the two component currents; that is, the envelope of curve C in Fig. 99 is of a frequency equal to f_A minus f_B, this frequency being known as the *beat frequency*. When the two frequencies f_A and f_B are the same, they are said to be adjusted to *zero beat*. In this manner, then, we have combined two alternating currents of constant amplitude to obtain a resultant alternating current of amplitudes, which periodically vary with a frequency equal to the difference between the frequencies of the two component currents.

Now let us see how this principle may be applied to the reception of continuous waves at a radio receiving station. Suppose we had a system such as that shown in Fig. 100, in which a crystal detector receiving set is combined with an oscillator. A continuous electromagnetic wave of the frequency to which the antenna system is tuned would induce an electromotive force in the aerial, and cause a corresponding current to flow through the antenna circuit. Because of the constant amplitudes of this current it could not be detected by the crystal detector alone. Now let us close the switch in the oscillator circuit. This will result in the induction of an electromotive force in coil L_1, which will cause a current of the oscillator frequency to flow in the antenna circuit, and at each instant this current will be added (algebraically) to the current due to the intercepted wave, so that the total antenna current will be of periodically varying amplitudes, the frequency of these variations in amplitude being equal to the difference between the wave frequency and the local oscillator frequency. The local oscillator frequency may be adjusted to a value which is one thousand cycles per second different from the frequency of the incoming wave, and the antenna current will then be of a similar form to that of an audio-frequency modulated wave, and therefore it can be detected by the crystal detector as previously explained. Obviously, it would be possible to adjust the local oscillator frequency, so that it differed by any desired number of cycles per second (within the audio range) from that of the incoming wave and, accordingly, the frequency or pitch of the note heard in the telephone receiver may be varied at will.

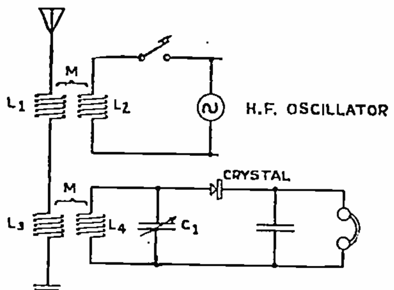


FIG. 100

Fig. 100. Heterodyne with Crystal Detector.

This scheme of combining a detector circuit with a separate oscillator circuit is called *heterodyning*, and the oscillators which are designed exclusively for this purpose are called *heterodynes*.

Heterodynes may be used with either the "C" bias or with the grid condenser-grid leak detector as well as with the crystal detector.

Another system employing this same principle, known as the *superheterodyne,* will be explained later.

It is a simple matter to make one vacuum tube perform simultaneously both the function of detector and oscillator. A circuit in which this is done is shown in Fig. 101, and is known as a *regenerative circuit.* The term *regenerative* is applied to any detector circuit in which coupling is provded between the plate and oscillatory grid circuits. In this case, this coupling between the plate circuit and the grid circuit is provided through the mutual inductance between the plate coil L_3, known as the *tickler coil,* and the grid coil L_2. If this coupling be properly adjusted, the circuit will sustain oscillations of the desired amplitude and of the frequency of circuit L_2C_2, and these oscillations in the circuit L_2C_2 will be combined with those induced in the coil L_2 due to the signal current in the antenna circuit with the same result as if the oscillator had been separate from the detector. The detection of continuous waves is possible, therefore, with a regenerative detector without the use of an auxiliary heterodyne. To distinguish this system in which oscillations are sustained by the detector circuit from the one in which the detector is combined with a separate oscillator, the former is called an *autodyne system* and the latter a *heterodyne system.*

If it were desired to use the regenerative circuit shown in Fig. 101 for the reception of audio-frequency modulated waves, the envelope of which must be preserved, it would be prohibitive to have the detector circuit oscillating in the manner required for the detection of continuous waves. In such a case, the coupling between the tickler coil L_3 and the grid coil L_2 should be made so loose that oscillations will not be sustained; but yet some coupling between these coils is desirable, because the feeble electromotive forces induced in coil L_2 from the antenna circuit are very much amplified in the plate circuit, and by causing the plate circuit to induce corresponding electromotive forces back in the grid circuit, the tube is made to amplify the signal current the second time. This system is known as regenerative amplification. The regenerative circuit shown in Fig. 101 is extensively used in modern radio detectors.

76. Preventing Undesirable Oscillations in Vacuum Tube Circuits.—It seems desirable in this chapter, where we are considering the things which make vacuum tube circuits oscillate, to call attention to the fact that when we arrange a circuit to perform the function of *radio-frequency*

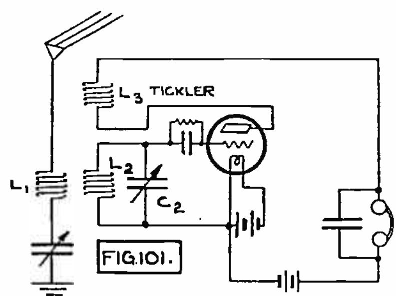


Fig. 101. Regenerative Circuit.

amplifier, this circuit also meets the requirements for sustained radio-frequency oscillations, which will combine with the incoming radio-frequency currents to produce audio-frequency oscillations and distortion in the receiving set of which this amplifier is a part. These oscillations are undesirable, of course, and must be eliminated.

Let us observe the circuit of a radio-frequency amplifier, and see what it is that causes it to oscillate.

A radio-frequency amplifier is shown in Fig. 102, in which the dotted lines indicate the inter-electrode capacity between the plate and grid. This same type of circuit might be used as an audio-frequency amplifier, but the coils L_1 and L_2 would then be radio-frequency chokes, and the inter-electrode capacity between the plate and grid is of such small value that it would offer considerable opposition to audio-frequncy currents.

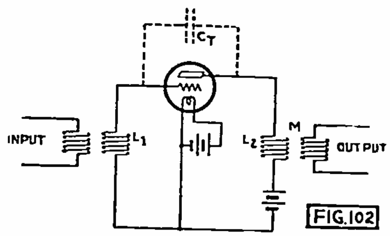


FIG. 102

Fig. 102. R. F. Amplifier.

However, this inter-electrode capacity and the inductance of coils L_1 and L_2 are such in radio-frequency amplifiers that this circuit, $L_1C_TL_2$, is a radio-frequency oscillatory circuit, and is associated with the tube and its batteries in the same way as in the oscillator shown in Fig. 93. This circuit, therefore, will sustain oscillations because the inductance and arrangement of the coils L_1 and L_2 and the inter-electrode capacity between the plate and grid constitute an oscillatory circuit which is so arranged with respect to the tube that the requirements for sustained oscillations are fulfilled. The only part of this system which is not essential to the performance of the intended function of the circuit, that is, the function of radio-frequency amplifier, is the inter-electrode capacity between plate and grid. This capacity, of course, is inherent to the tube, so that we cannot prevent oscillations by removing it. We can, however, compensate for this capacity by an arrangement which is known as a *neutralizing circuit,* or a balancing circuit, one form of which is shown in Fig. 103.*

A neutralizing circuit, in general, consists of a condenser and a coil connected in series between the plate or grid and the fila-

*Batteries have been omitted for simplicity since we are concerned only with alternating potentials.

ment of the tube, and so arranged with reference to the remainder of the circuit that the plate and grid are kept at practically constant relative potential.

The particular scheme of neutralization shown in Fig. 103 is known as the *Roberts system of neutralization*, and utilizes a separate coil L_n coupled to the plate coil L_2 and connected in series with a condenser C_n, as shown in the figure.

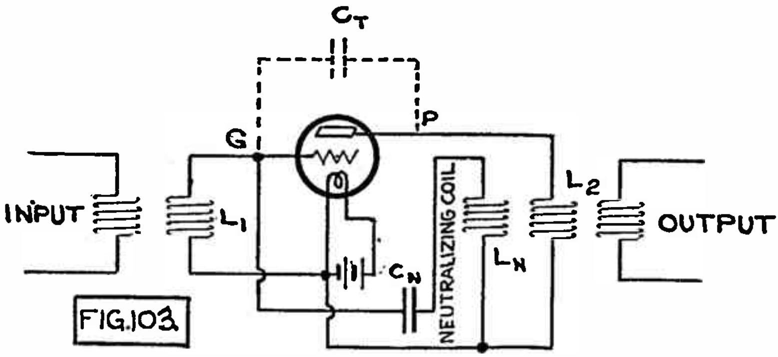


Fig. 103. Roberts Neutralization of Radio-Frequency Amplifier.

The inter-electrode capacity C_T might be regarded as equivalent to an external condenser connected from the point G to the point P; and, if it is so regarded, the circuit shown in Fig. 103 offers three external parallel paths from grid to filament, one through the condenser C_T and the coil L_2, another through the neutralizing circuit C_nL_n, and the third through coil L_1.

Remembering that the condenser C_T is consequential only for passing alternating current, we may neglect entirely the presence of the batteries normally employed in radio-frequency amplifiers and concern ourselves with alternating potentials only. This being the case, let us assume that at a certain instant the alternating grid potential is such that the grid is made more positive with reference to the filament. This would tend to make the grid less negative with reference to the plate; however, a current would now flow from the grid to the filament through the circuit C_NL_N, and because of the mutual inductance between the coils L_N and L_2, an electromotive force will be induced in coil L_2 which will be exactly equal and opposite to the change in relative potential from grid to plate at that instant, thus preventing current flow through the internal grid-plate capacity and through the circuit C_TL_2. In a similar manner the flow of current through the condenser C_T is prevented for all instantaneous values of the alternating grid potential, and the inter-electrode capacity between plate and grid is in effect removed from the circuit, so that the equivalent A.C. circuit might be represented in Fig. 104. Such a circuit will not produce oscillations.

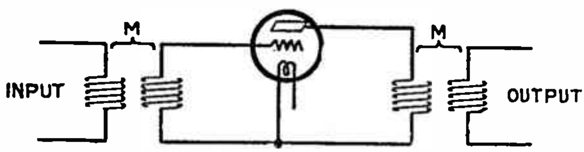


FIG.104

Fig. 104. Equivalent A.C. Circuit of Neutralized Amplifiers.

The Roberts system of neutralization described above is a modification of an older and perhaps more generally used system known as the Hazeltine system of neutralization, which is schematically shown in Fig. 105.

Hazeltine utilized a part of the secondary of the output transformer as the neutralizing coil, as shown in Fig. 105. Roberts simply modified this by using an entirely separate neutralizing coil.

Another method of neutralization, known as the *Rice system,* operates on the same general principles as the other systems, but the neutralizing coil L_n is now coupled to the grid coil and con-

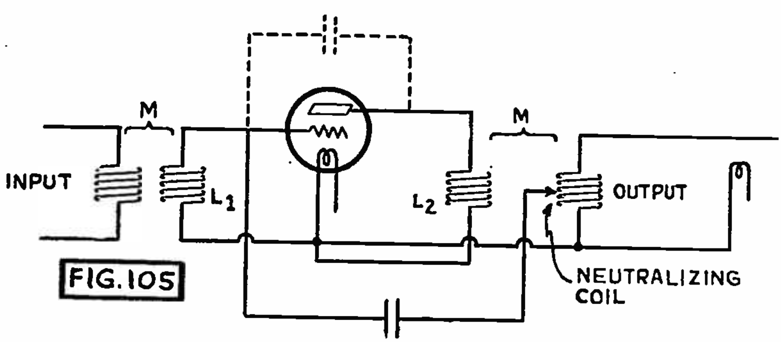


FIG.105

Fig. 105. Schematic Diagram of Hazeltine Neutralization.

nected through the neutralizing condenser to the plate of the tube. The Rice system is shown in Fig. 106(1).

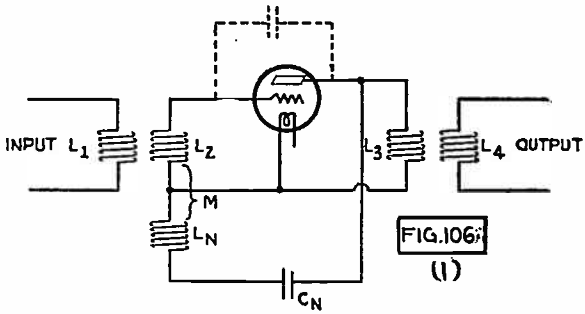


Fig. 106(1). Schematic Diagram of Rice Method of Neutralization.

We see, then, that any scheme of neutralization simply consists of a means whereby the inter-electrode capacity between plate and grid is in effect removed from the circuit. Neutralization of radio-frequency amplifiers is very important, and is almost universally used as a means of preventing undesirable oscillations.

Another method of preventing oscillations in radio-frequency amplifiers has been devised. This method employs a device known as a *Phasatrol,* which consists of a variable resistor and fixed condenser enclosed in a casing and connected in the circuit as shown in Fig. 106(2). The components of the *Phasatrol*

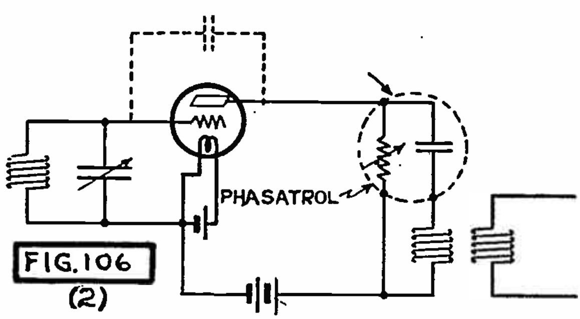


Fig. 106(2). Showing Method of Connecting Phasatrol to Prevent Oscillations in Radio-Frequency Amplifiers.

are shown in the dotted circle and its three external contacts are represented by the large dots. The resistor used in this device serves to adjust both the plate potential and the external plate impedance, while the fixed condenser is used to shift the phase of the current passing through the inter-electrode condenser.

There are two other methods of preventing undesirable oscillations in radio-frequency amplifiers, which are but slightly used because each of them entails the loss of considerable energy while accomplishing the desired result. The first of these systems, known as the *losser system,* consists of placing a rather high resistance in the grid circuit, so as to make the natural frequency of the oscillatory circuit very low. (It should be remembered that natural frequency of an oscillatory circuit depends upon resistance.) Such a system is shown schematically in Fig. 107.

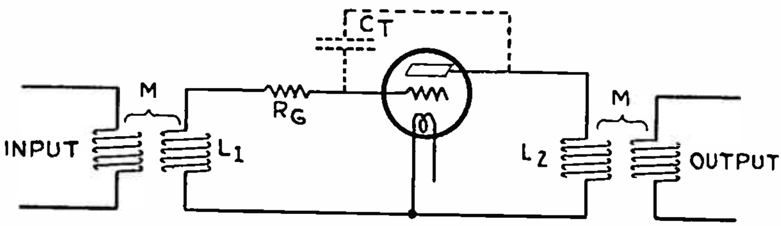


FIG. 107

Fig. 107. Losser Method of Preventing Oscillations.

In this method the resistor R_g is inserted in the grid circuit, so that it is a part of the oscillatory circuit $L_1R_GC_TL_2$, and this circuit is thereby caused to have a very low natural frequency, or else to be non-oscillatory, thus preventing radio-frequency oscillations.

The second of these lesser used methods of preventing undesirable oscillations is known as the *reverse feed back* system. It consists of inserting an additional series coil in the plate circuit of the tube and coupling this coil back to the grid coil in a similar manner to that employed in the regenerative set, except that this series plate coil is reversed so that the electromotive forces induced in the grid circuit oppose the oscillations of that circuit. The *reverse feed back* circuit is shown in Fig. 108.

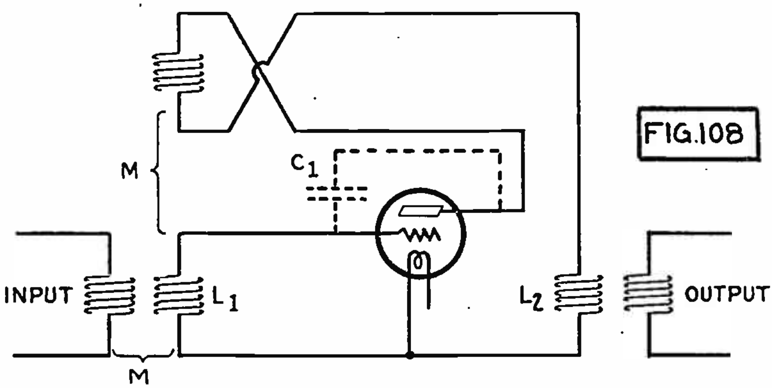


FIG.108

Fig. 108. Reversed Feed-Back Method of Preventing Oscillations.

77. Piezoelectric Effect and Its Utilization in Oscillators. The so-called *crystal controlled oscillator* has come into important use in radio transmitting sets, particularly where very short waves are used. The operation of crystal controlled oscillators depends upon the *Piezoelectric effect* in quartz crystals, and we shall, therefore, consider this effect first. The natural crystal of quartz is in the shape shown in Fig. 109, and the axis parallel to the lengthwise natural edges is called the *optic axis* of the crystal. The axis perpendicular to the natural edge in the direction shown in Fig. 109 is known as the *electric axis* of the crystal, and there is a third axis which is perpendicular to the other two axes, and is shown as the *B axis* in Fig. 109.

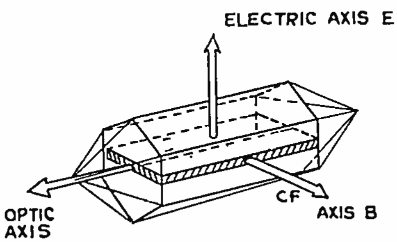


FIG. 109

Fig. 109. Natural Crystal of Quartz.

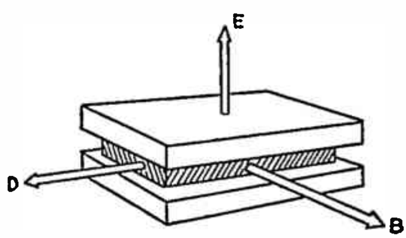


FIG. 110.

Fig. 110. Mounting of Crystal.

All of this is important, because when a slab is cut from such a crystal (as shown by the shaded part of Fig. 109) and mounted as shown in Fig. 110, it has been found that if this slab were subjected to an electric force of proper sign along its electric axis, the crystal expanded along the E axis and contracted along the B axis, and that a reversal of the electric force caused a reversal of these expansions and contractions. It is also true that when the crystal is subjected to a mechanical pressure tending to contract it along the B axis and expand it along the E axis, an electromotive force is developed within the crystal along the E axis. This electromotive force is opposite in sign to the external electric force which would have produced a corresponding expansion and contraction of the crystal.

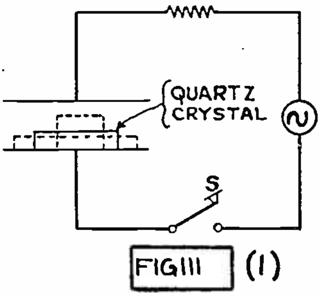


Fig. 111 (1). Action of Crystal Under Impressed E. M. F.

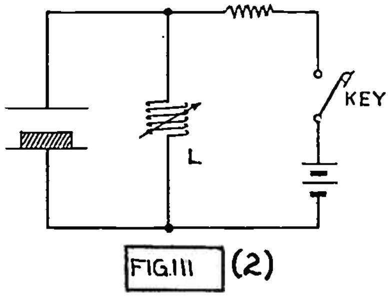


Fig. 111 (2). Crystal Oscillator Circuit.

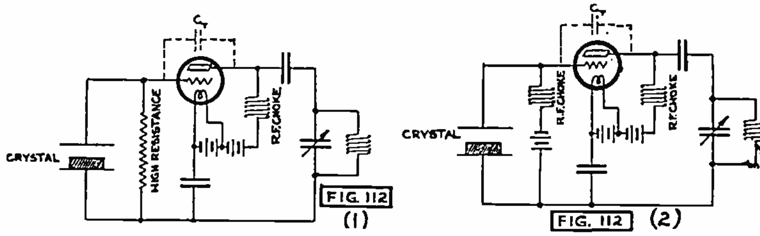
When an alternating electromotive force is impressed across such a crystal as shown in Fig. 111(1), the crystal expands and contracts along the vertical axis, and at the same time contracts and expands along the horizontal axis as shown in the figure. Any body capable of mechanical vibration has a certain natural frequency of vibration, and so the crystal in this case has a certain natural frequency of expansion and contraction along the vertical axis and some other natural frequency of expansion and contraction along the horizontal axis, each of these frequencies depending upon the dimensions of the crystal. In this sense, the crystal is analogous to a tuning fork which when struck will vibrate at its own natural frequency. If, then, the frequency of the impressed electromotive force, Fig. 111(1), were the same as one of the natural frequencies of the crystal, strong vibrations of the crystal will be obtained along the axis to which the particular natural frequency pertains. While the crystal is vibrating in this manner the switch S may be suddenly opened and the crystal will continue to vibrate for a short time, the amplitudes of its vibrations being gradually damped out. Now let us assume that such a crystal is connected in the circuit shown in Fig. 111(2). If the key were closed for an instant, the condenser formed by the plates of the crystal mounting would be charged, thus subjecting the crystal to an electrical strain which causes the crystal to expand along the vertical axis and contract along the horizontal axis. When the key is opened, the electrical strain on the crystal will be relieved and the crystal will tend to return to its normal shape, but because of its mechanical properties it will vibrate at one of its own natural frequencies for a short time in the same manner as a tuning fork will vibrate when it is jarred. The particular one of the two natural frequencies at which the crystal will vibrate depends upon the constants of the circuit with which it is associated, and may be varied from one to the other in this case by properly adjusting the inductance L.

These expansions and contractions of the crystal will result in the development of a corresponding electromotive force within the crystal between its top and bottom faces, and if we could measure this electromotive force with an oscillograph, it would be found to be of a damped oscillatory form, and its frequency, of course, would be the natural frequency of the crystal. Although this electromotive force would be very feeble and would be damped out in a short time, it would be of absolutely constant frequency, more so than might be obtained with any other type of electrical generator.

This Piezoelectric effect (pressure — electricity) in quartz crystals, together with their constant frequency of mechanical expansion and contraction as determined by their dimensions, makes possible their use as precision standards of frequency and wavelength, also as an aid in generating oscillations of a constant frequency.

In the so-called *crystal controlled oscillators,* which are used in a number of broadcasting stations and which are becoming extensively used in short-wave transmitters, a quartz crystal resonator, as described, is associated with a vacuum tube in circuits similar to those which produce self-sustained oscillations. The arrangement of any of these circuits is such that the surge of current through the crystal resonator starts it to oscillate, and its oscillations are amplified by the tube, and a part of the energy of these amplified oscillations is returned to the crystal resonator circuit, so as to give it another impetus periodically, to sustain its oscillations.

The two circuits shown in Fig. 112(1) and Fig. 112(2) are the most generally employed for this purpose. These circuits



Figs. 112 (1) (2). Typical Oscillator Circuits Using Quartz Crystals.

differ in the manner in which the proper grid bias is maintained, but the frequency developed by each set is independent of the electrical constants of the circuits, and depends only on the frequency of expansion and contraction of the crystal, which varies with the dimensions of the crystal, smaller crystals having higher natural frequencies.

78. Summary:

1. A vacuum tube oscillator is a generator of high-frequency electromotive forces (EMF's).

2. The vacuum tube oscillator consists of a vacuum tube with its associated batteries connected to an oscillatory circuit, in such a way that there is suitable coupling between the plate circuit and the oscillatory circuit and between the grid circuit and the oscillatory circuit.

3. The efficiency of a vacuum tube oscillator cannot exceed fifty per cent.

4. In the Colpitts oscillator, capacitive coupling is provided between the oscillatory circuit and the plate circuit, and between the oscillatory circuit and the grid circuit.

5. In the Hartley oscillator inductive coupling or direct (inductive) coupling is provided between the oscillatory circuit and

the plate circuit, and between the oscillatory circuit and the grid circuit.

6. Vacuum tube oscillators are used as generators at transmitting stations in the following manner:

1. Single tube with antenna as part of the oscillatory circuit.
2. Parallel tubes with antenna as part of the oscillatory circuit.
3. Master oscillator-power amplifier in which oscillatory circuit does not include the antenna.

7. Oscillations may be started in any vacuum tube oscillator by any change in plate or grid current.

8. Oscillators are used at receiving stations as heterodynes and autodynes to permit the detection of continuous wave telegraph signals.

9. An oscillator circuit is used at receiving stations to provide regenerative amplification, there being insufficient coupling between the plate circuit and the oscillatory circuit to sustain oscillations, but yet enough coupling to obtain amplification.

10. Radio-frequency amplifiers as normally designed satisfy the conditions for sustained oscillations, because of the inter-electrode capacity between plate and grid and the inductance of the required plate and grid coils. These oscillations are undesirable and must be prevented.

11. The best method of preventing self-sustained oscillations in radio-frequency amplifiers is by neutralizing the inter-electrode capacity between plate and grid by one of the following methods:

1. Hazeltine method;
2. Rice method;
3. Roberts method.

12. Self-sustained oscillations in radio-frequency amplifiers may also be prevented by:

1. Inserting a suitable resistance in the oscillatory circuit formed by the grid coil, the plate coil and the inter-electrode capacity between plate and grid;
2. Reverse feed back method;
3. Phasatrol;
4. Use of four-electrode tube. (See SECTION IV.)

13. Quartz crystals possess the property that when they are subjected to an electrical force along one axis they expand or contract along a perpendicular axis, and this expansion or contraction results in the generation within the crystal of an electromotive force which is in an opposite direction to the impressed electrical force. This is known as the Piezoelectric effect.

14. Because of the Piezoelectric effect, quartz crystals may be associated with a vacuum tube in such a manner that oscillations of one frequency only will be generated, the frequency depending

only on the natural frequency of expansion and contraction of the crystal.

79. Self-Examination:

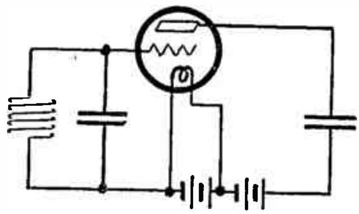
1. Explain the general function of a vacuum tube oscillator.

2. State the special requirements for sustained oscillations in a vacuum tube circuit.

3. Draw a diagram and describe the operation of a Colpitts oscillator.

4. Draw a diagram and describe the operation of a Hartley oscillator.

5. Explain why the circuits shown below will or will not oscillate.



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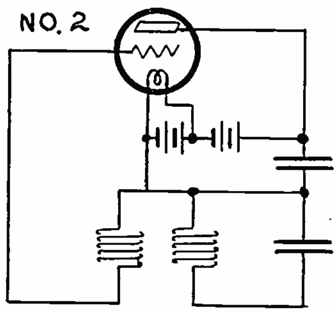

6. Explain three different methods of keying oscillators.

7. How and why are vacuum tubes connected in parallel in transmitting oscillators?

8. What is the advantage of the master oscillator-power amplifier circuit?

9. Why is it necessary to have the antenna a part of the oscillatory circuit of vacuum tube oscillators used in transmitting sets without power amplifiers?

10. Draw a diagram and explain the operation of each of the following:

    1. A one-tube radio-telegraph transmitting set;
    2. A radio-telegraph set using three tubes in parallel;
    3. A master oscillator-power amplifier radio-telegraph set.

11. What type of waves are radiated by vacuum tube transmitting sets (unmodulated)?

12. Explain the operation of a heterodyne.

13. An incoming signal has a frequency of 1,000,000 cycles per second, and the heterodyne associated with the receiving set is oscillating at a frequency of 999,000 cycles per second. What

is the beat frequency? What is the pitch of the note heard in the receivers?

