WIRELESS SIMPLY EXPLAINED

By the same Author:

RADAR: RADIOLOCATION SIMPLY EXPLAINED

TELEVISION SIMPLY EXPLAINED

WIRELESS

simply explained

by

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To J. L. B.

for being so cheerful
that he keeps me going

Author's Preface

THE gulf between the book of the " wireless without tears " kind and the large textbook is a wide one. Little has been done hitherto to throw any kind of bridge over it, with the result that many people who realise something of the fascination of the subject from their reading of elementary works and would like to go into it more deeply are brought up short by a hasty glance at the forbidding looking pages of the books offered when they ask for something a little more advanced.

To provide such a bridge has been my aim in writing *Wireless Simply Explained.* By this I do not mean that to understand what it contains it is necessary to have read one or more of the " without tears " books. The complete beginner will, I believe, find the going quite easy, for each new term or effect is explained as it occurs.

Many people shy at the mathematics of wireless. I have tried to show that these need not be so terrifying as they might seem at first blush. The subject involves numbers that may be almost fantastically large, or fantastically small—thousands of millions of cycles per second; fractions of a millionth of a second. For all that, the mathematics in the pages which follow are of the simplest kind. A short and easy method of writing and handling very large (or very small) numbers is described and explained.

A reasonably good understanding of many of the most interesting problems of wireless can be gained with no more than a modest equipment of mathematical knowledge. True, the mathematics of wireless can be formidable (as indeed can those of such everyday and apparently simple things as the wood-screw or the bicycle tyre), but that does not mean that one must be familiar with the higher mathematics in order to understand pretty thoroughly the means whereby radio transmission and reception take place.

Nor does it mean that unless one is a mathematician the normal wireless textbook cannot be read and understood. Given a sound knowledge of the elements, most textbooks are by no means beyond the understanding of the average reader. Some of the largest, the most comprehensive,* or the most specialised† of them seldom go far beyond such elementary mathematics as will become familiar to the reader in the pages which follow.

Some may object to my use of the term "wireless" both in the title of this book and frequently in the text, urging that it has been supplanted by "radio" in modern parlance. My reply is that it hasn't. In this country, at any rate, "wireless" is still the more familiar term. Most of us speak of buying a wireless set, of tuning in a wireless station, of wireless waves and of wireless transmissions. The laws which regulate the use of ether waves for telegraphy, telephony, broadcasting and television are contained in the Wireless Telegraphy Act. All of the fighting services make use of the term "wireless." Last, but by no means least, "wireless" is a good honest British word and was not imported from abroad.

* For example : "Radio Engineering," by F. E. Terman.
† For example: "The Technique of Radio Design," by E. E. Zepler.

There is one other point which should be mentioned. The new letter symbols for valves were brought out after the book had been set up by the printers and after the blocks of all the diagrams had been made. These symbols, which have hardly yet come into general use, are described and explained in an appendix. The reader is thus equipped for tackling both existing textbooks, using the old terms, and later books in which the new terms will probably appear.

BERKHAMSTED,
January, 1949.

R. W. H.

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CHAPTER I

Wireless To-day

WIRELESS may be defined as the transmission of intelligence from place to place by electrical means without the use of intervening cables or wires. Though it is barely half a century since practical methods of transmission and reception were evolved and but forty-six years since the first radio message was sent across the Atlantic, wireless is to-day man's most important means of communication at a distance.

Before the coming of wireless a vast network of submarine cables and of telegraph and telephone lines on land linked up the continents of the world. Messages could be sent between any of the towns and cities to which the wires had been brought; but there were vast areas of sea and land with which no communication by telegraph or telephone was possible.

To-day there is no corner of the earth which cannot be reached by wireless. Ships at sea are in constant touch with the shore; aeroplanes making long-distance flights need never be out of contact with meteorological and position-finding stations. Explorers and dwellers in remote and inaccessible places must no longer be cut off entirely from the life of the civilised world. The wireless receiving set brings them, wherever they may be, news of what is taking place the world over. If a wireless transmitter is available they can make known their progress, their discoveries or, if need be, their need of help.

Wireless telegraphy and telephony have not supplanted or rendered obsolete the great world-wide networks of message-carrying cables and wires. Both wired and wireless systems of communication are needed and often the one assists the work of the other. When, for instance, a telephone subscriber in this country calls a number in the United States we have a good example of the alliance of wires and wireless, which is illustrated in Fig. 1.

The microphone into which the British subscriber speaks is connected through various exchanges by the

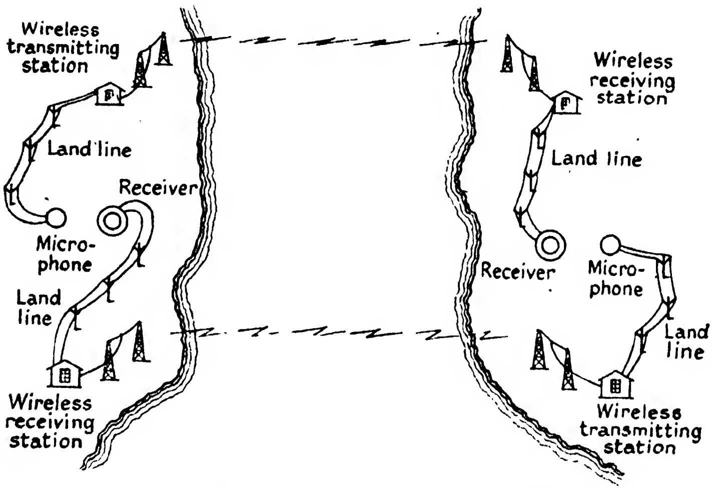


Fig. 1.—Illustrating the alliance of wired and wireless systems in long-distance telephony.

land-line to a wireless transmitting station, from which the message is sent across the Atlantic to a receiving station in America. Thence it travels by land-line to the receiver of the American subscriber's telephone. His microphone is connected by land-line to a radio transmitter many miles from the American receiving station. From this his message is sent to a receiving station in Britain, whence it travels by land-line to the British subscriber's telephone receiver.