14. Explain the difference between a heterodyne and an autodyne.

15. Explain the principle of *regenerative amplification.*

16. What causes radio-frequency amplifiers to generate sustained oscillation of radio frequency?

17. Explain the basic principle of *neutralizing* radio-frequency amplifiers.

18. Draw a diagram of a radio-frequency oscillator neutralized by each of the following methods:

   1. Roberts;
   2. Hazeltine;
   3. Rice.

19. Explain the *losser* method of preventing oscillations in radio-frequency amplifiers.

20. Explain the *reverse feed back* method of preventing oscillations in radio-frequency amplifiers.

21. Explain the phasatrol method of preventing oscillations in radio-frequency amplifiers.

22. What is meant by Piezoelectric effect in quartz crystals?

23. Draw a diagram and explain the operation of a crystal controlled oscillator.

Section VIII.

THE VACUUM TUBE MODULATOR

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General Explanation of Modulation	80
Analysis of Modulated Wave	81
Simple Types of Vacuum Tube Modulators	82
Practical Methods of Modulation	83
Special Type of Modulator	84
Summary	85
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80. General Explanation of Modulation.—It has already been explained that an audio-frequency modulated wave is a wave of high frequency, the successive amplitudes of which vary in accordance with some audio-frequency wave form. These audio-frequency modulated waves are utilized in radio telephony and in tone modulated radio telegraphy to send out an audio-frequency wave of some desired form using a radio-frequency wave as a carrier, and we have seen that the receiving station is tuned to the carrier frequency and that current of the audio-frequency and that current of the audio-frequency wave form is obtained in the telephone receivers. We are now ready to consider the manner in which the modulation of a wave is accomplished at a transmitting station.

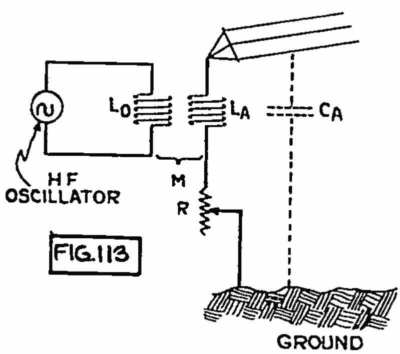


Fig. 113. Elementary Modulator.

Let us consider the circuit shown in Fig. 113, in which an oscillator is coupled to an antenna circuit containing a series rheostat R.

Because of the mutual inductance between the oscillator coil

L_o and the antenna coil L_a, an alternating electromotive force of constant amplitude will be induced in the antenna circuit, and we shall assume that the antenna is resonant to the frequency of this induced electromotive force. The current in the antenna circuit at each instant would then be equal to the instantaneous value of the induced electromotive force divided by the antenna impedance. With the rheostat R in some fixed position the antenna current would be as shown in Fig. 114(1). If the antenna

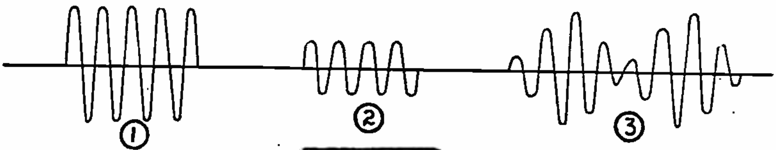


FIG. 114

Fig. 114. Variation of Antenna Current with Rheostat Resistance.

resistance were increased by displacing the rheostat contact so that more resistance was included in the circuit, the amplitudes of the antenna current would be reduced as shown in Fig. 114(2). Now suppose that we varied the rheostat contact back and forth periodically from its maximum to its minimum value. Obviously, the amplitudes of the antenna current would be varied accordingly and would be of the form shown in Fig. 114(3). Likewise, if the resistor R in Fig. 113 were replaced by a microphone similar to that used in telephony, as shown in Fig. 115, we could vary the amplitudes of the antenna current in accordance with the variations in the resistance of the microphone.

If the sound wave impinging upon the transmitter diaphragm of a certain line is of the form shown in Fig. 116(1), then the resulting antenna current will be of the form shown in Fig. 116(2) by the solid line. We see that the envelope of the curve representing the antenna current [envelope is shown in dotted lines, Fig. 116(2)] is of the same form as the sound wave which displaces the diaphragm of the microphone.

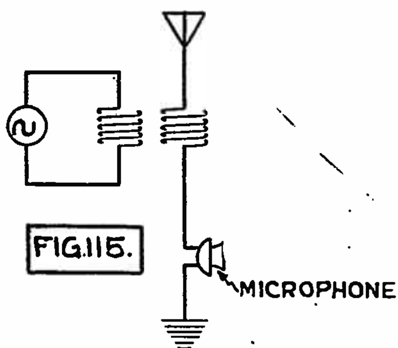
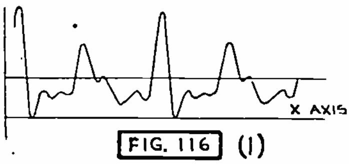


FIG. 115.

Fig. 115. Simple Modulator.

The sounds emitted by the human vocal system and by all musical instruments are made up of audio-frequency waves, so that any sound created in front of the microphone will produce corresponding variations in the microphone resistance, which in turn will result in corresponding variations in the successive amplitudes of the antenna current.



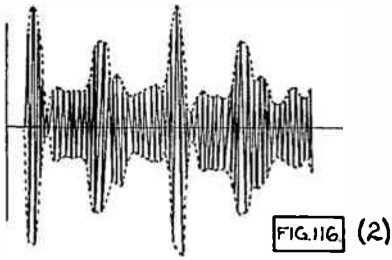


Fig. 116(1). Wave Form of the Sound of "a" as in "Father."
Fig. 116(2). Antenna Current in Radio Telephony Transmitting Sound of "a" as in "Father," Modulated Radio-Frequency Wave.

The electromagnetic wave radiated by the antenna is of exactly the same form as the antenna current, and therefore we have caused a wave to be sent out, the amplitudes of which vary in accordance with the form of the sound wave which we desire to have received at the receiving station.

81. Analysis of Modulated Wave.—If we consider the maximum height above the X-axis of the sound wave shown in Fig. 116(1) as being equal to unity and all other instantaneous values of this wave as the proper proportional parts of unity, then it will be seen by comparing Figs. 116(1) and 116(2) that the modulated antenna current is proportional at each instant to the product of the instantaneous value of the unmodulated high-frequency current and the instantaneous value of the sound wave. With the simple modulator shown in Fig. 115 it is easy to see that the antenna current is equal to the product of the induced electromotive force and the reciprocal of the antenna impedance. Since the electromotive force is sinusoidal and the antenna impedance is varied in accordance with the sound wave impinging on the microphone, the antenna current is proportional to the product of the two waves at any instant. The complete mathematical proof of this is given by Van der Bijl,* who obtains the

*Van der Bijl's "Thermionic Vacuum Tubes," page 319.

following equation for a modulated plate current:

$$i_p = A \sin pt\ (1 + B \sin qt),$$

where A and B are constants and the high- and low-frequency currents have periods of $\frac{2\pi}{p}$ and $\frac{2\pi}{q}$, respectively.

It can be shown mathematically that a modulated wave is not a simple radio-frequency wave of varying amplitude, but rather a complex wave consisting of three radio-frequency waves, one of which is an undamped wave of the oscillator frequency, one a modulated wave of a frequency equal to the oscillator frequency plus the modulating frequency, and another modulated wave of a frequency equal to the oscillator frequency minus the modulating frequency. The last two named of these frequencies are called *sidebands* of the modulated wave, and the first is referred to as the *carrier wave.*

It is obviously possible, with a given radio-frequency current, to modulate it in various degrees, as shown by Figs. 117(1), 117(2), and 117(3). If a high-frequency current is so modu-

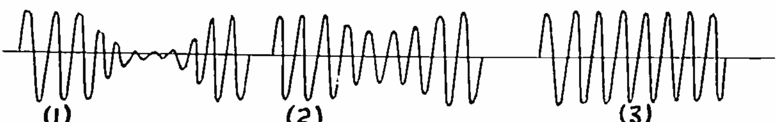


FIG. 117

Fig. 117(1). Completely Modulated Wave. **Fig. 117(2). Partially Modulated Wave.** **Fig. 117(3). Unmodulated or Continuous Wave**

lated that its minimum amplitudes are just reduced to zero, and its maximum amplitudes are equal to the amplitude of the unmodulated current, it is said to be *completely modulated.* A completely modulated wave is shown in Fig. 117(1).

82. Simple Types of Vacuum Tube Modulators.—In Fig. 118 a very simple vacuum tube modulator is shown, in which the resistor R and the tube with its associated batteries and microphone is substituted for the rheostat shown in Fig. 113. In this system the vacuum tube merely provides a path of variable resistance in parallel with the resistor R for the radio-frequency currents in the antenna circuit. The plate potential and grid bias of the tube are such that the operating point on the characteristic curve falls on the lower bend of the curve, so that a change in grid potential will vary the resistance of the tube from plate to filament. When the microphone diaphragm is displaced by a sound wave, a corresponding voltage will be induced in the coil

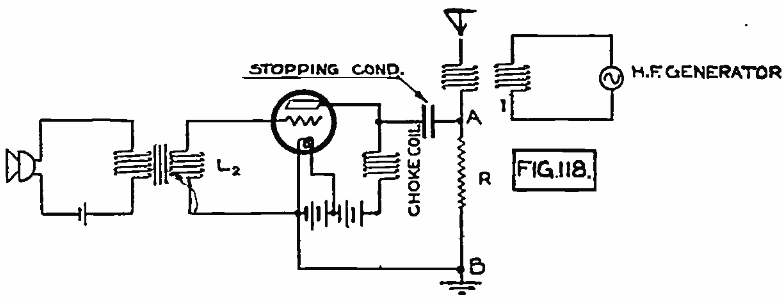


Fig. 118. Antenna Modulation.

L_2, and thus the grid potential and the internal plate resistance of the tube will be varied accordingly. The total equivalent resistance of the portion of the antenna circuit from A to B is consequently varied in accordance with the audio-frequency wave actuating the diaphragm of the microphone, and, as previously explained, the amplitudes of the antenna current are similarly varied.

This method of modulation, as well as that in which the microphone is inserted directly in the antenna system, produces the

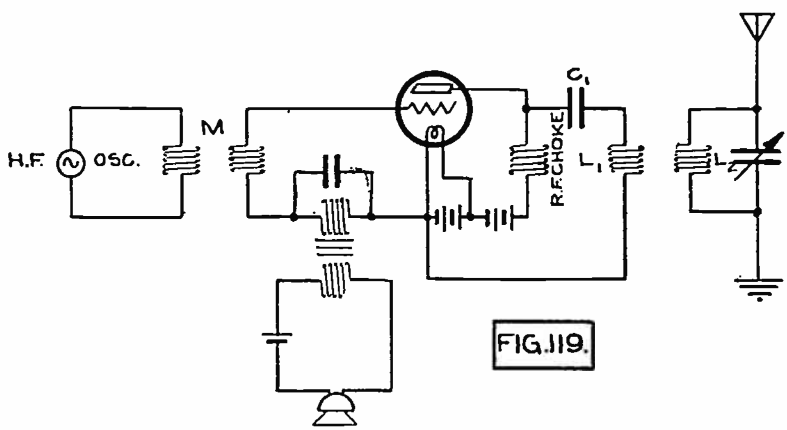
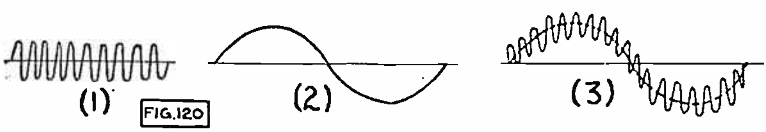


Fig. 119. Grid Modulator.

desired result by accomplishing changes in the antenna impedance and might be classified, therefore, as an *antenna modulating method.* Neither of these methods is employed in a practical system of radio transmission.

A somewhat more practical method of modulation, known as the *grid system of modulation,* is shown in Fig. 119. In this system of modulation, also, the grid bias and plate potential are such that the operating point on the characteristic curve falls on the lower bend of the curve. Both the oscillator and the microphone circuit are coupled to the grid circuit of the modulator tube, and the resulting grid potential at each instant is the sum of the instantaneous values of the audio-frequency electromotive force and the radio-frequency electromotive force induced in the grid circuit. For simplicity, let us assume that this radio-frequency electromotive force is of the form shown in Fig. 120(1) and this audio-frequency electromotive force is of the form shown in Fig. 120(2). The total grid potential will then be of the form shown in Fig. 120(3).



Figs. 120, 121. Action of Grid System of Modulation.

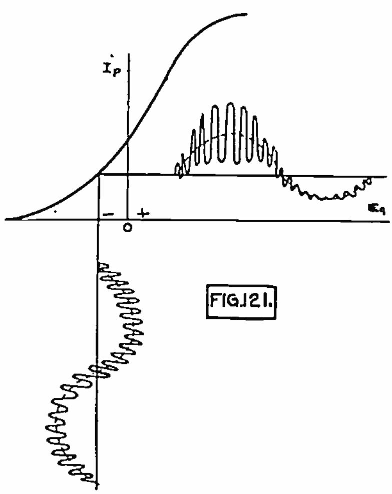


Fig. 121. Showing Principle of Modulation.

Referring to Fig. 121, we see that, because of the characteristic curve, the amplitudes of the resulting radio-frequency current in the plate circuit vary in accordance with the audio-frequency wave form. This resulting plate current at any instant is the sum of an audio-frequency component of the form shown in Fig. 122(1), and a radio-frequency component of the form shown in Fig. 122(2), and a direct component.

The envelope of this radio-frequency curve is of practically the same form as the audio-frequency electromotive force induced

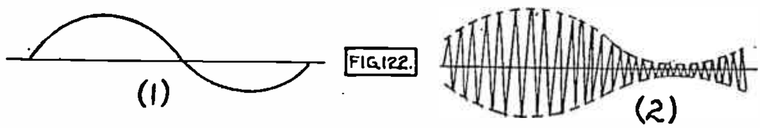


Fig. 122(1). Audio-Frequency Component.
Fig. 122(2). Modulated Radio-Frequency Current.

in the grid circuit, and a radio-frequency current of the form shown in Fig. 122(2) flows through the circuit L_1C_1, thereby inducing a corresponding voltage in the coil L_2 and resulting in the radiation of an electromagnetic wave of similar form.

83. Practical Methods of Modulation.—A system of modulation which is essentially the same as that described above as *grid modulation* is sometimes used in small radio telephone sets. In the practical form this system differs from that described above in that the audio-frequency electromotive force is induced directly into the grid circuit of a vacuum tube oscillator, as shown in Fig. 123. The theoretical principles of this method of modulation are essentially the same as those pertaining to the grid modulator described above.

Another method of modulating is shown in Fig. 124 and is

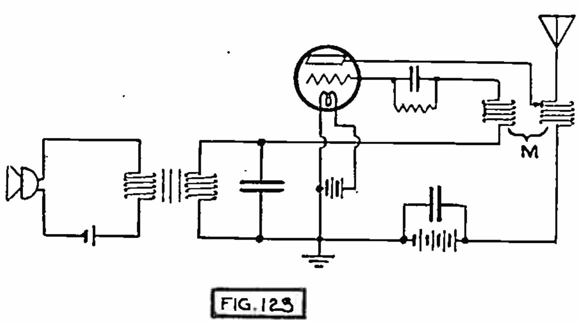


Fig. 123. Modulation of Output of a Tube Generator by Microphone Connected in Grid Circuit.

known as the *power output absorption* method. This system of modulation is more extensively used than any described above. This system of modulation, shown in Fig. 124, is called *power*

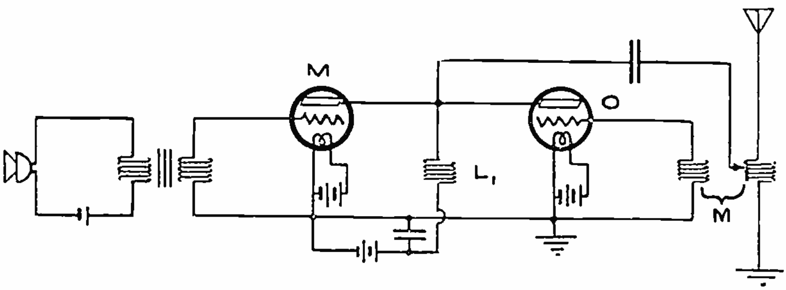


Fig. 124. Circuit for Radio Telephone Transmitter. Modulation by Absorption of Power Output of Generator Tube.

output absorption because the modulator tube M is so arranged with reference to the oscillator tube O as to continuously absorb some of the oscillators' plate power, the amount absorbed varying with the electromotive force induced in the grid circuit of the modulator from the microphone circuit. It is apparent from Fig. 124 that there are two return paths from the plate of the oscillator to the filament, one of these being through the antenna inductance and the other through the internal plate circuit of the modulator tube. The variations in the grid potential of the modulator tube, due to the changes in current in the microphone circuit, vary the internal plate impedance of the modulator tube and consequently change the amount of the current returned from the plate circuit of the oscillator to the filament through the modulator tube. If this current be increased, the current returned through the antenna coil to the filament must be proportionally decreased, and since the radiated waves depend upon the antenna current, the output of the oscillator is modulated in accordance with the form of the audio-frequency wave which actuates the microphone. The operation of this modulator also depends upon the curvature of the I_pE_g characteristic of the tube.

Fig. 125 shows another very extensively used method of modulation, which is somewhat similar to the power output absorption method. This system of modulation is known as *variation of the input power,* or *Heising system,* and as may be seen from the following discussion its operation somewhat resembles the operation of a simple choke coil, common battery telephone cord circuit. In this system the plate potential of both the oscillator tube O and the modulator tube M is supplied from a common "B" battery through a choke coil L of such large inductance that neither radio- nor audio-frequency currents can pass through it. The radio-frequency choke coil in the plate circuit of the modulator tube prevents the modulator tube from operating as a by-pass for radio-frequency currents, but permits audio-frequency current to flow through the circuit of which it is a part. By talk-

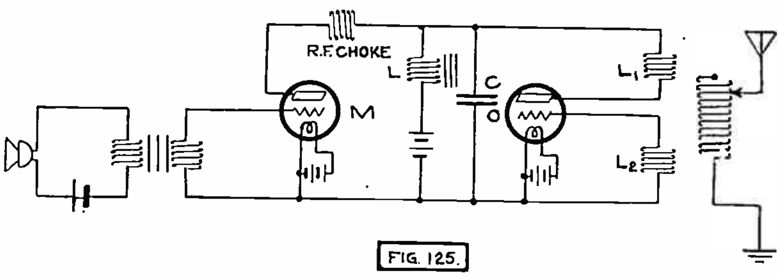


Fig. 125. Circuit for Radio Telephone Transmitter. Modulation by Variation of Power Input of Generator Tube or Heising Method.

ing into the microphone we may vary the grid potential of the modulator, as before, and thus the modulator plate current is varied. Suppose that at a particular instant this modulator plate current happened to be increased; then the steady component of the plate current of the oscillator would be proportionately decreased, since there can be no change in the plate battery current. Other things being equal, this would be equivalent to a decrease in plate potential on the oscillator tube, and would, therefore, result in decreased oscillations in the plate circuit, with the consequent decrease in amplitude of the radiated wave. In this manner the radiated wave would vary in amplitude according to the form of the sound wave created in front of the microphone.

The electromagnetic waves radiated from stations using the systems described in this section could be detected with any of the several types of detector circuits described in this text. There is a type of modulator, however, which is now being used in the trans-Atlantic radio-telephone service, which results in the radiation of waves of such a type as to require a local oscillator at the receiving station in the circuit built especially for the reception of this type of waves.

84. Special Type of Modulator.—There is another type of modulator, which consists of the arrangement shown in Fig. 126.

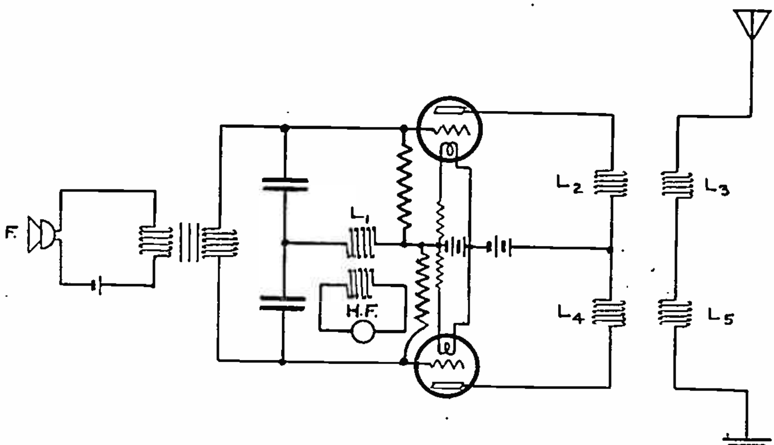


Fig. 126. Modulator System in Which Carrier Frequency is Suppressed.

This type of modulator is unique in that the radiated wave consists of only two components, which are the sideband components in the normal system of modulation. The component of the modulated wave which is of the oscillator frequency is completely suppressed by this system.

The high-frequency electromotive forces induced in the grid coil L_1 from the oscillator results in corresponding oscillatory currents in the plate coils L_2 and L_4, which induce corresponding voltages in coils L_3 and L_5, respectively. In this case, however, the coils are wound in such a relative direction that these two electromotive forces oppose each other, with the result that, as long as the high-frequency plate current of both tubes is the same, there will be no current in the antenna circuit, and consequently no radiated wave. If the microphone is spoken into, however, the grid potential of one tube will be increased, at a certain instant, and the grid potential of the other tube will be decreased. This will result in an increased high-frequency current in the plate circuit of one tube and a decreased high-frequency current in the plate circuit of the other, and consequently the electromotive forces induced in the antenna will not compensate each other and an antenna current will flow. The amplitudes of the antenna current oscillations will depend upon the degree of unbalance between the two opposing electromotive forces induced in the antenna circuit, which in turn depends upon the wave form of the sound actuating the microphone. The actual wave radiated by this system has an envelope which is not of the same form as the sound wave, but rather is of the form shown in Fig. 127(1). Such a wave is

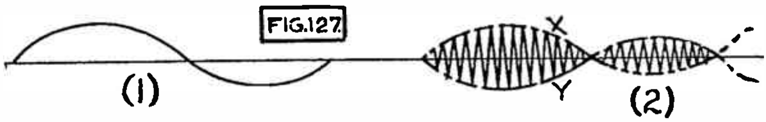


Fig. 127(1). **Sound Wave.** Fig. 127(2). **Radiated Wave.**

known as an over-modulated wave, for it is apparent that the dotted line X or the dot-and-dash line Y, Fig. 127(2), which would represent the envelope of a normally modulated wave, actually cross the zero axis. To detect this wave at the receiving station the detector circuit must contain a local oscillator which will supply in its proper phase the missing component of this type of wave; that is, the undamped component of the oscillator frequency.

This general system of modulation is now being used in the trans-Atlantic radio telephone service operated by the American Telephone & Telegraph Company.

85. **Summary:**

1. A modulator is a device for varying the successive amplitudes of a high-frequency undamped current in accordance with some desired wave form.

2. The simplest type of modulation is antenna modulation, in which the impedance of the antenna circuit is varied as desired.

3. A modulated wave is at each instant proportional to the

product of the instantaneous value of the high-frequency EMF and the modulating EMF.

4. A modulated wave consists of three radio-frequency components, one of which is called the *carrier wave* and is an undamped wave of the oscillator frequency, and the other two of which are called the *sidebands* and are of a frequency equal to that of the oscillator plus and minus (respectively) the modulating frequency.

5. A wave is said to be completely modulated when its minimum amplitudes are reduced to zero without decreasing its maximum amplitudes below those of the undamped wave.

6. Modulation by means of the grid system or the absorption system depends upon the changing slope of the plate current grid voltage characteristic curve, since it is over this part of the curve that the A.C. resistance of the tube is changing.

7. In the grid modulator the modulating EMF is induced in the grid circuit of a vacuum tube oscillator.

8. In the power output absorption method of modulation the modulator tube is a variable by-pass for the radio-frequency current from plate to filament in the oscillator, and the current which it by-passes is absorbed from the antenna circuit.

9. In the variation of the input power method of modulation the modulator tubes vary the direct current supplied to the plate circuit of the oscillator.

10. A special type of modulator, using two modulator tubes, is being used commercially to radiate waves, the detection of which requires special receiving sets.

86. Self-Examination:

1. What is meant by an audio-frequency modulated wave?

2. Describe the action of a simple antenna modulating system.

3. What is the difference between combining two waves by heterodyning and by modulating?

4. What is meant by complete modulation of a wave?

5. Draw a diagram and explain the action of a grid modulator.

6. Draw a diagram and explain the action of a radio-telephone transmitter system, in which modulation is effected by absorption of the output power.

7. Do the same (as in 6) for the system of modulation by variation of the power input (Heising system).

8. Draw a diagram and explain the operation of a two-tube modulating system, which results in the radiation of an overmodulated wave.

Section IX.

ANTENNAS AND THE RADIATION, PROPAGATION, AND INTERCEPTION OF ELECTRO-MAGNETIC WAVES

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87. Introduction.—Having discussed the theory of high-frequency currents and the various types of equipment used in transmitting and receiving sets, we are now ready to consider the antenna required to complete the station. Such an antenna functions to radiate the energy of high-frequency currents as electromagnetic waves at transmitting stations and to intercept such waves at the receiving station. A detailed analysis of the problem of electromagnetic radiation is beyond the scope of this book. However, it is believed worth while to consider the elementary theory of radiation, because of its great importance to radio communication.

88. Elementary Theory of Radiation and Interception.—In order to appreciate the mechanism by means of which energy is radiated from an antenna, let us first consider the simple oscillatory circuit shown in Fig. 128, in which a high-frequency electromotive force is impressed upon the *resonant* circuit containing the inductance L and the condenser C in series.

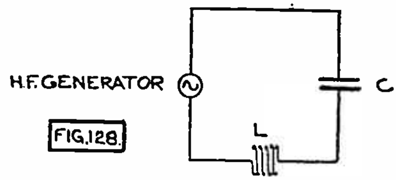


Fig. 128. Oscillator Circuit with Condenser Having Widely Separated Plates.

Let us assume that at a certain instant the current in this circuit is in such a direction that the top plate of the condenser is charged positively and the bottom plate negatively. This means that electrons have been conducted away from the top plate of the condenser and accumulated on the bottom plate. We can easily see that the electrons in the portion of the top plate nearest to the lead-in wire will leave this plate first and that these electrons will begin to accumulate on the portion of the bottom condenser plate nearest the lead-in wire. Electrostatic lines of force, which exist between electrostatic charges, therefore will be created first between the central portions of the condenser plates shown in Fig. 128, and they will progress toward the outer part of these plates as the charge spreads over the plate area. These lines of force will be in the direction indicated by the arrows in Fig. 129, during the time that the top plate is positive; and because they are all in the same direction they react on each other in the same manner as *like* charges, that is, they repel each other. As a consequence of this repulsion, some of the lines of force will ultimately extend beyond the space between the condenser plates, as shown in Fig. 129, in which the progress of their displacement is represented.

As the impressed electromotive force passes through its positive maximum value and begins to decrease, these lines of force

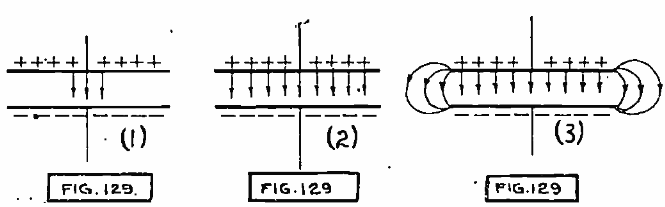


Fig. 129. Showing Progress of Lines of Force.

will start to collapse, the lines in the center portion of the condenser plates collapsing first and the adjacent lines moving in toward the center, where they in turn collapse. During the time that the current in the circuit is passing through zero there will be zero lines of force. As the current builds up in the opposite direction, lines of force will be created again in the condenser dielectric, beginning at the middle and traveling toward the periphery of the condenser plates. These lines of force, of course, will be in the opposite direction to those which existed during the previous half cycle of the impressed electromotive force.

We see, then, that as the high-frequency current flows through the circuit, electric lines of force are created in one direction, rapidly displaced from the center of the condenser plates toward its outer boundaries and back again toward the center, where they collapse and are recreated in the opposite direction and pass through the same series of displacements again.

These lines of force might be regarded as having the equivalent of mechanical inertia, and therefore when they are rapidly moving in one direction and are suddenly required to reverse their direction, those on the extreme edge are unable to make this change with sufficient rapidity and are forced out of the system, as shown in Fig. 130. In this way a certain amount of the energy stored in the condenser is lost from the system or is radiated during each cycle of the current.

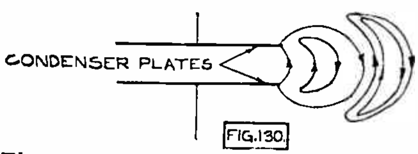


Fig. 130. Showing Lines of Force Detached from Circuit.

Now let us suppose that one plate of this condenser is a wire extending vertically from the generator and insulated from the ground, and that the other side of the generator is connected through the inductance coil to the ground, so that the ground constitutes the other plate of the condenser. Electric lines of force would be detached from this system in the same manner as described above, and after the current had passed through two and one-half cycles the electric field in one direction about this antenna would be as indicated in Fig. 131.

Observing this field at any instant, along any straight line, as for example along the surface of the earth, as shown in Fig. 131, it appears that there are equidistant points of condensation and rarefaction of the lines of force, so that if we indicate graphically the intensity of the field at various points along this straight line, it would be as represented by the sine curve shown in Fig. 131. These lines of force continue to be displaced outward from the

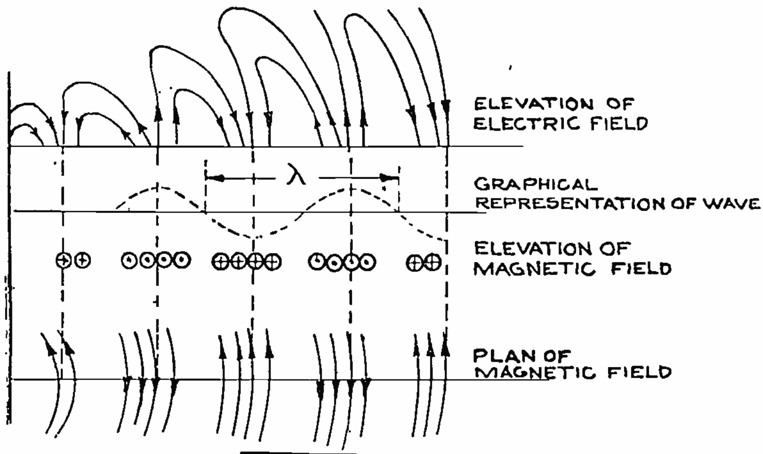


Fig. 131. Electromagnetic Field in One Direction About Vertical Wire Antenna.

antenna, due to the reaction between the lines created during successive half cycles, and therefore they are equivalent to moving electrostatic charges and give rise to a corresponding magnetic field, which is in phase with the electrostatic field. The magnetic lines of force, however, are in a direction perpendicular to the plane established by the direction of their displacement, the relationship between the directions of the quantities being given by the following right-hand rule: With the right hand extended so that the fingers are perpendicular to the thumb, place the palm of the hand so as to receive electric lines of force perpendicularly and so that the thumb is parallel to the direction of displacement, and the fingers will then indicate the direction of the resulting magnetic field.

The magnetic field in this case is, therefore, as shown in Fig. 131.

In this way an electromagnetic wave is radiated from a vertical wire antenna through which a high-frequency current flows, and the amount of energy so radiated is directly proportonal to the frequency of the current.

In a similar manner electric energy is forced out of all types of antenna, except the loop or coil type. In all of these cases the escape of electrostatic energy may be thought of as being due to, first, the reaction between like electrostatic lines of force and, second, the inertia of such lines of force; and the magnetic field may be considered as due to the displacement of the electrostatic field. Therefore, all types of antenna, except the loop antenna, may be considered primarily as condensers.

The loop antenna, which consists of a closed coil of wire (relatively small as compared to the dimensions of other antennas), is primarily an inductance coil, as magnetic energy escapes from it at high frequencies, and the displacement of the magnetic lines of force results in the electrostatic field. Radiation from a loop antenna is similar to that from other types, except that it is the magnetic energy which is forced out of the system instead of the electric energy.

In addition to the energy *radiated* from an antenna in the manner described above, there is, of course, the energy contained in the usual electric and magnetic fields pertaining to an oscillatory circuit through which current is flowing. To distinguish the field of the radiated lines of force from the field of the lines of force which are not detached from the circuit, the former is called the *radiation field* and the latter the *induction field.* It should be observed that the electric and magnetic components of the induction field are ninety degrees out of phase with each other, while in the radiation field these two components are in phase with each other. It is the radiation field which is utilized in radio communication, although it is possible to signal over relatively short distance by means of the induction field. The induction field is not nearly as useful in communication without connecting wires, because its intensity decreases as the square or cube of the distance from the transmitter, while the intensity of the radiation field decreases as the first power of the distance from the transmitter.

It is much easier to comprehend the manner in which the antenna intercepts electromagnetic waves, than to conceive of the means by which they are radiated. Perhaps the simplest way of thinking of the receiving action of an antenna is to consider that an electromotive force is induced in the antenna due to the relative motion between its stationary wire and the moving magnetic field of the electromagnetic wave.

Due to the distortion of the electrostatic lines of force near the surface of the earth, as shown in Fig. 128, there will be a difference of potential between the top and bottom of a vertical wire; and, because of the separation of the two ends of a horizontal wire antenna there is a difference of potential between the free end and the grounded end of such an antenna. In either case, therefore, a current flows in the oscillatory antenna circuit due to the difference in potential between its free end and its grounded end.

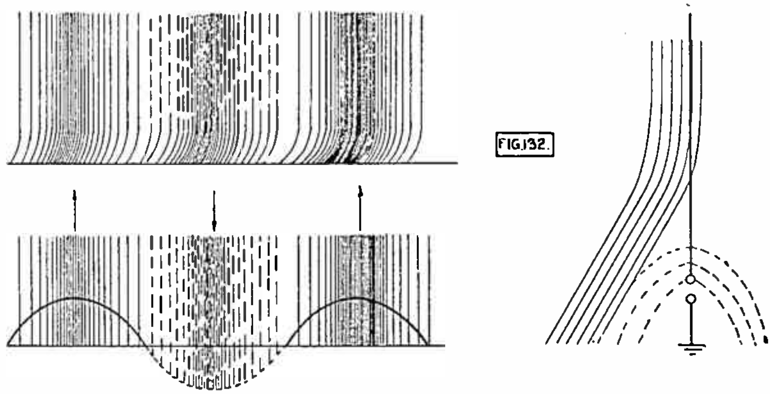


Fig. 132. Field About Vertical Receiving Antenna.

89. Propagation of Electromagnetic Waves.—Due to the nature of the medium in which the electromagnetic waves are created, these waves are propagated in all directions with little opposition. However, when they attempt to pass from one medium to another of different dielectric constant, they are refracted or reflected in the same manner as light waves are refracted in passing from air to water, or reflected when they fall upon a polished surface. This property of electromagnetic waves is very important in radio communication, because the earth itself is a conducting medium, and above the earth at a distance of from forty to one hundred or more miles there is a fairly good conducting layer of atmosphere, known as the *Heaviside layer*. When electromagnetic waves are created just above the surface of the earth, therefore, they are propagated through a space which is practically limited by the earth's surface and the Heaviside layer. Such waves are partly transmitted as guided waves along the surface of the earth, their direction of propagation being modified by refractions due to the earth's irregularities, and partly transmitted upward into space, where they are turned back by the Heaviside layer. The waves actually reaching a receiving station, therefore, are the algebraic sum of the *guided waves* and the *space waves.* The best available data seem to indicate that the guided waves of high frequency are absorbed more by the irregularities of the earth than are those of lower frequencies; but, on the other hand, the space waves are absorbed to a greater extent at lower frequencies than at higher frequencies.

Certain geological formations reflect, refract or absorb the guided waves to a great extent, and when such a formation occupies space intervening between a transmitting and receiving station, the major portion of the received energy is due to the space wave. It sometimes happens that two stations which are reasonably close together are unable to communicate, because neither the space wave nor the guided wave reaches the receiving station.

In communicating by means of short waves, that is, waves of very high frequency, a relatively large part of the energy intercepted at the receiving station is due to the space waves, and there are many areas in which no energy is detected but on both sides of which energy is received. This is referred to as the *skip space* characteristic of short waves, and is due to the fact that the space wave reflected back and forth between the Heaviside layer and the earth is 180° out of phase with the guided wave in these *dead areas.*

The existence of the Heaviside layer above the earth is due to the ionization of the rarefied portions of the earth's atmosphere by solar radiations. The height of this reflecting surface above the earth varies with the frequency of the electromagnetic wave, being highest for waves of highest frequency. This Heaviside layer is also more sharply defined at night than during the day, and for this reason signals received at night are in general stronger than those received during the day. Reflections from the Heaviside layer are more erratic when the inclination of the sun's rays to the earth's surface in the area over which it is desired to communicate is most nearly perpendicular. Such a condition exists in a particular locality to a greater extent in the summer than in the winter, and also exists to a greater extent in the tropics than in the less torrid zones of the earth; and therefore radio communications are less reliable in summer, particularly in the tropics. It is also known that charged clouds and other meteorological conditions influence the Heaviside layer, and consequently render radio communication erratic.

There are four principal sources encountered in practice other than interference, which make it difficult to receive readable radio signals. These are as follows:

1. Static;
2. Strays;
3. Fading;
4. Swinging.

Static is due to the physical contact between the antenna and charged masses of gas. This contact imparts charges to the antenna which results in undesirable antenna currents. Strays are electromagnetic disturbances in radio reception other than those produced by radio transmitting stations. Fading is the variation in the signal intensity received at a given location from a radio transmitting station, as a result of changes in the transmission path. The changes in the path followed by electromagnetic waves in traveling from one station to another are due to variations in the Heaviside layer for reasons described above. Swinging is the variation in intensity of a received radio signal due to changes in the frequency of the transmitting station. These definitions were taken from the 1926 report of the Standardization Committee of the Institute of Radio Engineers.

90. Types of Antenna Used in Radio.—There are a variety of different types of antenna used in radio transmitting and receiving sets, but these may be divided into the following basic categories:

1. Vertical wire type;
2. Inverted L type;
3. T-type;
4. V-type;
5. Umbrella type;
6. Loop or coil type.

The simple vertical antenna has already been described as consisting of a single vertical wire. Sometimes a number of wires are connected in parallel to form a sort of long cylindrical cage, in which case the antenna is called a vertical cage antenna. Both of these antennas are non-directional; that is, they transmit and intercept equally well in all directions.

The inverted L antenna is formed by connecting one end of one or more horizontal wires to a vertical wire, as shown in Fig. 134(1). The relative effectiveness of this antenna for both

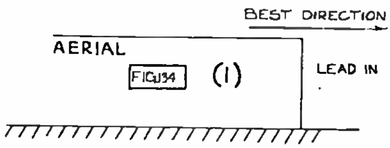


Fig. 134 (1). The Inverted L Aerial.

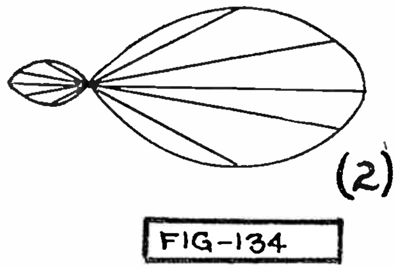
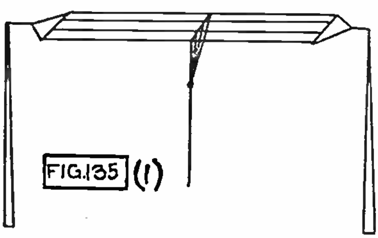


Fig. 134 (2). Directional Characteristics of Inverted L Aerial.

transmitting and receiving in various directions is graphically indicated by the length of the radius vector for any vectorial angle, shown in Fig. 134(2), which shows that the best transmitting and receiving direction is in prolongation of the horizontal wire toward the end to which the vertical wire is attached. The horizontal wire is known as the *aerial* and the vertical wire is known as the *lead-in.*

The T-type antenna is similar to the inverted L except that



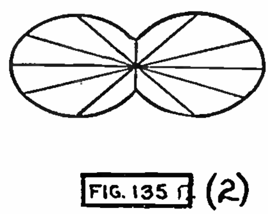


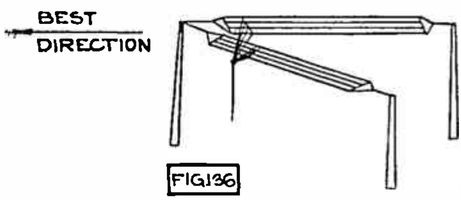
Fig. 135(1). T Antenna.

Fig. 135(2). Directional Effect of T Antenna.

the *lead-in* is attached to the center of the aerial, as shown in Fig. 135(1). This type of antenna transmits and receives best in prolongation of the aerial in either direction, as shown in polar co-ordinates by Fig. 135(2).

In the V-type antenna the aerial is composed of two groups of horizontal wires arranged in a V shape, each group containing one or more wires, and the lead-in is attached to the apex of the V, as shown in Fig. 136. This antenna transmits and receives best in the direction in which the V points.

The umbrella antenna consists of a number of aerial wires radiating from a vertical lead-in, as shown in Fig. 137. This antenna transmits and receives equally well in all directions.



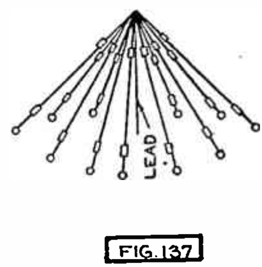


Fig. 136. V Antenna.

Fig. 137. Umbrella Type of Antenna (Non-directional).

The loop antenna consists of a completely closed loop of wire, as shown in Fig. 138. This type of antenna is used without a ground connection, and it is extremely directional, being incapable of radiating or receiving in a direction perpendicular to the plane of the loop and having a maximum effectiveness in prolongation of the plane of the loop in either direction. The loop antenna will be discussed in more detail, in connection with *radio direction finding*.

91. Current and Voltage Distribution in an Antenna.—When an electromotive force is introduced into an antenna, a current flows in the wires and through the antenna capacity back to ground. Each increment of the antenna wire forms a little condenser, with the earth acting as the other plate. The vertical wire antenna may be considered as equivalent to the system shown in Fig. 139. The effective current at the various points A-B-C along the wide will be different, due to the parallel paths back to earth through the condensers, and the maximum effective current will exist where the antenna is connected to ground and the

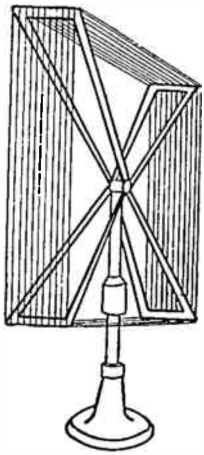


FIG. 138

Fig. 138. Typical Loop Antenna.

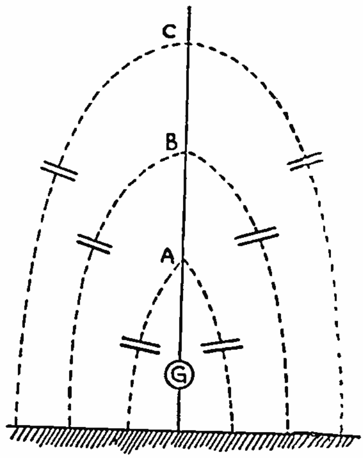


FIG. 139

Fig. 139. Capacity Effect of a Single Wire Vertical Aerial.

current will be zero at the free end C. The effective voltage between the ground and the various points A-B-C will be a maximum at the free end and zero at the ground, since the voltage of any point with reference to the ground is equal to the sum of the IX drop across each little inductance included between the ground and the point considered. We may represent, therefore, the relative effective current and voltage distribution along a vertical wire antenna in the manner shown in Fig. 140(1), in which the voltage and current are read by the horizontal distance from the antenna, provided the antenna is oscillating at its natural frequency.

It is possible to cause the antenna to oscillate with other distributions of current and voltage, but in any case, the free end of the antenna must be a current node and the ground end a voltage node. Fig. 140(2) shows the current and voltage distribution when the antenna is oscillating at a frequency which is three times its natural frequency.

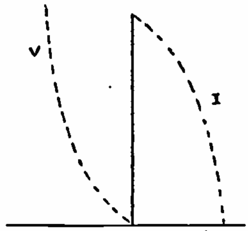


Fig. 140(1). Current and Voltage distribution at Natural Frequency.

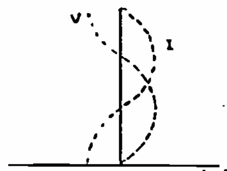


Fig. 140(2). Current and Voltage Distribution at Three Times Natural Frequency.

A large capacity to earth, concentrated at any point of the antenna, causes a large change in the current at that part of the antenna. If this bunched capacity is located at the top of the antenna, such as is the case with a flat-topped antenna of long wires, with only a few vertical lead-in wires, the average current in the flat-top portion will be large, and it increases slightly in strength as the charges pass down through the lead-in wire, hence giving a large current through the receiving apparatus. It is a distinct advantage to have as large a part of the total capacity of the antenna as possible at the top.

The action of antennas is discussed more fully in Bureau of Standards Circular No. 74.

*92. **Action of the Ground-Counterpoise.**—The electric oscillations in an antenna may be regarded as somewhat analogous to the vibrations of a string stretched between two points A and B and plucked at the middle, C, in Fig. 141(1). The stretching forces on the string are greatest at the points A and B, while the portion C is under very small force. The motion of the string is most considerable at C, while the points A and B do not move. If we regard current as similar to motion and voltage to force, we can see (according to statement in the pre-

*Paragraphs 92 to 96 are extracts from Radio Communication Pamphlet No. 40 S. C., U. S. Army, "Principles of Radio Communication."

ceding section) that the top of the antenna resembles in its behavior the end A (or B) of the string, while the bottom of the antenna corresponds to the point C of the string.

The part played by the earth may now be understood. If we suppose for a moment that the antenna is disconnected from the ground and insulated, as shown in Fig. 141(2), then the lower free end would become a point where the current would be zero and where the variations of voltage would be large [corresponding to point B or A, Fig. 141(1)]. The portion where the current would be a maximum would lie at some elevated point. To set a string in vibration requires the smallest force when it is plucked at the middle. Right at the ends it is almost impossible

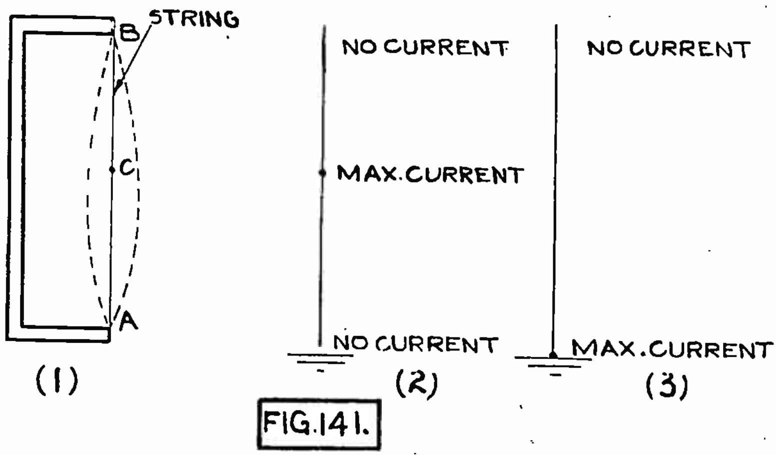


Fig. 141. Illustrating Similarity of Radio Aerial and Vibrating String.

to set it in vibration. Just so the antenna, if disconnected from earth, would be almost impossible to set in vibration if the electromotive force were applied at the bottom end. For successful working, the exciting apparatus would have to be joined to inaccessible points of the wire higher up. It is necessary, then, to make sure that the lower end of the antenna is a region where current is large, and with a good ground this condition is satisfied.

In places where the ground has poor conductivity (dry, rocky soil, with ground water at some considerable depth), it becomes difficult to satisfy the above condition. In such cases a *counterpoise antenna* or "earth capacity" must be used. The counterpoise is another antenna of suitable type, supported a few feet above the ground, and insulated from it. The station apparatus is connected to the regular antenna and the counterpoise, instead of to the regular antenna and earth. The use of a properly designed counterpoise is often advantageous even where the earth has fairly good conductivity. As far as the antenna is concerned, the counterpoise takes the place of the ground. To some extent the action of a counterpoise can be considered as that of two condensers in series; one antenna consisting of the regular antenna and the counterpoise, and the other consisting of the counterpoise and the more moist layers of the earth (W, Fig. 142) deep below the surface. The counterpoise is usually simply a number of wires supported a few feet from the ground, but may be a metal screen or netting. The wires may be distributed radially from the foot of the antenna. The area covered by the counterpoise should preferably be several times as large as the area of the antenna.

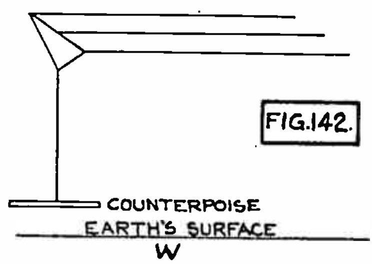


Fig. 142. Principle of the Counterpoise.

On aircraft, a counterpoise must necessarily be used. The counterpoise is furnished by the metal wires of the framework, the engine, stay wires, metalized wings, etc. The antenna may consist of a long wire which trails behind the plane when in flight, has a weight attached to its end, and is wound up on a reel before landing. With such an antenna the antenna is below the counterpoise, but the action is not different from the ordinary antenna and counterpoise systems. The trailing wire antenna is inconvenient in some respects. In many cases it is found more convenient on aircraft to use a coil antenna, which may be wound on the wings of a plane, or may be wound on a small frame and installed aft in the plane.

93. Antenna Capacity, Inductance and Resistance.—The behavior of an antenna depends upon its capacity, inductance, and effective resistance, just as is the case with any oscillating circuit. Let us consider these properties of antennæ.

Since the energy which can be given to a condenser, when it is charged to a voltage E, is equal to one-half the capacity C, multiplied by the square of the voltage, energy which is supplied to an antenna each time it is charged is

$$E = \frac{1}{2} CE^2.$$

We may, evidently, increase the supply of energy to an antenna by increasing the capacity, or by raising the voltage.

The voltage on the antenna cannot be made greater than about 50,000 volts without loss of energy through leakage and brush discharges. The only factor which can be varied is C in the above formula; therefore, a high-power sending antenna must have a large capacity. Large capacity means many wires of great length; that is, a large and costly structure.

The capacity of a single wire parallel to the ground can be calculated approximately, as also the capacity of certain simple arrangements of parallel wires.* Even in the simplest cases, however, the presence of houses, trees, and other neighboring objects, and the difficulty of allowing for the lead-in wire, makes any precise calculation impossible. It should be noted, however, that the capacity of a wire is proportional to its length. The capacity of two wires near together is less than the sum of their capacities, and, in general, although each added wire adds something to the capacity, it adds much less than the capacity it would have alone in the same position. As an indication of what values of antenna capacity may be expected, the following values may be cited:

Airplane and small amateur antennas, 0.0002 to 0.0005 microfarad.

Ship antennas, 0.0007 to 0.0015 microfarad.

Large land station antennas, 0.005 to 0.015 microfarad.

That is, in spite of their size and extent, antennas do not possess greater capacity than is found in ordinary variable air condensers.

The effectiveness of an antenna is proportional to its height and therefore the capacity cannot be increased by lowering the antenna without sacrificing efficiency.

Although principal stress has been laid upon the conception of the antenna as a condenser, the inductance which its wires

*See Bureau of Standards Circular No. 74.

necessarily possess is of equal importance in determining the wavelength of the radiated waves. The antenna is, in fact, an oscillating circuit, and as such the wavelength or frequency of free oscillation depends upon the product of the inductance and capacity.

The inductance in general is not large—50 to 100 microhenries is a common range of values; but larger capacity is necessarily associated with larger inductance, so that high-power antennas are naturally long-wave antennas.

The wires of an antenna offer resistance to the current, which is greater for the high-frequency antenna current than it would be for a steady current, on account of the skin effect. In addition to this, the radiation of energy in waves causes a further increase in the apparent resistance of the antenna. The "effective resistance of the antenna" is defined as the quotient of the power given to the antenna by the square of the antenna current. That is, if R is the effective resistance, the total power put into the antenna is RI^2, where I is measured at the base of the antenna. The effective resistance is different for different frequencies, as is shown below.

The total power is dissipated in the following ways: (1) As heat in the antenna wires and earth connection, (2) brush discharge, (3) leakage over or through insulators, (4) heat in the dielectric surrounding the antenna, and in any condensers that are in the antenna circuit, and (5) radiated waves. Part of (5) will also be turned into useless heat by inducing eddy currents in nearby conductors, such as guy wires or metal masts. If $R'I^2$ represents all the power except that radiated, and $R''I^2$ represents the power radiated as waves, then it is evident that $R'I^2 + R''I^2 = RI^2$, or $R' + R'' = R$, the effective resistance. R'' is called the "radiation resistance." It might be defined as that resistance which, if placed at the base of the antenna, would cause as great a dissipation of energy as the energy radiated in waves. It will be different at different frequencies. It gives an idea of the radiating power of the antenna for each ampere of antenna current.

When the effective resistance of an antenna is measured at a number of frequencies and the results are plotted, a curve is obtained like curve 4, Fig. 143. The shape of the curve is explained by considering the laws according to which the different kinds of resistance in the antenna vary with the wavelength. The radiation resistance decreases as the wavelength increases, the relation being that the radiation resistance is inversely proportional to the square of the wavelength. Such a variation is represented by curve 1, Fig. 143. The resistance of the conductors and earth connection is nearly constant with different wavelengths, curve 2. The dielectric resistance increases nearly as the wavelength, curve 3. Curve 4 is the sum of curves 1, 2, 3. If the losses in the dielectric are very small, the curve does not have a minimum, but becomes horizontal at the right end. If these are negligible, the curve merely falls toward a limiting value.

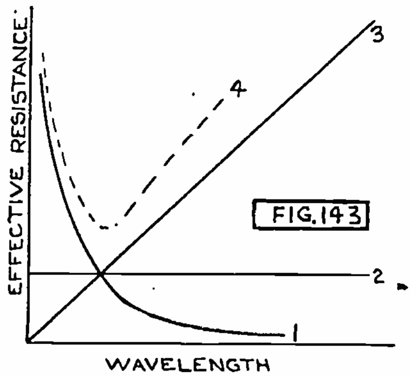


Fig. 143. Variation of the Effective Resistance of an Antenna.

To reduce the dielectric losses, no portion of the antenna should be near buildings or trees. To reduce eddy current losses, care should be taken to have the antenna a reasonable distance from guy wires, and especially large masses of metal. Guy wires may be cut up and insulated in sections. On shipboard, induced currents are produced in iron stacks and guy wires near the antenna, and in cases where the frequency of the waves agrees with the natural frequency of oscillation of these metal objects, considerable power losses may result. These show themselves, when they are present, as humps on the experimental curve 4, Fig. 143, at the frequencies in question.

The effective resistance of an antenna is often as high as 20 to 30 ohms at the fundamental wavelength. The minimum value may be 5 to 10 ohms for a land station and as low as 2 ohms for a ship station.

Methods for the measurement of the capacity, inductance, and resistance of an antenna will be described in a later section.

At high-power stations employing high-frequency alternators, an antenna of comparatively small effective resistance has been secured by the use of a *multiple-tuned antenna.* At such stations the antenna may be a mile or more in length and may constitute a considerable part of the total cost of the station equipment. The multiple-tuned antenna is a long antenna which is grounded at several points along its length through leading inductances, by means of which the individual sections are tuned to the wave-length which it is desired to radiate. (See Fig. 144.) A high-

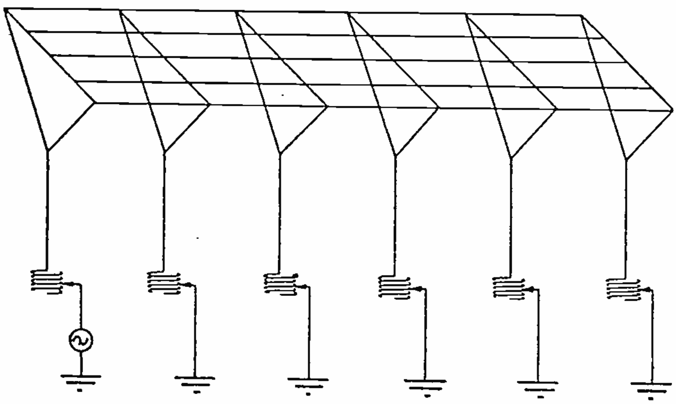


FIG.144.

Fig. 144. Multiple-Tuned Antenna.

frequency alternator or other transmitting apparatus may be inserted, as shown above. This is equivalent to connecting several antennas in parallel; the radiation resistance remains the same as for the antenna connected in the ordinary way, but the actual resistance of the ground connections of the whole antenna is the resistance of a single ground connection divided by the number of ground connections. The antenna at the high-frequency alternator station at New Brunswick, N. J., is about one mile long and has been grounded at five intermediate equidistant points. The antenna so connected is equivalent to six independent radiators, and the total resistance of the antenna has dropped from 3.8 ohms with the ordinary system of grounding to 0.5 ohm with the multiple ground at a wavelength of 13,600 meters. The ground resistance has been reduced from about 2 ohms to 0.33 ohm. Antennas of this type have so far been used only for high-power work, and a detailed description will not be given here. The multiple-tuned antenna is well adapted for use with the high-frequency alternator, because in this case the radiated wavelength of a given alternator depends only on its speed and not on the antenna. The multiple-tuned antenna does not, however, seem to be so well adapted to tube and arc transmitters and not at all to spark transmitters, because in such transmitters the radiated wavelength depends on the antenna.

94. **Wavelengths of Antennas.**—The wavelength of the waves emitted by an antenna, when no added inductance or capacity is inserted in the antenna circuit, is known as the *fundamental wavelength,* and depends upon the physical structure of the antenna alone. By putting inductance coils (*loading coils*) in the antenna circuit, longer waves may be radiated, while, on the contrary, condensers put in series with the antenna enable it to produce shorter waves than the fundamental. The use of a series condenser is avoided where possible, since it has the effect of decreasing the total capacity of the antenna circuit, and thereby diminishing the amount of power which can be given to the antenna. The addition of some inductance has a beneficial effect, since the decrement of the antenna is thereby lessened and a sharper wave results. It is not advisable to load the antenna with a very great inductance, however, as it is not an efficient radiator of waves.

A simple radio circuit has a reactance equal to zero at a single frequency, namely, the resonance frequency, and the maximum current possible with the given electromotive force will flow. This result is strictly true only when the capacity and inductance are concentrated at definite points of the circuit. In an antenna, however, the inductance and capacity are distributed, and it is found that a maximum of current is obtained for a whole series of different frequencies or wavelengths.

What is called the *fundamental frequency* is the lowest frequency for which the current attains a maximum when not loaded with either capacity or inductance. Denoting this by f, there are in the same antenna other resonance frequencies—$3f$, $5f$, $7f$, etc., called the "harmonic frequencies" of the antenna. With the usual methods of producing current in an antenna, it radiates principally waves of its fundamental frequency alone; free oscillations of the harmonic wavelengths are almost entirely lacking. However, when electromotive forces having the harmonic frequencies are applied, vigorous oscillations of those frequencies may be set up.

It should be noted that only the odd multiples of the fundamental frequency are considered as harmonics of an antenna. This is because the reactance of the antenna is zero at these odd multiples of the fundamental frequency. This can be shown mathematically, and also it can be similarly shown that the antenna reactance is infinite at frequencies which are even multiples of the fundamental frequency of the antenna. The variations of antenna reactance with frequency are shown in Fig. 145.

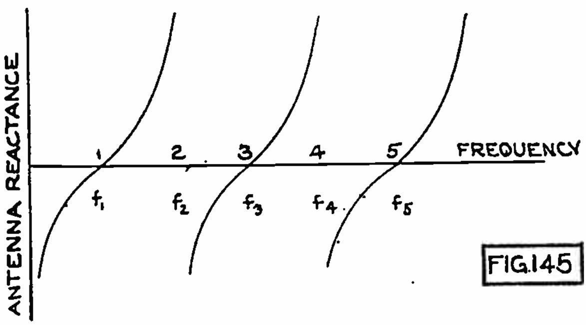


Fig. 145. Showing Relationship Between Antenna Reactance and Frequency.

95. Constructional Features of Antennas.—The masts usually employed at permanent radio stations to support antennas are made of structural steel, and those used in portable radio stations are most frequently made of wooden sections telescoped together. In any case, the antenna should be carefully insulated from the mast, particularly at the free end of the aerial, since it is at this point that the voltage between antenna and ground is greatest.

The insulators used in antenna construction must not only be good electrical insulators, but must be capable of supporting large mechanical strains. Such insulators are usually made of a composition of rubber, asbestos and shellac, and provided with surface corrugation so as to increase the distance between conducting parts over the surface of the insulator, which constitute leakage paths, particularly when the insulator is wet or dirty.

Antenna wire should be of high tensile strength and low ohmic resistance, should not be brittle, and preferably should be stranded. Hard drawn copper wire, phosphor bronze, and galvanized steel wire are the types generally used for this purpose.

A good ground connection is not possible at some localities. In any case, the best ground connection is obtained by burying copper conductors symmetrically around the station, and surrounding these conductors with charcoal, copper turnings and salt.

When a counterpoise is used it usually consists of an arrangement of parallel or radial wires, supported three or four feet above the ground and insulated from it, or else a metal screen similarly mounted. In portable sets the counterpoise often consists of heavily insulated wire laid on the ground.

96. Method of Measuring Antenna Inductance and Capacity.—The inductance of an antenna can be measured by the use of two loading coils whose inductance is known. The coils are successively connected into the antenna circuit, and the wavelengths for which the antenna is in resonance are determined. If the inductances of the coils are, respectively, L_1 and L_2, and the corresponding wavelengths are λ_1 and λ_2, then since:

$$\lambda_1 = K\sqrt{(L_1 + L_a)C_a} \quad \text{and} \quad \lambda_2 = K\sqrt{(L_2 + L_a)C_a}$$

we have the relation

$$\frac{\lambda_1}{\lambda_2} = \frac{\sqrt{L_1 + L_a}}{\sqrt{L_2 + L_a}} \quad \text{or} \quad L_a = \frac{L_2\lambda_1^2 - L_1\lambda_2^2}{\lambda_2^2 - \lambda_1^2}.$$

The simplest method of determining the capacity of an antenna is as follows:

Insert a coil of known inductance in the antenna circuit, and couple this coil to an oscillator of variable known frequency, such as a wavemeter. Adjust the oscillator until a maximum current is obtained in the antenna circuit, and read the frequency of the oscillator. Then, knowing the inductance of the antenna, the antenna capacity may be found, by substituting in the following formula:

$$C_a = \frac{1}{4\pi^2 f^2 (L_1 + L_a)}.$$

This method, of course, is only satisfactory for practical purposes, and is unsuitable for purposes requiring greater accuracy, due to the error introduced by the distributed capacity of the coupling coil and the constants of the device used to indicate resonance.

97. Radio Direction Finding.—It has already been stated that a loop antenna is especially directional in its ability to transmit and receive electromagnetic waves. This property of the loop makes it possible to determine the direction of a radio transmitting station with reference to the receiving station at which the loop is located.

To better understand the directional effect of the loop antenna, let us consider the manner in which an incoming wave would influence two vertical wires insulated from the ground and separated from each other by, say, 10 meters. Such an arrangement is represented in Fig. 146. If an electromagnetic wave reaches these wires from a transmitting station located in prolongation of the plane, established by the two vertical wires AB and CD, there will be a difference in phase between the wave at AB and at CD, as shown graphically in Fig. 146 by the dot-and-dash line. If the receiving set is connected across the lower ends of these wires and the top ends are connected by a conductor, a current will flow through the rectangular loop circuit thus formed, and this current may be detected in the usual way. Obviously, in this case, the greatest difference of potential between corresponding points on AB and CD would be obtained when these two vertical wires are separated by one-half a wavelength.

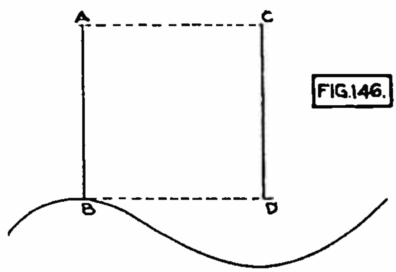


Fig. 146. Illustrating Loop Directional Effect.

Now suppose that the electromagnetic wave approaches from a direction perpendicular to the plane formed by these vertical wires; then the phase of the field at AB will be the same as that at CD, so that there will be no difference of potential between these two wires, and consequently no current will flow through the receiving equipment.

If the wave approached from any other direction than these two considered above, the difference in potential between the bottom of AB and the bottom of CD will vary between the limits of zero and some maximum, in accordance with its direction, as indicated in Fig. 147. Therefore, if the loop be mounted so that it is capable of rotation about its central vertical axis, the received current would be a maximum when the loop is oriented so that the direction of approach of the electromagnetic wave, that is, its displacement, lies in the plane of the loop, and a minimum current is obtained when this displacement of the wave is perpendicular to the plane of the loop, and this current will vary in accordance with the position of the loop between these limits.

Inspection of the curve shown in Fig. 147 shows that the angle of minimum current is more sharply defined than the angle of maximum current; that is, for a change of angular position of the loop, say, five degrees on either side of the position of maximum current a smaller change in current would result than would be effected by an equal rotation of the coil from its position of minimum current. For this reason, it is customary to determine the position of the loop for minimum current when it is desired to locate the direction of the transmitting station, the transmitting station being then in a direction perpendicular to the plane of the loop.

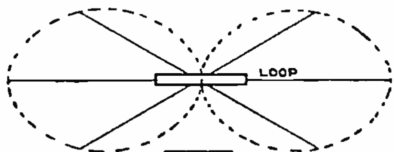


FIG.147.

Fig. 147. Directional Characteristics of Loop Antenna.

The circuit normally employed for radio direction finding is

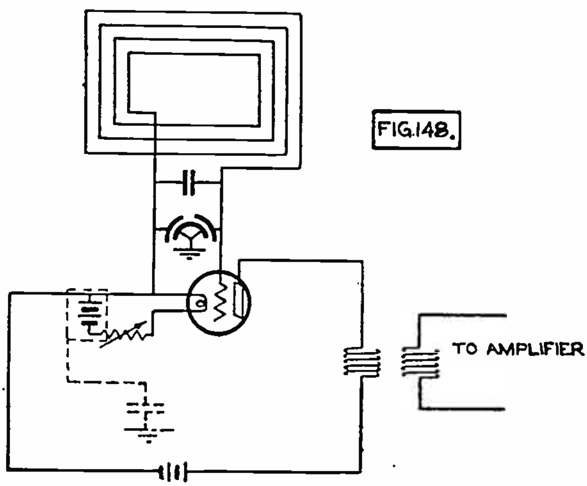


FIG.148.

Fig. 148. Coil Antenna Circuit with Balancing Condenser, for Use as Direction Finder.

shown in Fig. 148. In this circuit the capacity of each side of the loop to ground is adjusted by means of the balancing condenser. The balancing of this capacity is necessary, because the capacity of the storage battery plates to ground is included in the capacity-ground circuit of one vertical side of the loop, only.

It is worthy of note that in most instances two loops are mounted perpendicular to each other with a switch provided for connecting either loop to the receiving apparatus. This method provides a means of locating approximately the direction of the transmitting station on the maximum direction of one loop, and more accurately locating the transmitting station on the minimum direction of the other loop. Ordinarily, the existence of zero signal current might be due to the proper alignment of the loop, or the discontinuance of operation of the transmitting station. With two loops, throwing the switch to connect the maximum loop to the receiving set will enable a quick decision as to which of these causes is responsible for zero current in the minimum loop.

98. **Goniometric Radio Stations.**—It is sometimes desirable for a receiving station to ascertain the position of a radio transmitting station. In such cases the transmitting station is usually located by means of so-called *goniometric stations* located at the ends of a known base line. For example: Fig. 149 shows two direction-finding stations of the type described in the above-mentioned reference. These stations are located on the shore at A and B which are separated by some known distance. A transmitting station is in operation on a ship at T.

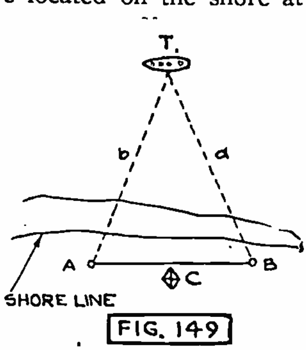


Fig. 149. Determining a Ship's Position.

If it were desired to locate the position of this ship with reference to a particular position, C, on the shore, the radio receiving station at A can determine the angle BAT, and the radio receiving station at B can determine the angle ABT. From these angles and the known base line AB, the position of T with reference to either A or B can be computed by substituting in the following trigonometric formula:

$$\frac{a}{\sin(BAT)} = \frac{b}{\sin(ABT)} = \frac{c}{\sin(ATB)}.$$

The relative position of A and B to C having been previously determined, the location of T with reference to C will have been established. Accurate location of a transmitting set is, of course, much more difficult over longer distances.

99. Radio Beacons.—Another radio system which depends upon the directional effect of a loop antenna is the so-called *radio beacon*. Such beacons are rapidly increasing in importance as an aid to marine and aerial navigation. Radio beacons may be divided into two classes, non-directional and directional.

A non-directional radio beacon is simply a radio transmitting station located at some known place and transmitting intermittently a preconcerted signal. As an aid to marine navigation such stations are ordinarily located at lighthouses or on light ships, and a ship equipped with radio direction-finding apparatus can determine its position with reference to two or more such beacons of known position, and consequently follow a desired course.

In aerial navigation the directional feature of such a system must be provided from the ground or transmitting station, because of the impracticability of conveying the required direction-finding receiving apparatus in an airplane. For this purpose, therefore, the radio beacon is made directional. This directional feature is provided in the antenna, which, in practice, consists of two loops mounted on the same vertical axis, but rotated 135 degrees with respect to each other. A suitable mechanical arrangement is provided on a transmitting set to cause this set to transmit the letter "A" from one loop, and the letter "N" from the other. In Fig. 150 the dotted lines represent signals from the loop transmitting "N," and the dash lines represent signals from the loop transmitting "A." If the strength of the signals is as indicated, it will be seen that as long as the airplane is flying directly along the bisector of the 135° angle, it will receive the "A" and "N" signals with equal intensity, but if the plane is displaced on either side of the line PO it will receive one of these signals stronger than the other. The transmitting stations are also synchronized so that when the plane is in a position along the bisector of the angle formed by the loops the operator hears one long dash. The pilot, consequently, is not only provided with a means of knowing when he is off his true course, but also which side of the course he is on, based on the relative intensity of the "A" and "N" signal.

Radio beacons have the advantage over visual beacons, in that they are effective over much greater distances, and that they may be used equally well in fog and clear atmosphere.

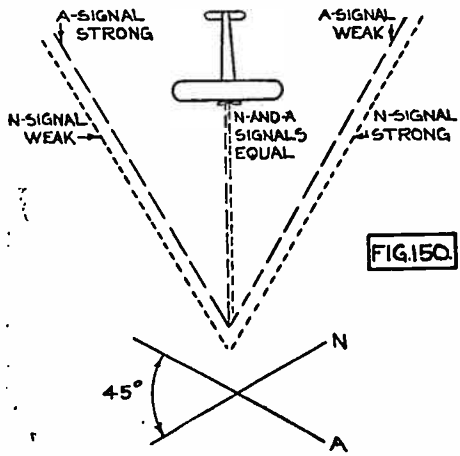


Fig. 150. Radio Beacon System for Aircraft.

100. Summary:

1. Electric lines of force are forced out of an open end antenna, and their displacement gives rise to a magnetic field which is in phase with the electric field, these two moving fields constituting an electromagnetic wave. In a similar manner magnetic lines of force are forced out of a loop antenna.

2. The lines of force which escape from an antenna constitute the radiation field, and those which do not escape constitute the induction field. The electric and magnetic components of the induction field are ninety degrees out of phase with each other, and these components of the radiation field are in phase with each other.

3. An electromotive force is induced in a receiving antenna due to the relative motion between the lines of force of the electromagnetic field and the antenna.

4. The Heaviside layer is a conducting layer of atmosphere from forty to one hundred or more miles above the earth, which reflects electromagnetic waves back to earth. The waves so reflected are called space waves to differentiate them from the

guided waves which follow along the earth surface. The height of the Heaviside layer above the earth is different for waves of various frequencies, being highest for waves of high frequency.

5. Dead spaces are areas on the earth which are not reached by electromagnetic waves from transmitting stations located at particular places or at which the space waves and the guided waves are 180 degrees out of phase.

6. An antenna may oscillate at its natural frequency or at an odd multiple of its natural frequency; in any case, however, the free end is a current node, and the ground end is a voltage node.

7. The fundamental frequency of an antenna is its natural frequency, with no added inductance or capacity. Its harmonics are the odd multiples of the fundamental frequency.

8. Reactance of an antenna is zero at frequencies corresponding to its fundamental frequency and odd multiples thereof, and this reactance is infinite at frequencies which are even multiples of the fundamental frequency.

9. The directional properties of loop antennas are utilized in radio direction finding, and two loop receiving sets on a known base line are used to locate a transmitting station, such loop receivers being called *goniometric* stations.

101. Self-Examination:

1. Explain the manner in which electromagnetic waves are radiated from an antenna.

2. What is the difference between the radiation field and the induction field of a transmitting antenna?

3. Explain the manner in which electromagnetic waves are intercepted by an antenna.

4. What is meant by the *Heaviside layer* of atmosphere?

5. What is meant by *skip space* transmitting distance?

6. What is meant by:
   1. Space waves;
   2. Guided waves?

7. Draw a diagram and indicate the best directional effect of six different types of antennas. Name each type.

8. Explain the possible current and voltage distribution of a vertical wire antenna.

9. What is meant by the fundamental wavelength of an antenna?

10. What are the first three harmonics of an antenna having a fundamental wavelength of 400 meters?

11. Where should the best insulator be provided on an antenna?

12. Explain the action of the ground in the antenna system.

13. What is a counterpoise?
14. Explain the action of a direction finder.
15. Explain the action of non-directional radio beacons.
16. Explain the action of directional radio beacons.

SECTION X.

COILS, CONDENSERS, RECEIVERS, LOUD SPEAKERS, PHONOGRAPH PICK-UPS, AND BATTERY ELIMINATORS USED IN RADIO EQUIPMENT

	Paragraph
REASON FOR SPECIAL EQUIPMENT IN RADIO	102
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TELEPHONE RECEIVERS USED IN RADIO	105
LOUD SPEAKERS	106
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"B" ELIMINATORS	108
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102. **Reason for Special Equipment in Radio.**—The development of radio communication has resulted in the perfection of coils, condensers and telephone receivers for the particular requirements of radio service, and also has caused the development of several different types of loud speakers. Because we are concerned in radio with high-frequency currents and because these currents are often very feeble, similar types of equipment used in other systems of communication are often unsuitable for use in radio apparatus.

103. **Inductance Coils.**—The great importance of the distributed capacity of inductance coils at radio frequencies has already been explained, and it is because of the effects of this distributed capacity that it is desirable and sometimes necessary that inductance coils be so constructed as to minimize distributed capacity.

The inductance coils used to carry radio-frequency currents are usually made of silk or cotton insulated copper wire wound in a single layer on tubing made from some insulating material.

As a means of minimizing the distributed capacity of such coils their adjacent turns are not placed contiguous to each other, but rather are separated, so that the capacity between turns will be relatively small. Such coils are known as *space wound coils.*

Space winding of coils not only decreases their distributed capacity, but also decreases their apparent resistance. Space winding has its limit, however, in the size of the coil, a coil which is wound with spacings of one diameter being twice as long as a closely wound coil. However, coils with a half or one diameter spacings usually effect sufficient reduction in the detrimental effects of distributed capacity and high apparent resistance.

Multilayer coils having a given inductance may be wound so as to occupy less space and have less distributed capacity than single layer coils of the same inductance. There are a number of different types of multilayer coils used in radio sets, the three most important of which are the *honeycomb coil,* the *duolateral coil* and the *spider web coil.* The winding of the honeycomb coil is shown in Fig. 151; that of the duolateral coil is similar to this, except that the wires of its successive layers are staggered with reference to each other, while in the lattice wound coil they are not staggered.

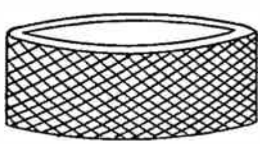


FIG.151.

FIG.152

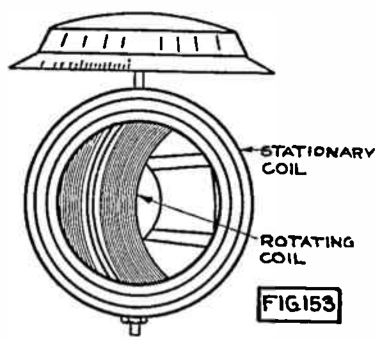


FIG.153

Fig. 151. Honeycomb or Lattice Wound Coil.

Fig. 152. Stagger Wound Coil.

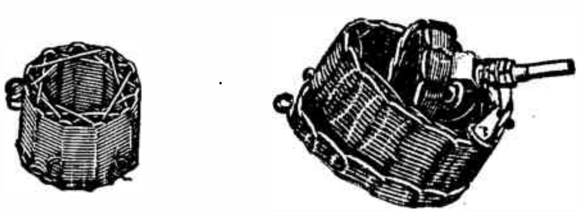
Fig. 153. Variometer.

The spider web coil is wound on a form consisting of radiating arms, arranged like the spokes of a wheel, the wire being wound in and out around the arms, as shown in Fig. 152. There are usually an odd number of arms, so that adjacent turns are on opposite sides of each arm, as shown in the figure.

The variable inductance coils used in radio are either tapped coils provided with a suitable switching arrangement to include the desired number of turns in the circuit, or so-called *variometers,* which consist of two coils electrically connected in series, and mounted so as to be capable of rotation with respect to each other, one coil being stationary and the other rotating, as shown in Fig. 153. This arrangement causes each coil to be in the magnetic field of the other. When the rotating coil is turned so as to be in the same plane with the stationary coil, the inductance is a maximum if the current flows in the same direction in the two coils (*i.e.,* clockwise or counter-clockwise), and a minimum if the current flows in the opposite direction in the coils, so that the inductance of the variometer may be varied from maximum to minimum by 180 degrees rotation of the moving coil. Variometers are more satisfactory than tapped inductances, because they are continuously variable, and also because the dead turns of tapped inductance coils are effective, as previously explained.

Variocouplers are similar in construction to variometers. However, the two coils are not conductively connected together in the circuit, but they are coupled together through the mutual inductance between them. A variocoupler may be varied from maximum coupling to minimum coupling by 90 degrees rotation of the moving coil.

Radio-frequency choke coils and audio-frequency choke coils are also used extensively in radio circuits. In designing choke coils it is necessary to minimize distributed capacity of the coils,



Typical Basket-Weave Inductance Coils.

so that radio-frequency currents cannot pass through the condensers established by the wires and the dielectric between them. The inductance of choke coils depends upon the service in which they are to be used. Audio-frequency chokes are invariably iron core and radio-frequency chokes are wound on non-magnetic cores.

Inductance coils such as are used in radio have what is known as a *gain factor*. The significance of the term may be understood from the following:

Assuming that a voltage is induced in a coil, the current which will flow at resonance is $\frac{E_a}{R_a}$, where E_a is the induced voltage and R_a the apparent resistance of the coil. The total voltage across the coil E_g is equal to IX_L, or

$$E_g = \frac{E_a}{R_a} \times 2\pi f L_a ;$$

$$\frac{E_g}{E_a} = \frac{2\pi f L_a}{R_a}.$$

The ratio of E_g to E_a is called the gain factor of the coil, and is large when $\frac{L_a}{R_a}$ is large. Thus it is apparent that for a good coil R_a must be kept small.

104. Condensers.—The fixed condensers used in radio are similar to those of equal capacity and voltage requirements used in other electrical systems, so we shall consider only the variable air condensers used in tuning.

Variable air condensers consist of a set of rotating plates connected in parallel and mounted so as to be capable of intermeshing with a set of stationary plates connected in parallel, the capacity being varied by changing the overlapping area of the two sets of plates. The capacity, of course, is proportional to the area of overlap. A variable air condenser is shown in Fig. 154.

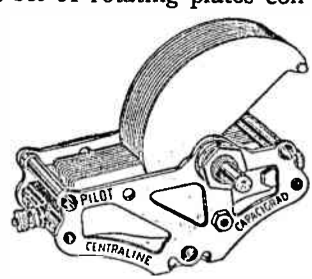


Fig. 154. Variable Condenser.

Variable air condensers are often rated by the total number of their plates; that is, a condenser having six plates in the rotor and seven plates in the stator would be rated as a thirteen-plate condenser. Condensers of this type are sometimes provided with one additional plate, which may be separately rotated for the purpose of accomplishing very small changes in capacity, such a condenser being called a *vernier condenser.* Commercial types of variable air condensers are usually of one of the sizes given below, and their capacity is approximately as indicated:

No. of Plates		Maximum Capacity in Microfarads
13	....	.00025
17	....	.00035
23	....	.00050
43	....	.001

If the plates of a variable air condenser are semi-circular in shape, the change in capacity for a given number of degrees rotation of the moving plates will be the same over any part of the scale; that is, if a change in capacity of .00001 microfarad is accomplished by varying the rotor setting from 10 degrees to 15 degrees, an equal change in capacity will be effected by five degrees rotation from 50 to 55 or any five-degree change in the rotor setting. Such a condenser is called a *straight line capacity* condenser, because of the linear relationship between its dial setting and its capacity.

Now let us suppose that we had an oscillatory circuit of which such a condenser was a part. We know from previous consideration that the frequency of this circuit varies inversely as the square root of the capacity, and that the wavelength of the circuit varies directly as the square root of the capacity. In other words, neither the frequency nor the wavelength of the circuit vary as the first power of the capacity. The change in frequency or wavelength of this circuit, therefore, would not be linear for uniform variations of the condenser dial, since linear changes in capacity (with inductance constant) do not give linear changes in either frequency or wavelength of the circuit.

Primarily, the reason for using variable air condensers in oscillatory circuits is to adjust the frequency of such circuits. The frequency of circuits is particularly important in radio, since frequencies are usually assigned to various broadcasting stations in such a manner as to give a constant separation of 10,000 cycles between them. If, then, we are interested in the possibility of tuning in a number of stations, it would be desirable that the distribution of these stations over the tuning dial be uniform. From the above consideration, we see that this would not be the case if the tuning dial were that of a straight line capacity condenser.

Variable air condensers are now made with logarithmic plates of such a shape that a linear relationship exists between the rotor setting in degrees and the frequency of the circuit of which one of these condensers is a series part. Such condensers are called *straight line frequency* condensers, and their plates are shaped as shown in Fig. 156(2).

Straight line frequency condensers are also manufactured with approximately semi-circular plates of tapering thickness, a cross-sectional view of which is shown in Fig. 155.

Straight line wavelength condensers may also be obtained, their plates being of such a shape that a linear relationship exists between rotor setting in degrees and wavelength of the circuit of which they are a series part. The shape of the plates used in such condensers is shown in Fig. 156(3).

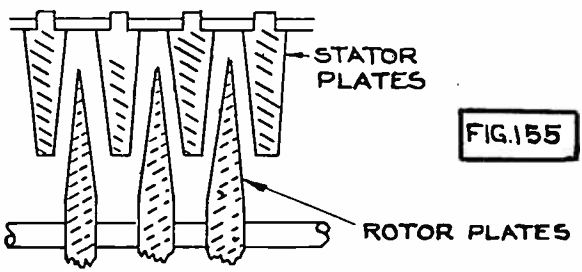


Fig. 155. Cross-Section of One Type Straight Line Frequency Condenser.

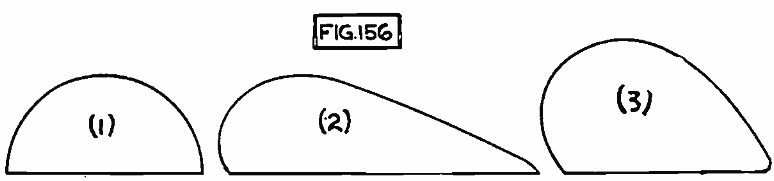


Fig. 156(1). Straight Line Capacity. **Fig. 156(2). Straight Line Frequency.** **Fig. 156(3). Straight Line Wavelength**

If four stations are transmitting at frequencies of f_1, f_2, f_3 and f_4, which are an equal number of cycles apart, it can be seen from Fig. 157 that these stations would be uniformly distributed over the tuning condenser dial of a receiving set if a straight line frequency condenser were used, and that the stations of higher frequencies would be very close together on the tuning dial of a straight line capacity condenser, and the stations of lower frequencies would be greatly separated. The distribution of these stations over the tuning dial of a straight line wavelength condenser is also shown in Fig. 157.

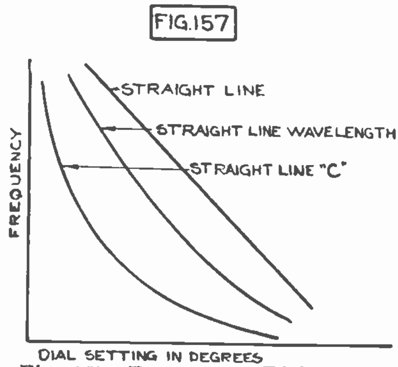
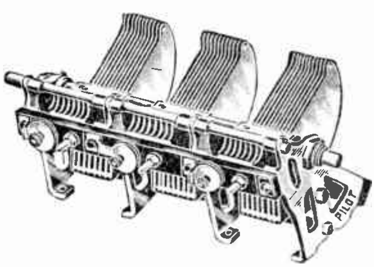


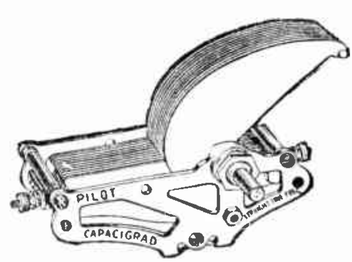
Fig. 157. Frequency—Dial Setting Curves of Condensers.

In all of these types of variable air condensers there is a certain amount of capacity between the ends of the stator and rotor plates, so that their capacity is not reduced to zero when the overlapping area is zero.

In modern radio receiving sets three or four circuits are tuned by a single control. This means that three or four condensers must be grouped on the same mechanical shaft. It is usually necessary that each of these condensers shall have the same rate of change in capacity as the others, for each position of the rotating shaft. Condensers which are so constructed are said to tract.

Differences in end capacity from one condenser to another in





Left: Typical Three-Gang Condenser. Right: Single Straight Line Frequency Condenser.

a group may be compensated by small adjustable condenser in parallel with each of the condensers in a group. These small condensers are known as *aligning condensers*. A group of tuning condensers mounted on the same shaft is known as a gang condenser.

105. Telephone Receivers Used in Radio.—The telephone receivers used in radio receiving sets operate on exactly the same principle as the receivers used in wire telephony, but radio receivers are susceptible to much smaller currents. This improved sensitivity is accomplished by increasing the number of turns on the electromagnets contained in the receiver, and the same magnetomotive force is, therefore, obtained with much smaller current through the receivers. Increasing the number of turns results in an increased inductance and resistance of the receivers, so that the watch case receiver used in radio has an inductance of somewhat greater than one-half henry and a resistance of approximately fifteen hundred ohms. In all cases two such watch case receivers are provided in one headset, the two receivers being connected in series with each other.

106. Loud Speakers.—In the ordinary telephone receiver the feeble currents due to the incoming signals displace a small diaphragm sufficiently to communicate the disturbance to the human ear held in close proximity to the receivers. The motion of this diaphragm is capable of setting only a small volume of air into vibration, and if it were desired that the sounds resulting from the incoming signals should reach all parts of a room, it would be necessary to have a more sensitive receiver provided with a larger diaphragm. To make a loud speaker, then, we are concerned with having the audio-frequency signal currents displace a relatively large diaphragm in order that a large volume of air will be set into vibration.

Loud speakers may be classified as follows, according to the means employed to displace the diaphragm:

1. Bipolar permanent magnet type;
2. Balanced armature type;
3. Moving coil or dynamic type;
4. Induction type;
5. Metal strip type;
6. Piezoelectric type;
7. Electrostatic type.

The bipolar permanent magnet type is shown in Fig. 158. This speaker consists of a permanent magnet, on each pole of which is mounted a coil of wire containing a large number of turns, and the two coils being connected in series. The speaker is substituted for the telephone receivers in the ordinary receiving set, so that it is a part of the plate circuit of the last tube, and the voltage output of the receiving station is thus impressed on the coils of the speaker. The resulting alternating current increases and decreases the magnetization due to the permanent magnet, with the consequent attraction and repulsion of the diaphragm placed immediately above the pole pieces, as shown in the figure.

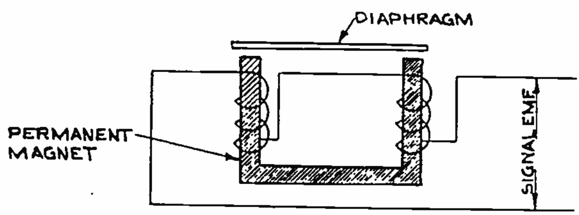


Fig. 158. Bipolar Loud Speaker.

We see, then, that this type of speaker operates in the same manner as the ordinary telephone receiver used in radio. However, the speaker diaphragm is larger, its permanent magnet is stronger and its electromagnets contain a larger number of turns. The strength of the permanent magnet used in this type of speaker is very important, because distortion will be minimized and the pull exerted on the diaphragm due to the signal currents will be accentuated by properly selecting the permanent magnet. The diaphragm in this type of speaker is made of magnetic metal, and the magnetic lines of force pass through it from the pole N to the pole S. The number of these lines of force is varied by the signal current, so that it is quite possible that the diaphragm will become magnetically saturated, and then it will not follow the instantaneous values of current and will produce distortion.

The balanced armature type of loud speaker is shown in Fig. 159. This type of loud speaker consists of an armature which is balanced between the poles of a permanent magnet. The signal current flows through a coil around this armature in such a way that the reaction between the magnetic field due to this current and that due to the permanent magnet causes the arma-

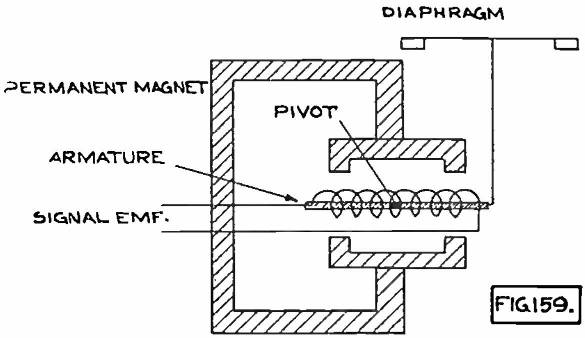


Fig. 159. **Balanced Armature Loud Speaker.**

ture to move up on the left and down on the right or vice versa. The effect of the signal current is to make the ends of the iron armature alternately north and south poles, which react with the poles of the permanent magnet. The resulting displacement of the right end of the armature is mechanically communicated to the diaphragm.

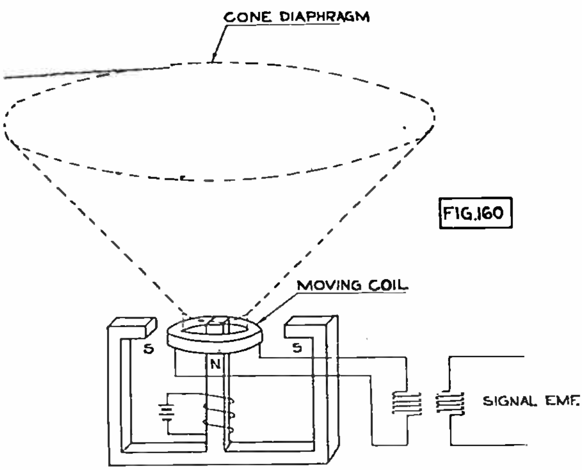


Fig. 160. **Moving Coil or Dynamic Loud Speaker.**

In this type of loud speaker the diaphragm does not have to be made of iron, as was the case in the bipolar type, and it can, therefore, be made of some lighter metal which will offer less opposition to displacement back and forth with audio frequency.

A moving coil type of loud speaker is shown in Fig. 160. This type is also called a *dynamic loud speaker*. In this type of speaker a moving coil through which the audio-frequency signal current flows is placed around the middle pole of a three-pole magnet, and the reaction between the permanent magnetic field and the magnetic field due to the current through the coil displaces the coil up and down, in accordance with the variations of the signal current. The diaphragm is mechanically connected to the coil so that it is correspondingly displaced. It is not necessary that the diaphragm in this type of speaker be made of magnetic metal. This speaker as it is usually manufactured requires an auxiliary direct current to provide the proper strength to the field magnets. Rectified A.C. is also used for this purpose.

A loud speaker of the induction type is shown in Fig. 161. A set of concentric coils is mounted on each side of an aluminum

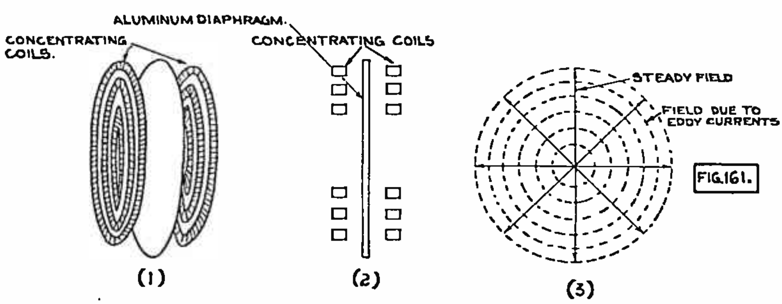


Fig. 161. Hewitt Induction Loud Speaker.

diaphragm, and a direct current is forced through the two sets in opposite directions. The resulting lines of force through the diaphragm are radial, as indicated in Fig. 161(3) (solid lines). The signal current is also passed through the coils and operates to increase or decrease the radial magnetic lines of force in the diaphragm. This change in magnetic field through the diaphragm induces in it eddy currents, the direction of which is perpendicular to the magnetic field at each point, and therefore these currents are circular, as shown by the dotted lines in Fig. 161(3). These eddy currents produce a magnetic field which at each point lies in a plane perpendicular to the diaphragm, and this magnetic field reacts with the steady magnetic field due to direct current through the coils to displace the diaphragm, the reaction between these fields being shown in Fig. 161(2). Since the eddy currents vary with the signal current, the telephone diaphragm is displaced accordingly. This type of loud speaker has been very successfully used in reproducing sounds to make them audible throughout large halls.

It should be noticed that the diaphragm of this type of loud speaker is not made of a magnetic metal, and that an auxiliary source of electrical energy is required to supply the steady magnetic field.

The next type of loud speaker is the *metal strip type,* the principles of which are exemplified by the system shown in Fig. 162(1).

A thin metal strip is suspended between the poles of either a permanent magnet or an electromagnet. The signal currents are passed through this strip, with the result that a magnetic field is established around it which reacts with the field, due to the permanent magnet to displace the metal strip in accordance with variations of the signal currents. In this case, the metal strip is the diaphragm, and, obviously, it need not be made of magnetic metal. A megaphone is invariably associated with this type of speaker.

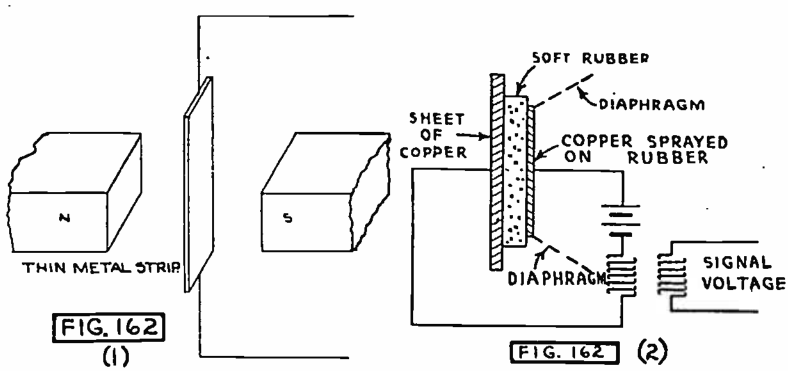


Fig. 162(1). Metal Strip Loud Speaker.

Fig. 162(2). Electrostatic Speaker.

A simple electrostatic type of loud speaker is shown schematically in Fig. 162(2). It consists of two conducting plates separated by a dielectric of soft rubber. One of the conducting plates is rigid, while the other is a thin layer of metal sprayed on the flexible rubber which constitutes the dielectric. By means of a direct potential, one of the conducting plates is kept at a positive potential with reference to the other. The signal voltage is caused to vary the potential between these plates, and consequently to change the electrostatic force of attraction between them. The electrostatic force of attraction between the two plates results in the compression of the rubber, which then acts as a restoring force to displace the plates outward when the signal current is in such a direction as to reduce the electrostatic force between the plates.

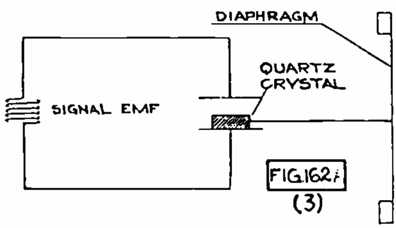


Fig. 162(3). Schematic of Crystal Loud Speaker.

The piezoelectric effect in quartz crystals was explained in connection with crystal controlled oscillators, and incident to this consideration it was shown that the crystal expands and contracts in accordance with the electric strains to which it is subjected. If, then, a signal current be impressed across a quartz crystal, the crystal will be set into mechanical vibrations which correspond to the signal current. These mechanical vibrations may be communicated to a suitable parchment diaphragm, and these produce a satisfactory type of loud speaker. A quartz crystal loud speaker is schematically represented in Fig. 162(3).

In general, loud speakers are required to set a large volume of air into vibration, and this is accomplished by having the diaphragm sufficiently large that its displacement will effect vibrations in a large volume of air, or by making the diaphragm somewhat smaller and concentrating the effect of its vibrations on a small volume of air, which in turn will set a larger volume of air in vibration. This last method requires the use of a megaphone and in this case the diaphragm is made to produce variations in pressure in the small end of the megaphone, which in turn set the air in the entire horn into vibration and send the sound waves in a particular direction. This last method is becoming obsolete, and the use of conical diaphragms made of parchment or airplane cloth is now the most generally used way of establishing vibrations in a large body of air. There are many problems which enter into the proper design of diaphragms; the most important of these, perhaps, is mechanical resonance, or natural frequency of vibration. For our purpose, it will suffice to say that the diaphragm must respond to all frequencies within the range of audibility without producing distortion.

106-A. Phonograph Pick-up.—A number of modern broadcast receivers are combined with a phonograph and so arranged that the audio-frequency amplifier of the radio set may be used to amplify the output of the phonograph. To do this a phonograph pick-up is required. This device is similar to a balanced armature speaker in so far as its electro-mechanical features are concerned. A typical phonograph pick-up is shown in Fig. 163(1).

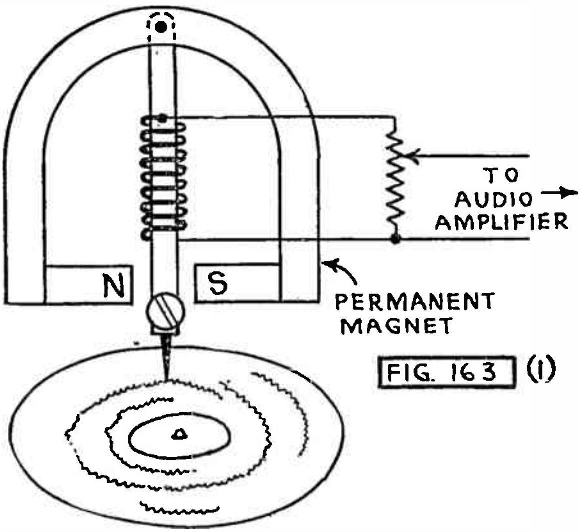


Fig. 163(1). Phonograph Pick-Up.

As the phonograph needle is displaced from left to right, the direction of the flux in the middle arm of the magnetic circuit is reversed, thereby inducing an EMF in the coil. This coil is connected to the audio frequency amplifier where it is amplified and the wave form of the record is reproduced in the loud speaker.

107. Battery Eliminators.—The use of batteries in connection with the operation of vacuum tubes in radio sets has been a source of continued annoyance, because of the necessity of recharging or replacing them. This annoyance has resulted in much effort on the part of engineers to produce satisfactory battery eliminators; and, as a consequence of this effort, the most modern broadcast receivers are operated from the electric power line in homes, without the employment of batteries. In most places the available source of electrical energy produces alternating currents, and the problem of utilizing these sources as a substitute for radio batteries is one of converting these alternating currents into the form of direct currents. To do this the alternating current must first be rectified and then passed through a filter which will surely smooth out any variations in this unidirectional current. It may be said, then, that the two general components of any battery eliminator are, first, a rectifier and, second, a filter.

There are four general types of rectifiers used in battery eliminators. The first is a two-electrode vacuum tube having a heated cathode and a plate, and containing a small amount of rare gas such as argon. This type of tube is exemplified by the *Tungar rectifier*, or the R.C.A. tube, type UX-280. The second type of rectifier contains a large plate and a very small plate enclosed in a tube filled with either helium or neon gas, such as the *Raytheon rectifier*. The third type of rectifier consists of two suitable substances practically in contact, such as the *Kuprox rectifier*. The fourth type is the electrolytic rectifier. These types of rectifiers will be discussed in the following paragraphs.

The filters used in battery eliminators invariably consist of a combination of condensers, inductance coils and resistors, which vary in size according to the voltage and current requirements of the eliminator with which they are associated.

108. "B" Eliminators.—The elimination of "B" batteries from radio sets is accomplished by so-called "B" eliminators. Let us first consider the Raytheon "B" eliminator, since it exemplifies the principle of a number of "B" eliminators. The rectifier used in this set consists of a cylindrical cathode and two unheated anodes, all being made of aluminum and enclosed in a glass bulb containing helium gas. The arrangement of the electrodes in this tube is shown in Fig. 163(2).

This tube is essentially an enclosed spark gap, and its operation depends upon the laws of the conduction of electricity through gases as discussed incident to our consideration of spark gaps. We should remember that for a given condition of gas between the electrodes, the voltage required to break down a gap varies inversely as the sharpness of the electrodes. In the Raytheon tube there is one large electrode (cathode) and a very small electrode (either one of the anodes), and it is found that whenever the small electrode is positive with reference to the large one, that the voltage required to break down the gap is somewhat lower and the conductivity of the gap is much greater than when the polarity is reversed. This conductivity should be high in one direction and zero in the other direction, if the tube is to approach a perfect rectifier.

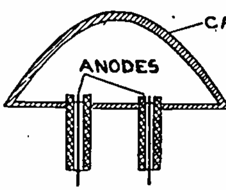


FIG.163t
(2)

Fig. 163(2). Arrangement of Electrodes in Raytheon Rectifier Tube.

The difference in conductivity in the two directions depends upon the relative areas of the two electrodes, it being desirable that one electrode be much smaller than the other. It is mainly in the manner of accomplishing this greatly unequal plate area that the Raytheon tube differs from other tubes functioning on this same principle. The conduction of electricity between the electrodes in such tubes is by means of ions. Before the gap breaks down the gas is essentially an insulator, and the electric strain due to the applied electromotive force must first ionize some few atoms and set them in motion toward the electrode of opposite polarity. These moving ions collide with other atoms and displace one or more of their orbital electrons, thereby causing their ionization. In order to do this the distance through which the original ions travel must be at least equal to the space between adjacent atoms of the gas at the given pressure. In the Ratheon tube the sides of the anodes are in closer proximity to the cathode than the distance between atoms of the helium gas; consequently little or no ionization takes place in these regions. At the very tip of the anodes the distance to the cathode is sufficiently great that ionization will take place, and thus the effective area of the anode is limited to that of a small point at the end of this electrode.

The tube contains two anodes, so that full-wave rectification may be obtained; that is, so that both halves of the ordinary alternating current cycle may be used. The manner in which this is accomplished, and the way in which the tube is associated with the filter, is shown schematically in Fig. 163(3).

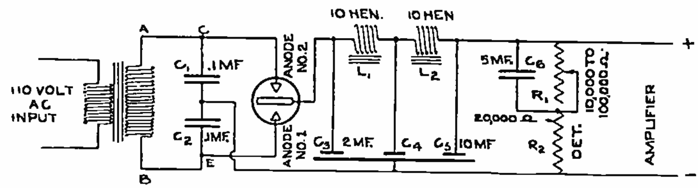


FIG163. (3)

Fig. 163(3). Raytheon Tube "B" Eliminator.

The way in which this rectifier is associated with its transformer and filter is typical, in a general way, of all types of "B" eliminators, and it will be well for us to consider this circuit in some detail. Let us assume that the phase of the alternating-current cycle is such at a certain instant that the point A is positive with reference to B. This will result in a current down through CDE which will charge the condensers C_1 and C_2, so that point C is positive with reference to D, and point E is negative with reference to D. Anode No. 1 will now be positive with reference to the cathode and a current will flow through the tube from anode No. 1 to the cathode and down through the condenser C_3 and back to the point D, thus charging the condenser C_3 with its top plate positive. If the impressed A.C. had been passing through such a phase that the point B had been positive with reference to A, then the condensers C_1 and C_2 would have been charged in the opposite direction and the point E would have been positive with reference to D, while the point C would have been negative with reference to D. Under these circumstances anode No. 2 would be positive with reference to the cathode, and a current would flow from this anode to the cathode and down through condenser C_3, charging this condenser with its top plate positive, as in the previous case. We see, then, that the condenser C_3 receives a charge in the same direction during both half cycles. This condenser discharges continuously through the remainder of the filter. The ten-henry choke coil L_1 prevents the pulsation of the current received from the tube from passing on to the remainder of the filter, and insures that the discharge of the condenser

C_3 will be at a practically constant rate. Any slight variations in the current through the choke L_1 will be returned to the secondary of the transformer through the condenser C_4, which will be charged with its top plate positive. After the transient condition has passed, the steady component of the current through L_1 will pass through coil L_2, which also acts as a choke to prevent variations in the current which it passes. The condenser C_5 is now charged with its top plate positive and a steady current flows down through the resistors R_1 and R_2 in series. The series combination R_1 and R_2 is tapped by means of a sliding contact so that the potential difference between G and K may be adjusted to whatever value is desired for establishing the plate potential of the detector tube which this "B" supplies. The variation in the total resistance R_1 plus R_2 provides a means of varying the current through this part of the circuit, thus increasing or decreasing the current through the coils L_1 and L_2, and the voltage drop due to the resistance of these coils, with the consequent change in potential between the points F and K. This permits some adjustment of the potential difference across the points from which the plate potential of the amplifier tubes is supplied. These adjustments in potential difference between the points FK and GK are necessary because of slight variations between receiving tubes, and because this "B" eliminator is designed for use with different sets employing different types and numbers of receiving tubes.

These condensers, C_5 and C_6, serve as alternating-current by-pass condensers when the eliminator is associated with a receiving set.

"B" eliminators of this type are manufactured in various sizes, usually with a maximum output of approximately 60, 85 or 350 milliamperes. The maximum voltage developed by these eliminators depends, of course, on the voltage of the available source and the turn ratio of the transformer used. The output voltage is then slightly less than the maximum instantaneous value of the input voltage multiplied by one-half of the turn ratio.

Next, let us consider the so-called contact rectifiers, a number of which have come on the market during the last two years for use in "B" eliminators. It has been found that when certain conducting substances have been placed practically in contact in the presence of some non-conductor which separates them a very little bit, that it is easier to transfer electrons from one of these conductors to the other than it is to effect this transfer in the opposite direction. The exact details of this phenomena are not well understood. However, it is well known that nearly unilateral conductivity is obtained when certain substances are placed practically in contact in the presence of some non-conducting material, as was discussed in connection with crystal detector receiving sets. If these contact rectifiers are to be used in eliminators intended to supply an amount of current sufficient to furnish the plate current for several tubes, they must be so arranged and their constituents must be so selected that their resistance in the best conducting direction is sufficiently low that the heat developed will not be detrimental. It is in this regard that contact rectifiers have been recently improved to the point of serviceability in battery eliminators.

Several different combinations of materials have been used in commercial contact rectifiers for "B" eliminators. Among these are copper and an oxide of copper used in the Kuprox rectifier, and granular silver and a metallic alloy separated slightly by dehydrated sulphuric acid (non-conducting) as used in the Raytheon "A" rectifier.

Many other combinations have been used in commercial rectifiers used in both "B" and "A" eliminators.

The *electrolytic rectifier,* although usually classified as a separate type, is merely a contact rectifier in which the very thin layer of non-conducting material which separates the two conductors which are said to be in contact is formed by electrolytic dissociation of an electrolyte. This type of rectifier consists of two pieces of dissimilar metal immersed in an electrolyte which is dissociated under the action of an electric current. One prevalent form of such a rectifier consists of a strip of lead and one of aluminum immersed in a very weak solution of sodium bicarbonate and water. When a current is passed through such a device from the lead to the aluminum, the water is dissociated and the hydrogen goes to the negative or aluminum electrode, where it forms a thin layer of gas which slightly separates the electrode from the electrolyte. The aluminum and the electrolyte then become a contact rectifier, which will pass current from the electrolyte to the aluminum, but not in the reverse direction.

The operation of the ordinary two-electrode tube with a heated filament as a unilateral conductor was explained incident to the previous consideration of vacuum tubes, and it is not considered necessary to repeat this here. It will suffice to say that tube manufacturers have in effect combined two such tubes in one bulb, so that there are two plates and one filament which may be externally connected in such a way as to give full-wave rectification of an available alternating current. Such a tube is sold by the Radio Corporation of America under the name of UX-280, and its employment in a "B" eliminator is shown in Fig. 163(4).

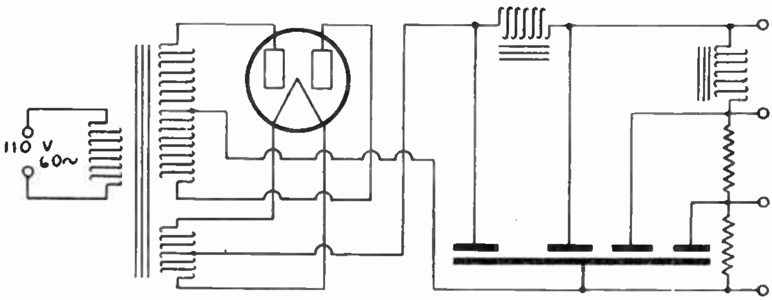
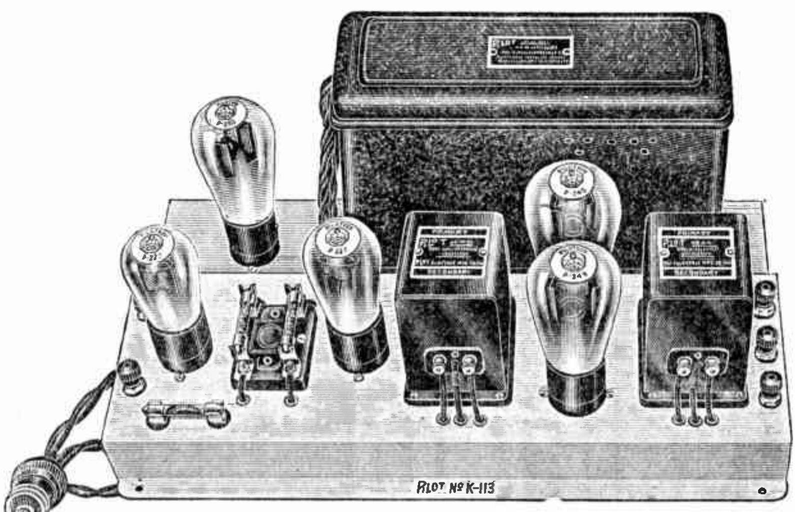


FIG. 163 (4)

Fig. 163(4). "B" Eliminator Employing UX-280.



Typical Combination "B" Eliminator and Audio Amplifier Using 280 Rectifier Tube.

109. "A" Eliminators.—The necessity for a substitute for the "A" battery of a radio set is perhaps greater than for a "B" battery substitute, because of the frequency with which storage batteries must be charged. The "A" battery may be eliminated either by use of the four-electrode A.C. tube with the heater element, as previously described, or by use of ordinary three-electrode tubes with an "A" eliminator. The "A" eliminator consists of a rectifier and filter suitable for converting the available alternating current into direct current, just as in the case of the "B" eliminator. The difference between these two eliminators is that the "A" eliminator is required to furnish a relatively large current at relatively low voltages, as compared to the "B" eliminator. These differences necessitate some changes in both the rectifier and the filter. The rectifier, for example, must deliver more current than the rectifiers ordinarily used in "B" eliminators are capable of delivering. The Tungar rectifier is therefore often used in "A" eliminators, because of its ability to deliver relatively large currents. The Tungar rectifier consists of a heated filament and a plate enclosed in a glass tube containing a small amount of argon. The electrons emitted by the heated filament are attracted toward the plate only during the half cycle when the plate is positive with reference to the filament. This electron displacement and the displacement of the ions of argon gas, formed by collisions between the moving electrons and the atoms of argon, constitute the current which flows through the interior of the tube and through the external circuit in one direction only. Contact rectifiers, such as the Kuprox in somewhat larger sizes, are also used in "A" eliminators.

The filters employed in "A" eliminators also differ from those used in "B" eliminators, in that the inductance coils are smaller and the condensers are larger. To obtain very high inductance in coils it is necessary to have a great number of turns of wire, and if this wire were large enough in diameter to carry 3 or 4 amperes (as is required of "A" eliminators), the physical dimensions and weight of the coils become excessively large; and, consequently, coils of smaller inductance are used in "A" eliminators. Fortunately, the voltage requirements of "A" eliminators are relatively low, since it is easier to obtain condensers of large capacity when they are required to support low voltages than it would be to obtain the same large capacity and support high voltages. However, some special design is required for condensers used in the filters associated with "A" eliminators, in order to obtain sufficiently large capacities within the confines of a convenient space. The type of condenser often employed for this purpose is the so-called "Electrolytic Condenser," which resembles somewhat an electrolytic cell, since it contains two metallic electrodes immersed in an electrolyte. A type of electrolytic condenser is contained in the filter known commercially as the "Abox" filter. This condenser consists of a plate of nickel and one of iron immersed in an aqueous solution of potassion hydroxide, and so connected in the circuit that the current flows through the condenser from the nickel to the iron electrode. Probably due to the formation of very thin layers of gas on the electrodes, a condenser is formed between the electrolyte and each electrode. The conducting elements of this condenser are, of course, very close together, being separated only by the thickness of the layer of gas. As a consequence of this, the capacity per unit area is very high, and in the case of the "Abox" filter is said to be 6,625 microfarads per square inch.

110. Summary:

1. Inductance coils are space wound or wound in special multilayer forms as a means of minimizing distributed capacity.

2. Variometers are continuously variable inductance coils and are free from the disturbing effects of dead turns, which are present in tapped inductance coils.

3. Radio-frequency choke coils are wound on non-magnetic cores, and audio-frequency choke coils are wound on iron cores. Distributed capacity must be negligible in coils intended to stop radio-frequency currents.

4. The ratio of IX_L to the voltage induced in a coil is called the *gain* factor of the coil.

5. The variable air condensers used in radio are rated according to the total number of their plates and their maximum capacity, and they are classified as straight line capacity, straight line frequency, and straight line wavelength, according to the shape of their plates.

6. A number of variable condensers which are grouped and operated by the same mechanical shaft is called a Gang Condenser.

7. Aligning condensers are small adjustable condensers associated with the separate condensers of a gang condenser to adjust their end capacity.

8. In a straight line capacity condenser the relationship be-

tween capacity and degrees of rotation is linear, while in a straight line frequency condenser a linear relationship exists between degrees of rotation and resonant frequency of the oscillatory circuit of which the condenser is a part. Similarly, the relationship between circuit wavelength and degrees of condenser rotation is linear for straight line wavelength condensers. This assumes that the inductance with which the condenser is associated is constant.

9. The telephone receivers used in radio sets are more sensitive than those used in wire telephony, by reason of a larger number of turns contained on their electromagnets. This increased number of turns results in larger resistance and inductance.

10. Loud speakers used in radio receiving sets are sensitive receivers, which displace large diaphragms.

11. Loud speakers may be classified according to the means employed to displace their diaphragms as follows:

1. Bipolar permanent magnet type;
2. Balanced armature type;
3. Moving coil or dynamic type;
4. Induction type;
5. Metal strip type;
6. Piezoelectric type;
7. Electrostatic type.

12. Battery eliminators consist of a rectifier and a filter.

13. The four general classes of rectifiers employed in modern battery eliminators are:

1. Two-electrode tube with heated cathode;
2. Two-electrode tube with unheated cathode;
3. Contact rectifiers;
4. Electrolytic rectifiers.

111. **Self-Examination:**

1. What is meant by *space winding of a coil?*

2. Name three types of windings used in multilayer coils to minimize distributed capacity.

3. Describe the variometer and varicoupler used in radio.

4. What is meant by *gain factor* of a coil?

5. What are the advantages of a variometer over a tapped inductance coil?

6. How many degrees of rotation are required to vary each of the following from maximum to minimum:

1. Variometer;
2. Varicoupler?

7. Describe a variable air condenser used in radio sets.

8. How are variable air condensers rated?

9. What is meant by each of the following:

1. Vernier condenser;

2. Aligning condenser;
3. Gang condenser?

10. State two forms in which straight line frequency condensers are manufactured.

11. What is the advantage of straight line frequency condensers?

12. How is increased sensitivity in radio telephone receivers accomplished?

13. Why is the resistance and inductance of radio telephone receivers high?

14. Describe each of the following types of loud speakers:
1. Bipolar;
2. Balanced armature;
3. Moving coil;
4. Induction type;
5. Metal strip type;
5. Piezoelectric type;
7. Electrostatic type.

15. With regard to a "B" eliminator:
1. What is its function?
2. What are its general components?

16. With regard to an "A" eliminator:
1. What is its function?
2. What are its general components?

17. Describe each of the following:
1. Raytheon rectifier.
2. Contact rectifier;
3. Electrolytic rectifier;
4. Tungar rectifier;
5. Electrolytic condenser.

SECTION XI.

RADIO SETS

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112. Introduction.—Now that we have considered the several component parts of radio equipment and the phenomena of the transmission and reception of electromagnetic waves, let us consider some of the more important combinations of this equipment which are used to form complete radio sets. There are so many different types of radio sets in use, both for transmitting and receiving, that it would be quite impossible to cover all of them in a short treatise. Consideration will be given, therefore, only to sets which exemplify some basic principle, or which indicate the trend of modern radio development. We shall consider radio sets as divided into three categories, namely, receiving sets, transmitting sets, and portable transmitting and receiving sets.

113. Receiving Sets.—Every receiving set contains a detector, and with it there is associated, almost invariably, one or more stages of amplification. If two stages of amplification are sufficient for a particular purpose, these stages are usually of audio frequency, because audio-frequency amplifiers are easier to design and operate than radio-frequency amplifiers. However, two stages of audio-frequency amplification with transformer coupling is all of the amplification of this type that is normally used in any receiver; although three stages of audio-frequency amplification

are sometimes used with other types of coupling. If more amplification is required, the additional stages are of radio frequency. It should be remembered that while radio-frequency amplification is somewhat more difficult to design and operate, it provides a means of amplifying the input voltage of the detector, the output of which varies as the square of the input voltage. A combination of both radio- and audio-frequency amplification also makes possible a greater total amount of amplification without distortion than could be obtained with only one type of amplifier.

A detector which provides regenerative amplification is equivalent to a non-regenerative detector and a one-stage amplifier, and for this reason regenerative amplification is employed in a large number of detectors. The greater part of all detectors are of the grid condenser-grid leak type.

Fig. 164 shows a simple receiving circuit containing a regenerative detector and two stages of transformer-coupled audio-frequency amplification. In this circuit tube number one is a regen-

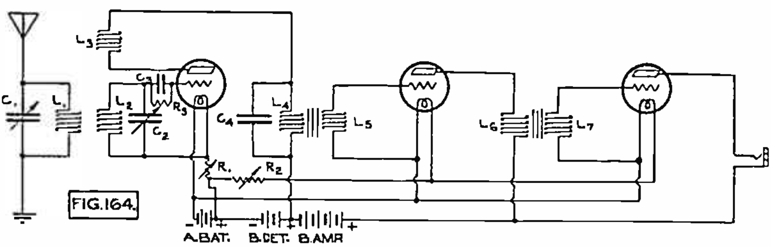


Fig. 164. Receiving Set—Regenerative Detector and Two Audio-Frequency Amplifiers.

erative detector of the grid condenser-grid leak type, and tubes two and three are the transformer-coupled audio-frequency amplifiers. It should be observed that the filaments of these tubes are operated in parallel and that the filament current of the detector tube is controlled by the resistor R_1, while the resistor R_2 controls the filament current of the amplifier tubes two and three. The "B" battery used in this set consists of a number of cells in series and provided with a middle tap, so that one-half of the cells are used to supply the plate potential of the detector tube and all of the cells are used to supply the plate potential of the amplifier tubes.

It is customary in this and all other types of receiving circuits to connect the rotor side of variable air condensers to the filament side of the circuit, and to ground the negative terminal of the filament battery. This is done in order to minimize the effect of hand capacity as the hand is placed on the knob of the tuning condensers.

The circuit shown in Fig. 165 employs one stage of neutralized radio-frequency amplification, a regenerative grid condenser-grid leak detector and three stages of impedance-coupled audio-frequency amplification. In this circuit the Hazeltine method of neutralizing the radio-frequency amplifier is used, and also the proper grid bias of the audio-frequency amplifier tubes is established by use of a "C" battery and grid resistors. The last stage of audio-frequency amplification employed in this case utilizes a power tube which requires a different filament current, plate potential and grid bias from those used on the other audio-frequency amplifiers. No switch is required in the filament circuits of these tubes, as the jack is arranged to automatically open the filament circuits when the receiver plug is removed.

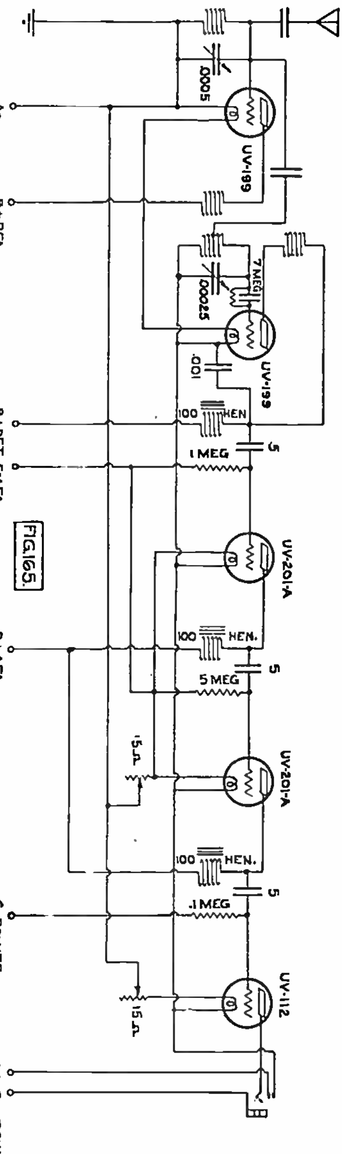


Fig. 165. The Browning-Drake Receiver, Using one stage of neutralized R. F. Amplification.

Fig. 166 shows a special circuit containing two stages of transformer-coupled radio-frequency amplification, a grid condenser-grid leak detector and three stages of double impedance-coupled audio-frequency amplification. The last tube is a power tube. The set contains the resistor and by-pass condenser which are normally a part of the "B" eliminator, this feature being provided so that only two leads will be necessary between the set and the "B" eliminator, and these leads will carry direct current only. The volume is controlled by means of a 200,000-ohm resistor connected in parallel with the antenna coil. This resistor is open circuited for maximum volume. Phasatrols are used to prevent the radio-frequency amplifiers from oscillating. The double impedance units used to couple the audio-frequency amplifiers are selected to give practically uniform amplification over the entire range of audio frequencies employed in radio broadcasting. Two of the tuning condensers are controlled from a single mechanical shaft, and the balancing condenser is provided between them so that they will be kept in step with each other. Terminals are provided for supplying alternating current to the filament of the last tube alone, when this is desired in order to minimize the drain on the "A" batteries. The "C" minus (—) four volts is grounded because

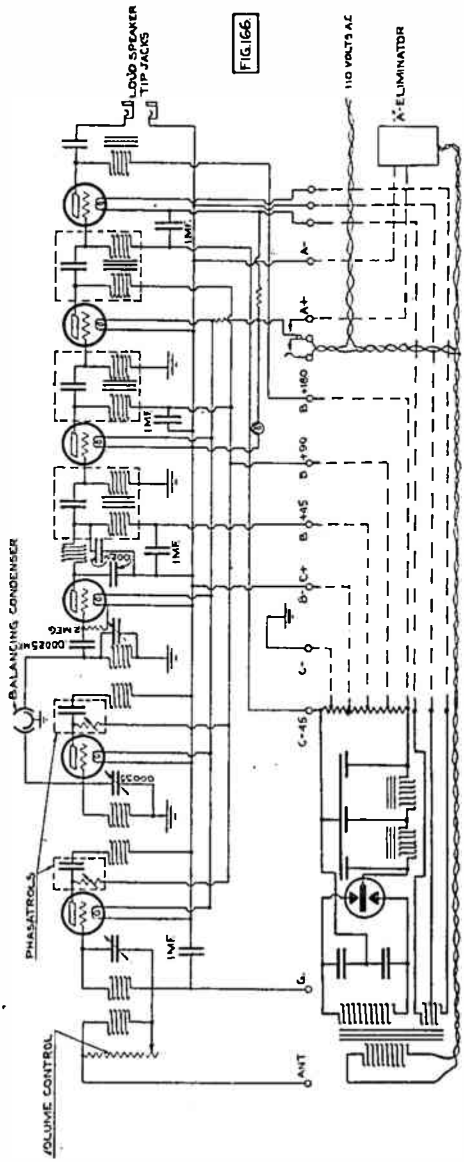


Fig. 166. A. C. Receiver Using Two Stages of R. F. Amplification.

this bias is required for the amplifier tubes and the tuning condensers of radio-frequency tubes can be most conveniently mounted in a manner which grounds their rotors. Only one switch is used to control both the filament and the input to the battery eliminators.

The Hammarlund Roberts circuit shown in Fig. 167 exemplifies the Roberts system of neutralizing the radio-frequency amplifiers and exemplifies the use of two tubes in parallel as a substitute for a power tube.

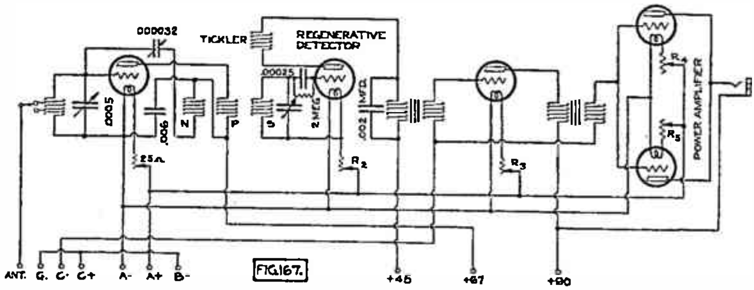


Fig. 167. Hammarlund Roberts Circuit.

There are a number of extremely sensitive receivers, known as superheterodynes, which are employed in modern radio sets, the first of which was developed by Armstrong, who subsequently perfected this type of circuit in several different ways. The unique principle of the superheterodyne is the scheme whereby the high-frequency currents resulting from the intercepted wave are reduced to some intermediate frequency, at which frequency these currents can be more efficiently amplified.

In the superheterodyne receiving circuit a local oscillator is provided, the frequency of which is deliberately adjusted to some value which is from 30,000 to 70,000 cycles per second different from the frequency of the incoming wave. Currents of the local oscillator frequency and of the signal frequency are caused to flow simultaneously in the same circuit, and they will produce *beats* in the same manner as previously described in connection with an ordinary heterodyne. The frequency of these beats will be the difference of the frequencies of the two currents, of course, and in the case of the superheterodyne this difference in frequency is above the range of audibility, being an intermediate radio frequency.

This method of heterodyning the incoming signal not only produces beats of a frequency of 50,000 cycles, but the amplitudes of these surges vary in accordance with the variations of amplitude in the signal current.

The intermediate or beat frequency current is separated from the high radio frequency by means of a detector or frequency changer. This beat frequency current is then passed through a few stages of amplification. The constants of these amplifiers are so chosen that maximum efficiency and minimum distortion is obtained for frequencies of the order of 50,000 cycles. These amplifiers are known as intermediate frequency amplifiers, and the superior quality and sensitivity of the Armstrong superheterodyne is due to the fact that more satisfactory amplifiers can be built to operate at frequencies of this order than at high radio frequencies. In order to make this 50,000-cycle current audible, it is necessary to pass it through a second detector, from which an audio-frequency current may be obtained. This audio-frequency current may then be amplified if desired.

Because of the reaction of one coupled circuit on another, Armstrong experienced the difficulty in his early superheterodyne that tuning the antenna circuit also changed the frequency of the oscillator, and to minimize this and also combine in one tube the function of oscillator and first detector, a so-called second harmonic superheterodyne was perfected. In this circuit the frequency of the oscillator is greatly separated from that of the antenna circuit, and the second harmonic of the oscillator beats with the incoming signal current to produce the desired intermediate frequency.

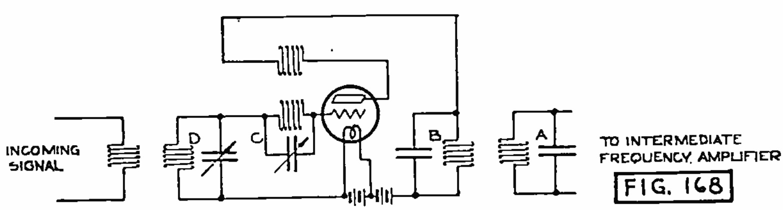


Fig. 168. Circuit of Second Harmonic Superheterodyne.

The heterodyne feature of this second harmonic superheterodyne may be schematically shown in Fig. 168. The oscillatory circuit D is tuned to the frequency of the incoming signal, the circuit C is tuned to one-half the frequency of the incoming signal plus or minus one-half the intermediate frequency, and the circuits B and A are tuned to the intermediate frequency.

PRESSLEY SUPERHETERODYNE

A superheterodyne designed by Pressley utilizes a balanced Wheatstone Bridge as a means of preventing radiation from the antenna. This scheme can be understood best by consideration of Fig. 169(1).

If an oscillatory electromotive force be impressed from D to E, and it is desired that no current pass through the loop connected from A to B, the constants of the circuit C_3, C_4, C_1 and C_2 may be adjusted (just as a resistance bridge may be balanced), so that no current will pass through the loop. When the bridge is balanced so that no current from the oscillator passes through the loop, then the current which flows through C_3 from D to A will flow through condenser C_4 from A to E. This current may be represented by i_A. Similarly, the current which flows through C_1, flows through C_2. This current may be represented by i_B.

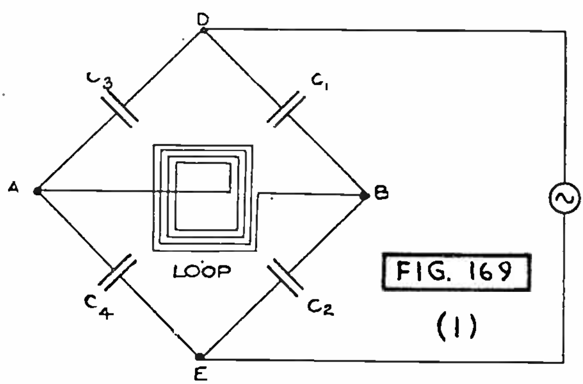


Fig. 169. The Pressley Superheterodyne.

From a consideration of the instantaneous values of potential we may then say:

$$i_A X_{C_3} = i_B X_{C_1},$$

or

$$\frac{i_A}{i_B} = \frac{X_{C_1}}{X_{C_3}}.$$

Also

$$i_A X_{C_4} = i_B X_{C_2},$$

or

$$\frac{i_A}{i_B} = \frac{X_{C_2}}{X_{C_4}},$$

$$\frac{X_{C_1}}{X_{C_3}} = \frac{X_{C_2}}{X_{C_4}},$$

or

$$\frac{\dfrac{1}{2\pi f C_1}}{\dfrac{1}{2\pi f C_3}} = \frac{\dfrac{1}{2\pi f C_2}}{\dfrac{1}{2\pi f C_4}},$$

or

$$\frac{C_3}{C_1} = \frac{C_4}{C_2}.$$

This gives us the condition for balance of this bridge and in the Pressley circuit these constants are so adjusted as to satisfy this condition. It follows, therefore, that no energy from the oscillator tube will be radiated by the loop antenna, but an incoming signal will induce a voltage in the loop, which will be communicated to the oscillator tube, which also acts as the detector tube.

The actual wiring diagram of a Pressley Superheterodyne is shown in Fig. 169 (2).

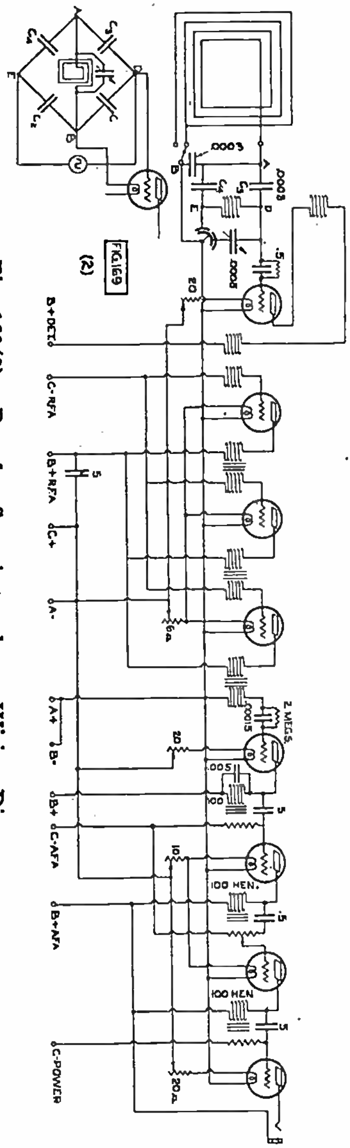


Fig. 169(2). Pressley Superheterodyne—Wiring Diagram.

Fig. 170 shows a screen grid tube circuit. This circuit is included here to show the general type of circuit used with the screen-grid tube.

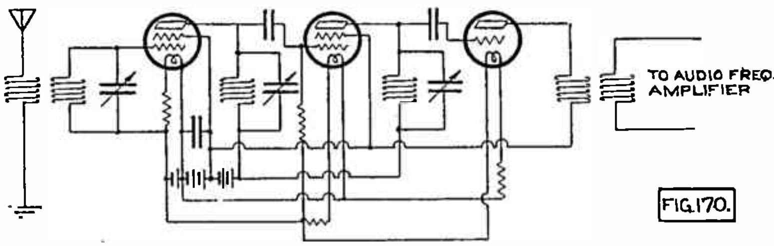


Fig. 170. Screen-Grid Tube Circuit.

The circuits used with the screen-grid tube are practically the same as those used with the 201-A tube, except that a higher external plate impedance is desirable with the screen-grid tube. This high plate impedance is accomplished either by a suitable choke or a tuned plate circuit, or else by use of specially designed transformers with relatively high impedance primaries.

There is another type of circuit which exemplifies a unique principle sometimes used in radio receiving sets and known as "reflexing." Such a circuit is shown in Fig. 171.

In reflexed circuits a principle is utilized which is similar to that employed in regenerative circuits where the output of the

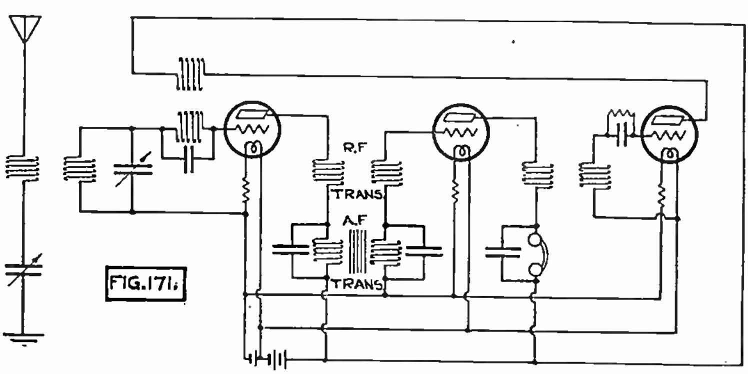


Fig. 171. Reflex Circuit.

detector is coupled back to the input of the same tube. As shown in Fig. 171, the plate circuit of the detector is coupled back to the grid of a preceding amplifier, so that the amplifiers are made to perform simultaneously the functions of radio- and audio-frequency amplifiers. This results in a saving of tubes (two in the case of the circuit shown in Fig. 171), and a slight saving in space and weight; however, more difficulty is experienced in the operation of such a circuit as compared to the equivalent non-reflexed circuit.

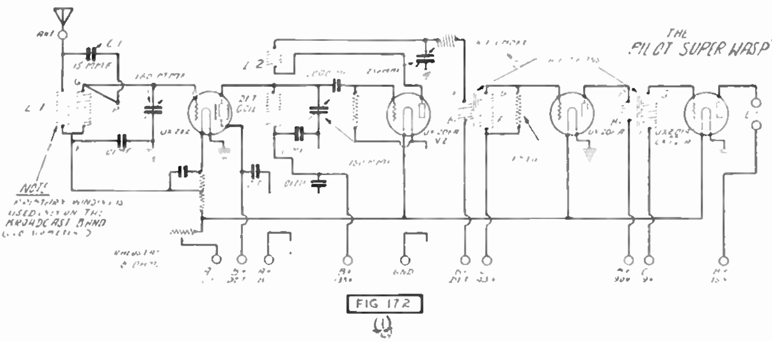
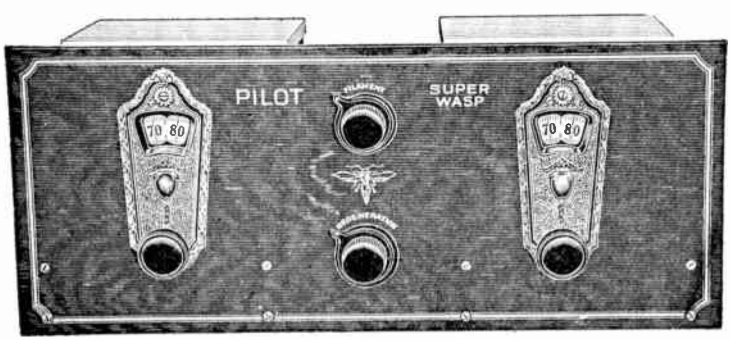


Fig. 172(1). Circuit of the "Super-Wasp" Receiver.

One very interesting application of the screen-grid tube is made in a short-wave receiver known as the "Super-Wasp," the circuit of which is shown in Fig. 172(1). In this set advantage is taken



Front Panel Appearance of the "Super-Wasp."

of the low inter-electrode capacity of the tube, and considerable amplification is obtained in the tuned radio-frequency circuit on wavelengths as low as 14 meters. The inductances L1 and L2 take the form of plug-in coils, five pairs of coils being used altogether to cover, in steps, the range from 14 to 500 meters.

On waves up to 200 meters, the antenna is coupled to the screen-grid tube through a small variable condenser C1, having a maximum capacity of 15 micromicrofarads. When the largest coils, covering the broadcast band, are plugged in, this condenser is automatically disconnected and a primary coil thrown in the circuit instead. This changeover is accomplished by means of a simple arrangement of cross connections in the bases of the coils.

The radio-frequency and detector stages are tuned by variable condensers having a maximum capacity of 160 mmf. The regenerative action of the detector is controlled by another condenser, of 250 mmf. The detector is followed by a two-stage transformer coupled audio amplifier. The components of the radio-frequency and detector stages are enclosed in aluminum shield cans, which entirely prevent hand capacity effects.

Hundreds of people who have assembled Super-Wasps and other short-wave receivers are enjoying trans-oceanic reception of broadcasting stations in many parts of the world. It is quite common for those listeners residing in the Eastern part of the United States to eat their dinners to the accompaniment of music transmitted from station G5SW, in Chelmsford, England.

Two 1929 model radio receivers are shown schematically in Figures 172(2) and 172(3). The broadcast receiver shown in Fig. 172(2) contains three stages of radio-frequency amplification, using the 227 type, alternating-current tubes; a grid condenser-grid leak detector and an intermediate audio-frequency amplifier using the same type of tube; and two 245 type tubes in push-pull in the output stage. In this circuit the three condensers, C_2,$C3_3$,C_4, are mechanically connected together and also to the variometer used in tuning the antenna. A small trimming condenser connected in parallel with the variometer provides a separate panel control of the apparent inductance of the variometer so that it may be kept accurately tuned with respect to the other tuned circuits. The voltage gain across the variometer increases as the wavelength of the set increases, while the voltage gain in the coils used in the remaining tuned circuits decreases as the wavelength increases. By combining the two types of tuning devices a more uniform sensitivity is obtained over the entire broadcast band. The volume control used on this set provides a

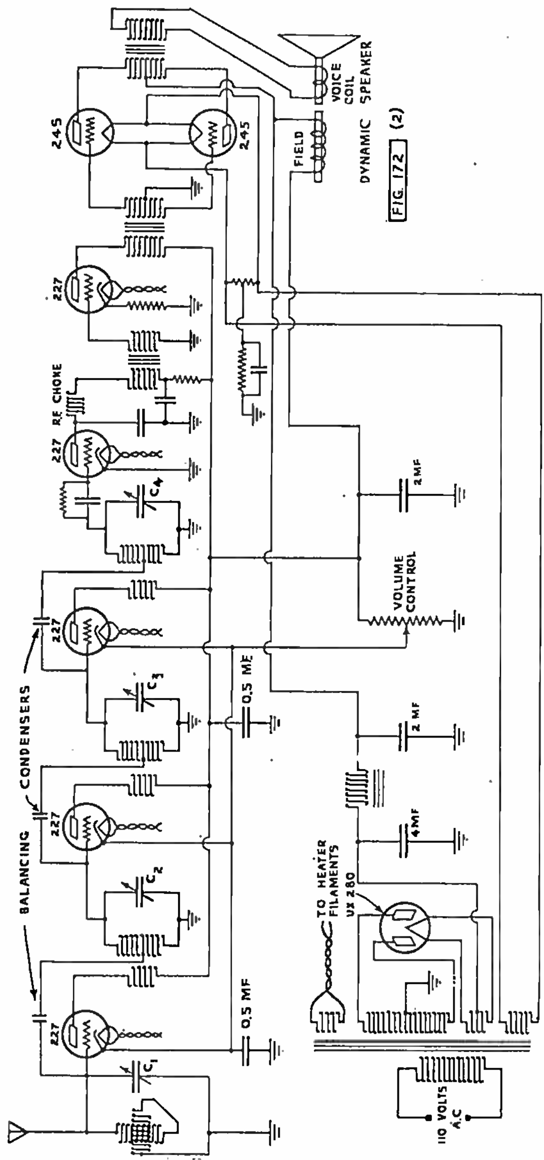


Fig. 172 (2). Schematic Diagram of a Modern All-Electric Broadcast Receiver. There Are Three Stages of R. F. Amplification, a Detector of the Grid Condenser-Grid Leak Type, and Two Stages of Audio Amplification with Two 245 Tubes in the Push-Pull Output Stage. A Dynamic Loud Speaker is Used.

means of varying the plate potential and grid bias on the radio-frequency amplifiers. The loud speaker field is utilized as one of the choke coils required for proper filtering of the rectifier output.

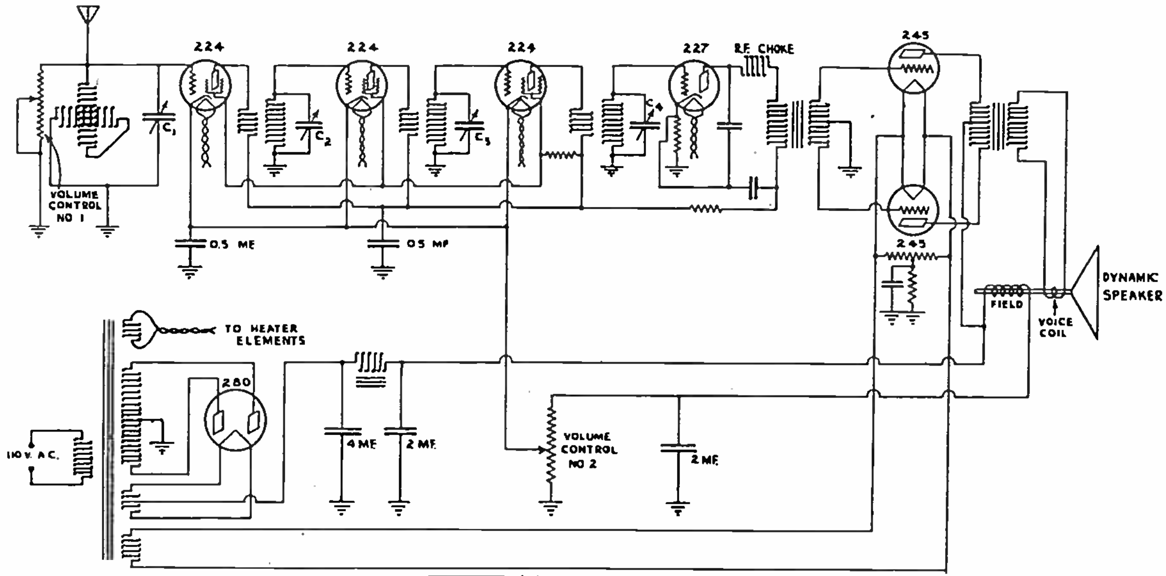


FIG. 172 (3)

Fig. 172 (3). A Modern Broadcast Receiver Using A. C. Screen-Grid Tubes in the Three R. F. Stages, a "Power" Detector, and a Single Push-Pull Audio Stage. This Circuit Represents the Most Up-to-Date Practice in Broadcast Receiver Design.

A radio-frequency choke coil is connected in series with the primary of the transformer in the plate circuit of the detector in order to prevent the passage of radio-frequency current through the distributed capacity of the transformer winding. This is found to be necessary in sensitive receivers in order to prevent the detector tube from oscillating.

The receiving set shown in Figure 172(3) uses three stages of screen-grid, transformer-coupled, radio-frequency amplification, with 224 type tubes, a power detector supplying the grid signal voltage to two 245 type tubes in push-pull. All of the features referred to above with reference to the circuit shown in Figure 172(2) are also provided in the screen-grid receiver. In addition, the screen-grid set has a double volume control consisting of a potential divided for varying the antenna input and another for controlling the plate potential and grid bias on the radio-frequency amplifying tubes. It should also be observed that this set employs a power detector without an intermediate audio amplifier between the detector and power output tubes. The radio-frequency components of this set must be very carefully shielded. This set is often referred to as the "Tetrode Set."

Shielding simply consists in surrounding the various component parts of a receiving set with sheet metal which is electrically grounded. The purpose of shielding is to minimize the induction of electromotive forces in one part of a circuit from another part or from foreign sources, and also to minimize the effects of the operator's body capacity to ground. Shielding is effective because of the eddy currents set up in it by induced electromotive forces.

Tone control devices are sometimes used in broadcast receivers. They are adjustments by means of which the relative intensity of low and high frequency audio notes may be varied at will. They usually take the form of a variable condenser connected across the secondary of the audio-frequency transformer between the detector and first audio tubes. This condenser by-passes the high audio notes to a greater extent than the low ones. A similar condenser is sometimes provided across the voice coil of loud speakers.

113-A. Laboratory Testing of Receiving Sets.—The performance of radio receivers may be studied by means of several tests which are now reasonably well established among manufacturers of broadcast receivers and recommended by the Institute of Radio Engineers. The properties of receiving sets which are of greatest importance are sensitivity, selectivity, and fidelity.

These properties of receivers are measured quantitatively by use of a so-called "Standard Signal Generator" or "Microvolter." This microvolter consists of a variable, calibrated, radio-frequency oscillator which is modulated thirty percent by a 400-cycle audio oscillator, and a suitable attenuation net work. The net work is so designed and calibrated that the magnitude of the electromotive force impressed on the output terminals of the microvolter may be adjusted at will. A simple microvolter is shown schematically in Figure 172(4).

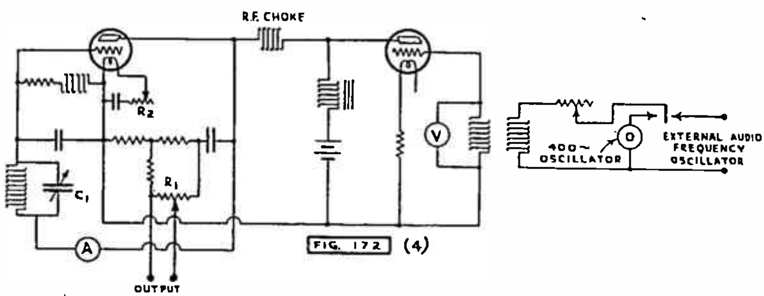


Fig. 172 (4). A Simple Microvolter.

In this microvolter circuit the frequency of the radio oscillations is adusted by means of the condenser C_1, the oscillatory current is read on the ammeter A and adjusted by the resistor R_2, and the degree of modulation from the reading of the voltmeter V and controlled by the resistor R_3.

For any given oscillatory current the voltage existing across the output terminals may be regulated by the position of the sliding contact on resistor R_1. The resistance of R_1 is low and so proportioned with respect to the remainder of the circuit that variations in the load connected across the output terminals do not appreciably influence the potential across these terminals or the total radio-frequency current in the oscillatory circuit. With standardized readings of the ammeter A and the voltmeter V, the dial associated with resistor R_1 may be calibrated directly in microvolts.

Sensitivity is defined by the Institute of Radio Engineers as the degree to which a receiving set responds to signals of the frequency to which it is tuned. This property of receivers may be measured at any desired frequency with the microvolter. For this purpose the radio-frequency oscillations of the microvolter are modulated thirty percent by the 400-cycle audio-frequency oscillator. The output terminals are connected, through a standard phantom antenna, to the input terminals of the set under test. The standard antenna consists of a series combination of a 200-micromicrofarad condenser, a 20-microhenry inductance coil, and a resistance of 25 ohms. The microvolter is adjusted to give a rather strong output signal of some desired frequency and the receiving set is tuned to resonance at this frequency, as manifested by maximum response in the loud speaker.

The voice coil of the speaker is then switched out of the circuit and the microvolter is adjusted to zero. A resistor and ammeter connected in series is then substituted for the voice coil of the speaker. The resistor used in this connection is selected to give maximum power output per volt input for the type vacuum tube and associated circuit used in the output stage of the set being tested. The microvolter output is then advanced slowly until the ammeter reads a value corresponding to an alternating-current output of fifty milliwatts in the resistance of the output circuit. It should be noted that the direct-current component of the output tube plate current should not pass through the resistor and ammeter used in this test. In this manner the number of microvolts output from the signal generator required to give the standard output of fifty milliwatts in the set under test is determined for a sufficient number of radio frequencies to permit the plotting of a curve showing the sensitivity of the set over its entire tuning range.

Selectivity is defined by the Institute of Radio Engineers as the degree to which a radio receiver is capable of differentiating between signals of different carrier frequencies. This characteristic of receiving sets is also measured with the microvolter modulated thirty percent by a 400-cycle oscillator. In this case the microvolter is tuned to some desired frequency, such as 1,000 kilocycles, the output is adjusted to give a rather strong signal in the loudspeaker of the receiving set which is connected to the microvolter, through the standard phantom antenna described above, and tuned to resonance with the microvolter output. The output of the microvolter is adjusted to practically zero and the loud-speaker voice coil is switched out of the circuit and replaced by the resistor and ammeter as referred to in the sensitivity test described above. The microvolter output is then adjusted to give standard output of fifty milliwatts in the output circuit of the set under test, in the same manner as described above. By means of a vernier condenser associated with the tuning condenser on the microvolter, the frequency of the microvolter output is varied in steps of five kilocycles to a total of thirty kilocycles on each side of the resonant frequency. The number of microvolts input required to give the standard output of fifty milliwatts in the receiving set is determined for each microvolter frequency. Throughout this entire test the tuning of the set under test remains constant. From the data thus obtained a curve is plotted with carrier frequency as abscissa and the ratio of the microvoltage at each test frequency to the microvoltage at the resonant frequency of the set as ordinate. The scale of ordinates is usually logarithmic.

Fidelity is defined by the Institute of Radio Engineers as the degree to which a radio receiver accurately reproduces at its output terminals the modulation of the radio-frequency wave impressed upon its input terminals. Fidelity is also determined with the microvolter, but in this case an external audio-frequency oscillator is used. This audio-frequency oscillator has a range of frequencies from 25 to 10,000 cycles per second. The microvolter is tuned to the radio frequency at which the fidelity is to be measured and modulated thirty per cent at 400 cycles, and its output is then adjusted to give standard output of 50 milliwatts in the output of the receiving set connected to the microvolter through the standard antenna as described above. The modulation frequency is then adjusted from 40 to 10,000 cycles per second at thirty per cent modulation, the radio-frequency output of the microvolter and the tuning of the set under test remaining constant. The reading of the ammeter in series with the standard resistor in the output circuit of the receiving set being tested is taken at each frequency of modulation. A graph is plotted with modulation frequency as abscissa and the ratio of the output voltage at the modulation frequency of measurement to the output voltage at the modulation of 400 cycles per second as ordinate. The scale of abscissa should be logarithmic.

Typical selectivity and fidelity curves of a modern broadcast receiver are shown in Figure 172(5), and the stage by stage sensitivity of such a receiver is shown in Figure 172(6).

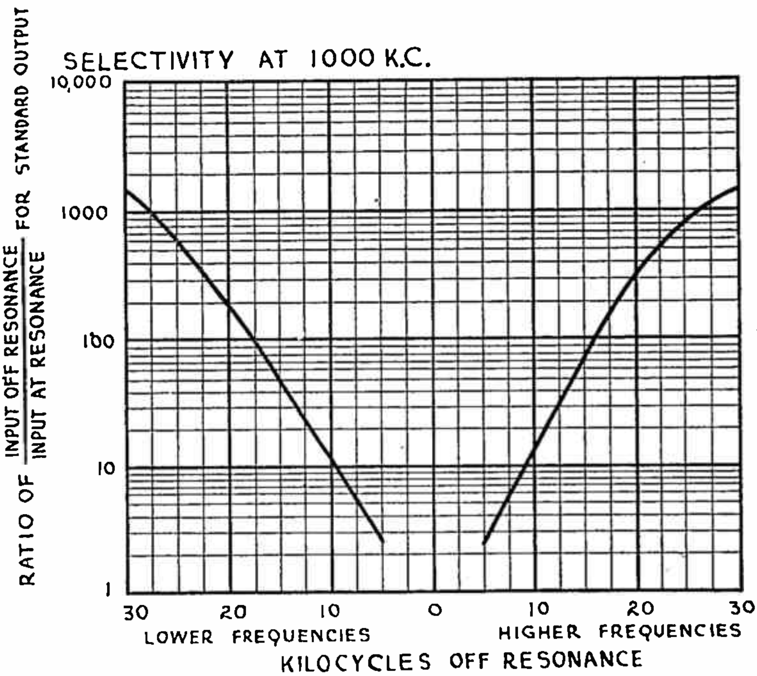
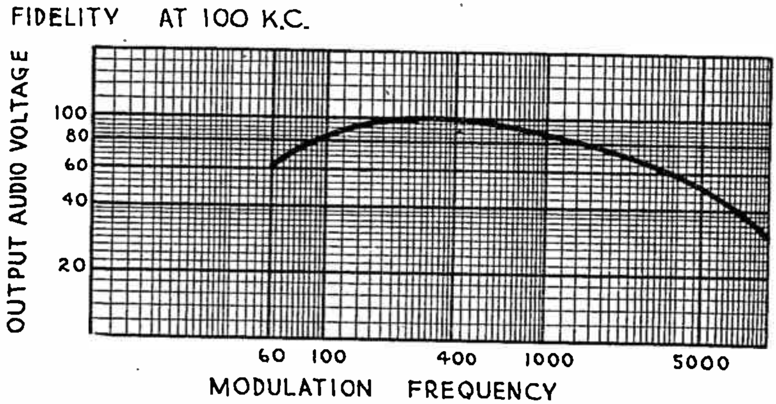


FIG. 172 (5)

Fig. 172 (5). Typical Selectivity Curve.

114. Transmitting Sets.—Incident to the study of the spark set, the Poulsen arc, the Alexanderson alternator and the vacuum-tube oscillator and modulator, the complete transmitting circuits of radio sets were considered. With a view to showing the similarity of the circuits used at commercial broadcasting stations to those already considered, a broadcast transmitting circuit is included here. Also a short-wave transmitter is included for the same reason.

The circuit diagram of a broadcasting station operated in Washington, D. C., is shown in Fig. 173.



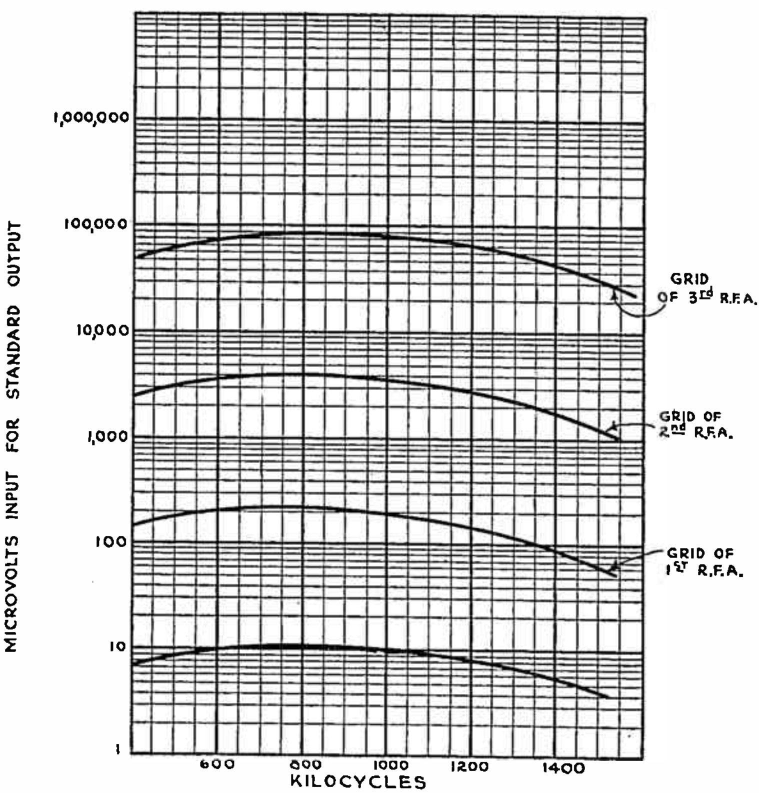


FIG. 172 (6)

Top: Typical Fidelity Curve; Bottom: Stage-by-Stage Sensitivity.

The oscillator used in this circuit contains two tubes in parallel and is of the Meisner type. The modulator also employs two

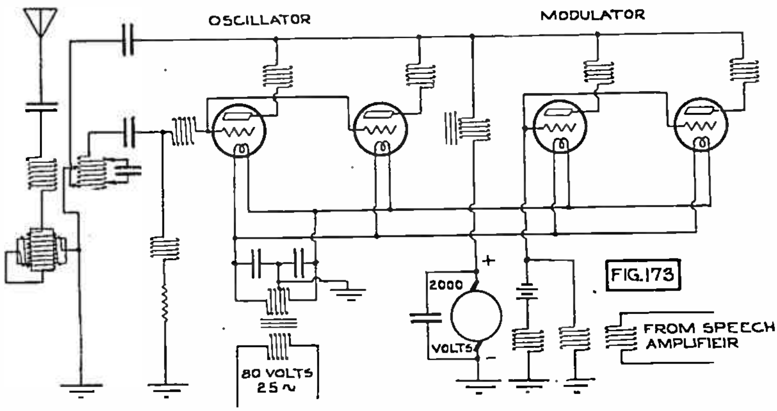


Fig. 173. Transmitting Circuit of a Broadcasting Station.

tubes in parallel, and modulation is effected by means of variation of the input power (Heising system).

The short-wave transmitter, shown in Fig. 174, exemplifies the type of circuit which is used in short-wave transmitters. This particular figure shows an oscillator of a type which is a combination Colpitts and Meisner circuit and is referred to as a *Split Colpitts* circuit in the Engineering Circular of the Burgess Battery Company, from which it was taken.

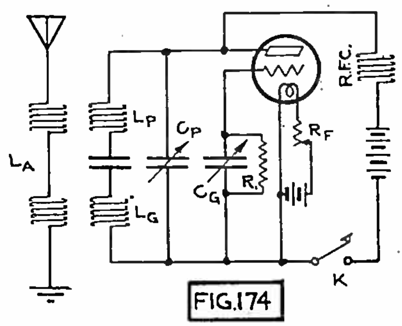


Fig. 174. Split Colpitts Oscillator.

115.—Portable Radio Transmitting and Receiving Sets.—In the field service the paramount requirement of radio equipment is to provide light, compact, portable sets, capable of both transmitting and receiving over some desired distance and range of wavelengths. This involves a combination of both transmitting equipment and receiving equipment in one set, and the design of this equipment in such a manner that two or more such sets may communicate with each other over some predetermined distance, this distance being limited by the power of the transmitter and the sensitivity of the receiver.

In combining transmitting equipment with receiving equipment the same antenna is used for both transmitting and receiving, and likewise the storage batteries used to heat the filaments of the receiving tubes are used to heat the filaments of the transmitting tubes, and to supply the motor current necessary for the operation of the dynamotor used to supply the plate potential of the transmitting tubes. Facility in switching this common equipment back and forth between the transmitting and receiving circuits is essential, otherwise considerable time is lost between transmitting and receiving. In practice the operation of a single switch accomplishes all the necessary changes.

To exemplify this and also to afford us an opportunity to study the method of analyzing the circuit of a complete radio set, let us consider the circuit shown in Fig. 175.

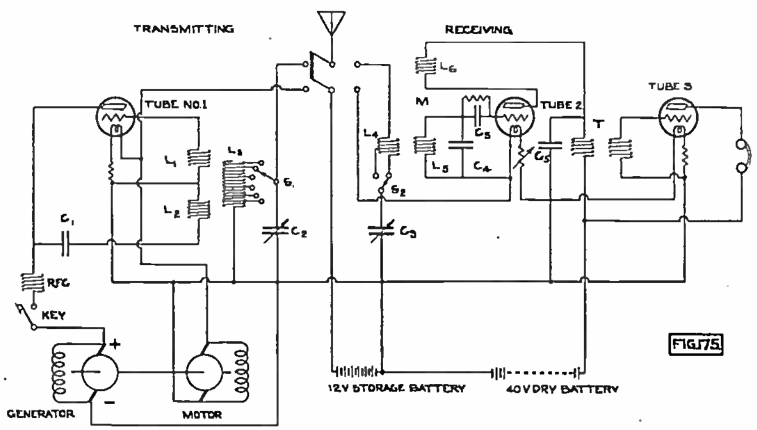


Fig. 175. Complete Transmitting and Receiving Set.

It should first be observed that the transmitting side of this set is controlled by a key and that no modulator is provided, and therefore this set is a continuous wave telegraph set.

The double-pole double-throw switch may be thrown to either the transmitting or receiving position. Let us assume that it is thrown to the transmitting position; the antenna aerial will then be connected to ground through the coil L_3 and the condenser C_2 in parallel. The antenna circuit may be tuned, therefore, by adjusting the rotory switch S_1, or the condenser C_2.

Tube No. 1 is used as an oscillator, its circuit being of the Meisner type, in which the coils L_1 and L_2 provide the coupling between the antenna or oscillatory circuit and the grid and plate circuits, respectively.

The lower blade of the double-pole double-throw switch provides a connection from the positive terminal of the storage to the filament of the transmitting tube, and to the positive side of the motor. The negative sides of both the motor and the filament are permanently connected to the negative terminal of the storage battery, which is grounded.

The generator side of the dynamotor is connected between the negative side of the filament circuit and the plate of the oscillator tube, the radio-frequency choke coil included in this circuit functioning to prevent radio-frequency currents from flowing from plate to filament through the generator. The condenser C_1 serves as a stopping condenser to prevent the generator current from flowing through the low-resistance coil L_2, and at the same time it by-passes radio-frequency currents.

When the double-pole double-throw switch is thrown to the receiving position, the coil L_4 and the condenser C_3 are included in the antenna circuit, and the storage battery is transferred to the receiving circuit, where it heats the filaments of the detector tube and the audio-frequency amplifier tube. The antenna circuit is now coupled to the grid circuit of the detector tube through the mutual inductance between coils L_4 and L_5, and the condenser C_4 in parallel with the coil L_5 permits the tuning of this grid circuit. Coil L_6 provides the coupling between the plate circuit and the oscillatory circuit L_5C_4 of the detector tube, so that this detector circuit will produce sustained oscillations. This regenerative detector is of the grid condenser-grid leak type, and its plate circuit is coupled to the grid circuit of the amplifier through the transformer T_1. The condenser C_5 is the radio-frequency by-pass around the primary of this transformer, and serves the same purpose as the telephone condenser used in separate detectors.

We see, then, that this set is capable of radiating continuous waves of any desired frequency within certain limits, and that it is capable of receiving either continuous waves, damped waves or audio-frequency modulated waves.

We are often concerned with radio-telephone sets or combination telephone and telegraph sets as well as telegraph sets, but in all cases the analysis of the circuit diagram may be made as above. It may be stated, then, that the steps in analyzing the circuit diagram of a complete portable radio set are as follows:

1. Determine general function of set.
2. Trace antenna connection.
3. Ascertain type of oscillator.
4. Ascertain type of modulator or other controlling system.
5. Observe manner of transferring antenna and power equipment from transmitting to receiving system.
6. Determine function of each component part of transmitter.
7. Determine number of stages of radio-frequency amplification.
8. Determine type of detector.
9. Determine number of stages of audio-frequency amplification.
10. Determine type of coupling used between tubes.
11. Determine function of each component part of receiver.
12. Determine type of waves radiated and detected by such a set.

116. Considerations Relative to Communication Between Sets of Different Types.—In order that communications may be established between radio sets of different types it is necessary that certain conditions be satisfied. The basic conditions are as follows:

1. Transmitting set must radiate waves of a type which can be detected by the receiving station.
2. The operating wavelengths of the two stations must overlap.
3. The distance by which the two stations are separated must be within the working range for the particular conditions existing.
4. Electromagnetic waves emanating from the transmitting station must reach the receiving station.

There might be occasions when one would be interested in deciding whether or not communications may be carried on between two particular radio sets of different types; one-way communication may be sufficient or two-way communication may be required. In such cases the first three items listed above may be investigated, and, if any of these conditions are not satisfied, communications will not be possible from the particular transmitting station to the particular receiving station considered. Obviously, it might be possible to have two radio stations, each complete with transmitting and receiving apparatus, and inter-communication between these sets might be impossible, or perhaps communications might be possible from one set to the second set, but not in the other direction.

The information relative to range of wavelengths and transmitting distance must usually be obtained from existing instructions provided with the sets, although the wavelength range might be determined with a wavemeter or computed from known values of inductance and capacity. However, sets of similar power have approximately the same transmitting distance, and therefore the transmitting distance of a particular set may be approximated from observations of the circuit arrangement, the type of equipment, etc., and comparing same with a similar set of known transmitting distance. In considering transmitting distance of sets radiating modulated waves, cognizance must be taken of the decrease in this distance due to modulation, as compared with the ability of the same set to reach a distant station by radiating continuous waves.

The student should be able to determine from the circuit diagrams of the sets under consideration, whether or not one- or two-way communication will be possible based on the ability of the receiving set to detect the particular kind of waves radiated from the transmitting station.

Among the four basic conditions listed above as being pertinent to successful communications, the following was stated: "Electromagnetic waves emanating from the transmitting station must reach the receiving station." This is the one condition about which nothing can be predetermined, except on the basis of experience in the exact locality of the stations concerned.

For our purpose it will suffice to say that, because of the electromagnetic shielding of certain geological formations in specific localities and the skip space reflection from the Heaviside layer, communication is sometimes impossible between two specific points on the earth. It is sometimes possible to establish communications, in such cases, by displacing the sets short distances.

117. **Remote Control of Radio Sets.**—It is often desirable

to control a radio-telegraph set from some distant point which provides better facilities for the erection of a suitable antenna, and also because of the *break-in feature* which is made possible by a combination of such a remotely controlled transmitting set and a local receiving set. Let us consider the following case to illustrate this possibility.

A certain headquarters is located in a permanent building around which there is no large open field suitable for the erection of an antenna intended for use in communicating with a distant headquarters. At a distance of two miles from the local headquarters there is a suitable field for the antenna. If the radio station is established on this field, it will necessitate courier service between headquarters and the radio station, with consequent delay in the transmission or delivery of the messages sent by this agency. To avoid this and also to provide a *break-in system*, it would be possible to erect the large transmitting antenna on the available field and establish the radio transmitting set at this point, but control its operation from the local headquarters by utilizing existing or specially constructed land lines between the two places. A small receiving antenna might then be erected on the roof of the local headquarters building and connected to a receiving set. If arrangements are made for the distant station to transmit on a different wavelength from that on which the local station transmits, then the operator of the local headquarters receives on a set tuned to the distant sets transmitting wavelength and controls the transmitting set on the field two miles away, his set being tuned to a different wavelength. The receiving set at the distant station is tuned to the transmitting wavelength of the local station. If the distant station is also provided with a separate reeciving and transmitting antenna, it will then be possible for either operator to break in on the other, just as this might be done on ordinary land telegraph systems.

In order to remotely control a radio set, the operator must have control over the power equipment of the set and the transmitting key. A simple scheme which provides this control may be made up by use of telegraph sounders and relays, as shown in Fig. 176. With the apparatus at the transmitting station connected as shown below, heating of the tube filaments and the operation of the dynamotor may be controlled by closing the switch C_1 at the local headquarters, and the operation of key K_1

at local headquarters, completes the same circuit as the K_2 on the transmitting set.

Closing the switch C_1 at the local headquarters connects ground on the line L_1 which is connected through relay R_1 and battery B_1 to ground, causing a current to flow through relay R_1, energizing this relay and causing it to attract its armature. This

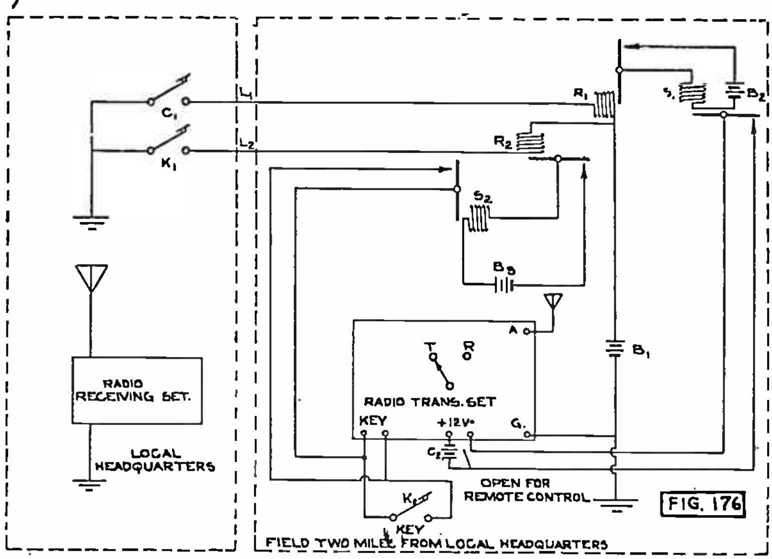


Fig. 176. Remote Control of Radio Set.

completes a local circuit containing the sounder S_1 and the battery B_2, causing a current to flow through S_1, which energizes it and results in the attraction of its armature. The armature of the sounder completes the connection of the 12-volt storage battery to the radio set, which by reason of connections within the set then heats the filaments of the transmitting tubes, and starts the dynamotor. Opening the switch C_1 at the local headquarters breaks the circuit through relay R_1, which breaks the circuit through S_1, which disconnects the storage battery from the radio set.

The closing of the key K_1 at the local headquarters connects ground to the line L_2, which is connected through relay R_2 and battery B_1 to ground, thus energizing the relay R_2 and attracting its armature. The relay armature completes a local circuit containing battery B_3 and sounder S_2, thereby energizing the sounder and attracting its armature. The sounder armature completes a circuit which is in parallel with the circuit of the key K_2 on the radio.

This circuit gives the operator at the local headquarters control over the transmitting set using the large antenna. This set may be adjusted to any desired wavelength previous to operation. Suppose this wavelength to be 1,350 meters. The transmitting wavelength at the distant headquarters might be made 1,300 meters. The receiving apparatus at local headquarters would then be tuned to 1,300 meters and the receiving set at the distant headquarters tuned to 1,350 meters. If, during the transmission of a message between these two stations, the receiving operator desires to break in on the transmitting operator, he may do so by operation of his transmitting key.

In practice it is found that the arc which occurs when the storage battery circuit at the transmitting station is broken is very large and destructive to the contacts. For this reason it is often necessary to provide two contacts on the sounder S_1, insulate them from each other and connect one of them so that it will complete the filament circuits of the transmitting tubes and the other so that it will complete the low-voltage dynamotor circuit.

The remote control of radio-telephone sets from a distant telephone subset is much more difficult than the remote control of radio-telegraph sets as described above. However, the general scheme is the same in both cases. In the remote control of a radio-telephone set from a telephone subset, two antennas are employed at each end, one for transmitting and one for receiving, the telephone subset being associated with repeaters and relays which cause the microphone to control the radiation from one antenna and the receiver to receive the energy intercepted by the other antenna.

118. Summary:

1. Two stages of transformer-coupled audio-frequency amplication or three stages of audio-frequency amplification with other types of coupling are ordinarily used in receiving sets.

2. Radio-frequency amplifiers are more difficult to design and operate than audio-frequency amplifiers. However, they provide

a means of amplifying the input voltage of the detector, and a combination of radio and audio amplifiers makes possible a greater total amount of amplification without distortion than could be obtained with only one type of amplifier.

3. A regenerative detector is practically equivalent to a non-regenerative detector and one stage of amplification.

4. The grid condenser-grid leak detector is most extensively used in receiving sets.

5. It is customary in receiving circuits to connect the rotor side of variable air condensers to the filament side of the circuit and to ground the negative terminal of the filament battery.

6. The receiving circuits used in modern radio sets combine neutralized radio-frequency amplifiers with a detector, audio-frequency amplifiers and power supplies in various manners to produce the desired results.

7. The superheterodyne provides a local oscillator at the receiving station which produces intermediate radio-frequency beats with the signal current, then rectifies the resulting current by means of a detector, and passes this rectified current through several stages of intermediate frequency amplification and a second detector.

8. Superheterodynes are extremely sensitive because of the great efficiency of the intermediate frequency amplifiers which they employ, and which are designed to operate over a very limited range of frequencies.

9. The Pressley superheterodyne employs a balanced Wheatstone Bridge principle to prevent radiation.

10. In the reflexed receiver the plate circuit of the detector tube is coupled to the grid circuit of a preceding amplifier, so that the amplifier performs simultaneously the function of radio- and audio-frequency amplifier.

11. Reflexing a circuit results in the saving of tubes, but increases the difficulty of operation.

12. The circuits used in short-wave receivers are similar to those used in other receivers, but the circuit constants are different.

13. Shielding a circuit consists in surrounding the various component parts with sheet metal which is electrically grounded.

14. Tone control is accomplished in broadcast receivers by use of an adjustable condenser connected across the grid circuit of an audio amplifier or the voice coil of a loud speaker. By means of this device the relative intensity of high and low audio-frequency notes in the loud speaker is adjusted.

15. The microvolter is a modulated, variable radio-frequency oscillator with a calibrated attenuation net work, and is used as a standard signal generator.

16. Sensitivity is the degree to which a receiver responds to signals of the frequency to which it is tuned.

17. Selectivity is the degree to which a receiver differentiates between signals of various carrier frequencies.

18. Fidelity is the degree of exactness with which a receiver reproduces the modulation of its radio-frequency input.

19. The circuits employed in commercial broadcasting stations and in short-wave transmitting sets are similar to the corresponding circuits used in other radio transmitters.

20. In complete portable transmitting and receiving sets the same antenna and storage batteries are used in both transmitting and receiving circuits, and facility in switching this equipment back and forth is essential.

21. In order that communication may be established between radio sets of different types, it is necessary that the following conditions be fulfilled:

1. The transmitting set must radiate waves of a type which can be detected by the receiving station.
2. The operating wavelength of the two stations must overlap.
3. The distance by which the two stations are separated must be within the working range for the particular conditions existing.
4. Electromagnetic waves emanating from the transmitting station must reach the receiving station.

22. The remote control of radio-telegraph sets is made possible by suitable combination of radio and wire telegraph equipment; and likewise the remote control of radio telephone sets may be accomplished by a suitable combination of radio and telephone equipment.

119. Self-Examination:

1. How many stages of the following types of audio-frequency amplification are normally used in receiving sets.
   1. Transformer coupled;
   2. Impedance coupled;
   3. Resistance coupled?

2. What are the advantages and disadvantages of radio-frequency amplifiers?

3. Why are regenerative grid condenser-grid leak detectors so extensively used in radio sets?

4. What side of a variable air condenser is grounded, and why?

5. What special features are provided and what is the function of each of the component parts of the circuits shown in Figures 165, 166, 167, 169, 170, 171, 172(1), 172(2), 172(3).

6. Describe the unique features of the superheterodyne.

7. Describe the method of preventing radiation used in a Pressley superheterodyne.

8. Describe the manner of reflexing a circuit. Does reflexing save transformers?

9. What is the advantage of variometer tuning when mechanically associated with a gang condenser?

10. What types of volume controls are used in modern broadcast receivers?

11. How does a tone-control device operate?

12. Describe a simple signal generator or microvolter.

13. Define the Sensitivity of a broadcast receiver and explain how it is measured.

14. Describe the Selectivity of a broadcast receiver and explain how it is measured.

15. Define the Fidelity of a broadcast receiver and explain how it is measured.

16. How is shielding accomplished, and why is it desirable?

17. What parts of a complete portable radio set are used both in transmitting and receiving?

18. What conditions must be fulfilled in order that two-way communications may be established between two radio sets?

19. Describe a system for remotely controlling a radio telegraph transmitting set.

SECTION XII.

LINE RADIO AND TELEVISION

	Paragraph
LINE RADIO	120
TELEPHOTOGRAPHY	121
TELEVISION	122

120. Line Radio.—Line radio is the method of transmitting telegraph or telephone signals over conductors used to guide electromagnetic waves. It is different from ordinary radio in that the transmitting and receiving stations are connected by means of metallic conductors, and it is different from ordinary wire telegraphy and telephony in that it employs the high-frequency currents, electromagnetic waves and methods used in ordinary radio communications.

In ordinary radio systems electromagnetic waves radiated from the transmitting antenna are propagated in all directions throughout space. On the other hand, the electromagnetic waves created by the transmitter used in line radio systems are guided along the conductors connecting the stations, so that a relatively large portion of the energy leaving the transmitting station actually reaches the receiving station.

The apparatus used in line radio is the same as that used in ordinary radio systems, as may be seen from Figs. 177 and 178.

Fig. 177 shows a simple line radio-telegraph system, in which the transmitter consists of a modified Hartley oscillator coupled to the coil L_1 so that an electromotive force is induced in this coil, and when the key K is closed a corresponding current flows in the circuit L_1, line 1, L_2, C_2, line 2, and C_1. Because of the high frequency of the current used in this system, the major portion of the energy transferred from the transmitting to the receiving station is really due to the displacement of the electromagnetic field along the wire rather than the transfer of electrons through the conductors. For this reason, this system is often referred to as *guided wave telegraphy*, or *wired wireless*. The

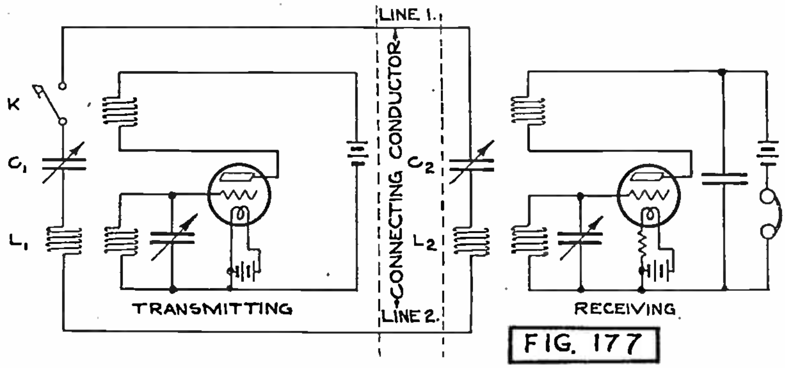


Fig. 177. Line Radio Telegraph Set.

current through the coil L_2 induces a corresponding voltage in the gride coil of the detector, and the signal is detected as in the case of ordinary radio.

The circuit shown in Fig. 178 is similar to this, except that this circuit represents a telephone rather than a telegraph system.

It is possible to use the same pair of conductors between two places to guide a rather large number of electromagnetic waves simultaneously. For example, in Fig. 179 a pair of wires con-

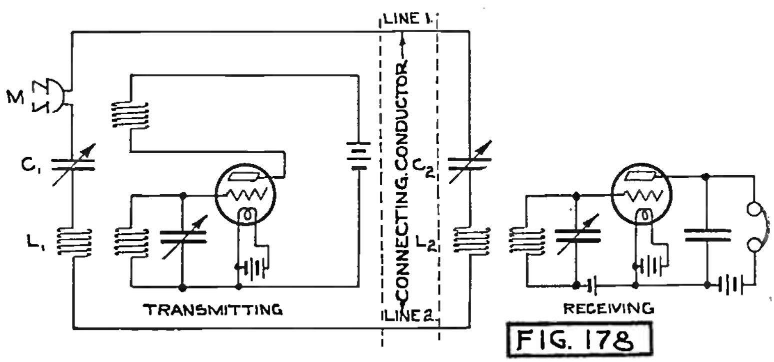


Fig. 178. Line Radio Telephone Set.

necting the cities of New York and Pittsburgh are represented. Three transmitters of different frequencies are connected at the New York end of the line, and three detectors with associated circuits, one of which is tuned to each of these frequencies, are connected at the Pittsburgh end. In this system three messages

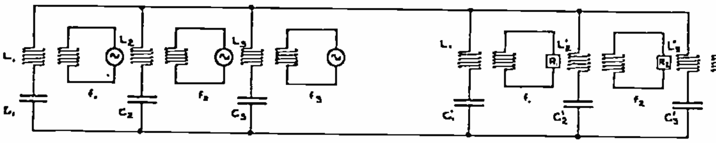


FIG 179.

Fig. 179. Multiplex Line Radio.

are transmitted over the same pair of conductors simultaneously. These messages may be either telephone or telegraph, and likewise it is possible to transmit a larger number of messages over the same pair of wires in one or both directions simultaneously. The frequencies of the currents employed in this system must be above the range of audibility, and they must be separated from each other sufficiently that the path of low opposition for one frequency will offer high opposition to another. If relatively low-frequency currents are employed, more of the energy is transferred between stations as electron displacements, and as the frequency of the current is increased, the relative amount of energy transferred as guided electromagnetic waves is increased.

Line radio may be employed on ordinary telephone lines, even though the lines are in use at the same time for the transmission of ordinary telephone or telegraph signals.

121. **Telephotography.**—Telephotography means the process of transmitting pictures by means of electric currents or electromagnetic waves. At the present time, pictures have been successfully transmitted over wires connecting two distant places and also across great distances by means of electromagnetic waves. Several different systems have been devised for this purpose. However, each of these systems contains a device for effecting variations in an electric current corresponding to variations in the intensity of a beam of light at the transmitting station, and a device for performing the converse function at the receiving station. A so-called "photoelectric cell" is employed for the first of these purposes, this device being capable of converting varia-

tions in light intensity into variations in electrical resistance.

The early type of photoelectric cell consisted of a small amount of some particular chemical element arranged so as to provide a path for electric current, and so mounted that it could be exposed to light from some particular source. The chemical element must be one which changes its electrical resistance, when the intensity of light falling upon it is varied. Selenium is the most frequently used element for this purpose, and a photoelectric cell in which selenium is used is often referred to as a selenium cell. Several other chemical substances are also satisfactory for this purpose.

The latest and best type of photoelectric cell consists of a gas-filled vacuum tube containing an anode of molybdenum and a cathode of potassium hydride. Potassium is an element which emits electrons when light of certain wavelengths falls upon it, and this electron emission varies with the intensity of the incident light. If the electrons so emitted are attracted to the anode by reason of its positive potential maintained by an external battery, a current will be established in the external circuit. By varying the intensity of the light falling upon the potassium, the electron emission, and consequently the current, in the external circuit will be varied.

Now let us see how this photoelectric cell is used in the transmission of still pictures from one place to another over wires.

At the transmitting station a pencil of light from a lamp is concentrated by a lens, and falls on a small area of a photographic film which contains the picture to be transmitted, as shown in Fig. 180. The transparency of the film is different from

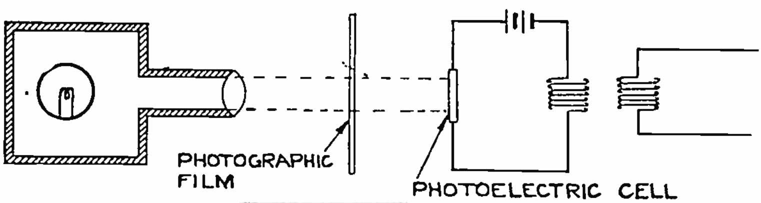


FIG. 180

Fig. 180. Schematic Diagram Showing Manner of Producing Changes in Current, Which Are Proportional to Changes in Density of a Photographic Film.

one spot to another, and if the film be progressively displaced, the intensity of the light falling upon the photoelectric cell will be varied according to these variations in transparency over different spots on the film. The electrical resistance of the photoelectric cell will be likewise varied, and an alternating electromotive force of corresponding form will be induced in the coil. This electromotive force is caused to modulate the output of an oscillator by any one of the methods previously described.

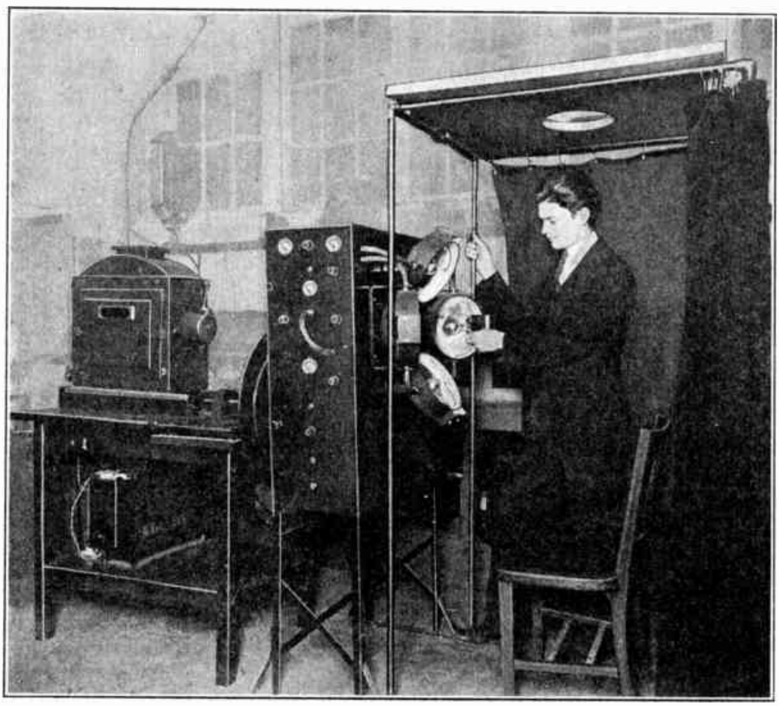
At the receiving end this modulated current is detected and then caused to change the current through a shutter controlling a pencil of light from a local source falling on a photographic film, so that the intensity of the light falling on the receiving film varies in accordance with the density of the film at the transmitting station. Next, the receiving photographic film is progressively displaced in exact synchronism with that of the film at the transmitting station. In this manner each spot of the film at the receiving station is exposed to light which is of an intensity proportional to the density of the corresponding spot on the photograph which it is desired to transmit, and a positive print is obtained if the transmitting film is a negative, or else a negative print is obtained if the transmitting film is a positive.

The movement of the two photographic films must be exactly synchronized, as stated above. In practice this is accomplished by controlling synchronous motors by means of a high-frequency current sent over the same channel as that used in transmitting the shades of the picture. These currents usually synchronize the vibration of two tuning forks of equal pitch, which in turn control the synchronous motors used in moving the photographic film.

122. Television.—Instead of transmitting still pictures over wires or by means of radio waves, we might be interested in transmitting images of moving objects. This, of course, is much more difficult, because it is equivalent to transmitting eighteen still pictures per second, while in telephotography the process may be slow and actually consumes about five or ten minutes. Television has not been perfected to an entirely satisfactory point as yet, but great strides have been made in this direction during recent years.

In the most modern system of television a spot of light is passed over the subject in parallel lines so that the whole subject is scanned in one-eighteenth part of a second. The light reflected from each spot on the subject as it is illuminated is collected by large photoelectric cells, which are so connected as to control the modulation of an electromagnetic wave or the current flowing over wires, as the case may be.

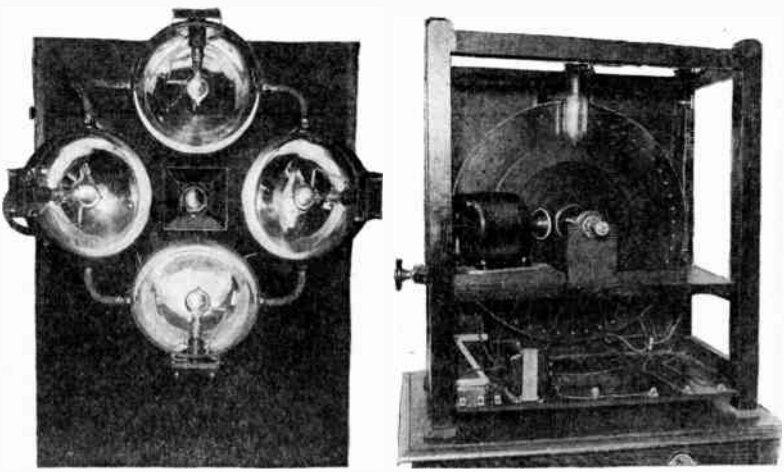
The apparatus used at the transmitting station is shown below. The rotating disk is driven by a synchronous motor at the rate of eighteen revolutions per second. This disk contains fifty small apertures arranged in a spiral. A very limited area in the path of these moving apertures is highly illuminated by light coming from an arc lamp and concentrated by a lens, so that a small beam of light passes through each aperture as it appears before a frame. A lens on the other side of the disk concentrates this small beam of light on a spot of the subject. As the disk makes each revolu-



John Geloso and His Compact Television Transmitter. His Left Hand Is Resting on One of the Photoelectric Cells That Pick Up the Light Reflected from the Surface of the Image.

tion, the subject is completely scanned in a series of parallel lines by a rapidly moving spot of light. The light reflected from each spot on the subject as it is illuminated falls on one of several photoelectric cells, which are electrically connected in parallel and which control the signal or picture current.

At the receiving station the picture current controls the brightness of a neon lamp, from which the image is constructed by means of a small aperture moving in synchronism with the aperture at the transmitting end. As the light passes through this



Left: What You Would See If You Were Being "Televised." Right: A Simple Television Receiver.

aperture it falls on a screen, and because of the persistence of vision the observer sees the complete image constructed by one revolution of the disk.

The neon tubes recently manufactured for use in television receivers contain a relatively large plate which serves as the screen, and the observer looks at a portion of this screen corresponding to the portion of the subject being scanned at that instant. In small television receivers the synchronism of the rotating disk with that of the transmitter is accomplished manually.

The apparatus described and pictured on these pages was manufactured by the Pilot Radio and Tube Corporation, of Brooklyn, N. Y., and was successfully used to demonstrate television at the 1928 Electrical and Industrial Exposition held in New York City.

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