What is known as the radio link is also used in many British telephone circuits. If you speak, for example, from Devon or Somerset to South Wales, messages travel to and from the shores of the Bristol Channel by land-line, but are sent over the water by radio. There are many similar radio links in this country across estuaries, or between shore and island.

One specialised form of wireless, known as Radar, was the deciding factor in the recent great war, since it enabled this country, at the time when we stood alone, to defeat both the raiding bombers and the submarines of the enemy. Radar is already proving a splendid aid to the safety of travel both on sea and in the air. It is developing rapidly in many directions and it will undoubtedly become in the near future the most important of all navigational aids to shipping and aircraft.

Radar apparatus " illuminates " objects with streams of wireless waves. Such illumination is invisible to the eye but not to the wireless receiving set. The navigator of an aeroplane fitted with apparatus of the type known as H_2S sees on a screen like that of a television receiver a picture of the ground below him. And the Radar eye sees equally well through pitch darkness, dense cloud, the smoke pall over great cities, fog, or falling snow.

Another form of Radar, already installed in many ships and sure before long to become part of the standard equipment of all but the very smallest, is making navigation perfectly safe even when weather conditions limit visibility to only a few yards. In the thickest fog it shows clearly the exact positions of icebergs, of other ships, of rocks or of islands. Though the human eye may be blinded, the navigator who has Radar to aid him can see not only the outlines of the coast which his ship is approaching, but also the buoys which mark the fairway or give warning of danger.

Those are but two of the wonderful things that Radar can do for man. There are countless others, but these two suffice to show of what service to him is just one of the many departments of wireless.

The two aspects of wireless that touch all of us most nearly are broadcasting and television.

Television has not yet established its full importance in everyday life, for its benefits are still restricted to a very small proportion of the human race. At the time of writing the only full television service in the eastern hemisphere is that of our B.B.C. And that service still covers less than one-third of the homes of Britain. Few other countries have yet any kind of regular television service save the United States of America. There, several services are in operation; but the areas which they serve are small in comparison with the whole huge country.

Nation-wide television services are bound to be established one day in all civilised countries, though it may be some little time before this is accomplished. The broadcasting of sound, however, not merely on a nation-wide but on a world-wide basis, has been an accomplished fact for many years now, and such broadcasting has proved itself to be one of the most profound of the influences on human life that have come into being since remote ancestors of ours ceased to gibber in the tree-tops and became the most primitive of men.

Broadcasting means far more than that the owner of a wireless receiving set has always at hand a means of enlivening moments that would otherwise be dull. It is, without a doubt, the most successful method of education without tears that the fertile mind of man has ever devised. Thanks to broadcasting, the ordinary man and woman of to-day make a completely painless contact with great books, great music, great plays, great achievements in science and, above all, with great political issues both national and international.

The average man or woman of the present time has a far wider fund of general knowledge than the average man or woman of twenty-five years ago. It is no exaggeration to say that this is due in very large measure to wireless broadcasting, which for so many has opened books that would otherwise have remained closed.

An amazing aspect of broadcasting is that through it great men and women can now establish something like personal contact with a large proportion of the world's civilised population. Up to a quarter of a century ago no one had ever spoken to an audience of more than a few hundred people. To-day an audience reached by broadcasting may number scores of millions. One man can, in fact, speak to listeners in every corner of the world.

One of the first to realise the possibilities of broadcasting as a power for good was King George the Fifth, of whom it has been said that he broadcast his way into the hearts of the peoples of the Empire by making his listeners feel that all were members of one great family.

The potential audience is far larger nowadays, for the numbers of broadcasting stations and of broadcast receiving sets have greatly increased. Our King's Christmas talk now reaches almost a quarter of the population of the world.

In all civilised countries men and women eminent in the arts, in science, in politics, in travel, in sport and in countless other departments of knowledge or experience speak to people in their own homes. Nor are their broadcasts necessarily confined to their own countrymen. Wireless knows no frontiers and the owner of a reasonably good receiving set can hear transmissions from many other countries besides his own. Thanks to wireless, the old saying that one half of the world does not know how the other half lives is becoming less and less true.

Wireless broadcasting has made possible the exchange between nations of ideas and points of view on a scale that would have been incredible a quarter of a century ago. Properly used, it can be the greatest of all aids to the international understanding that is so necessary to-day. Unfortunately, it can also be employed for other ends.

Broadcasting has been misused, as the gifts of science to humanity so often are. It has been—and it still is—employed too frequently to disseminate evil propaganda, distorted news and distorted views. But science cannot be blamed for that. Science has provided mankind with a means of conveying intelligence to a world-wide audience. If some parts of the human race choose to misuse the gift, science can hardly be held answerable for their misdeeds.

The services which are now conducted by wireless may be summed up as follows:

1. *Wireless Telegraphy.* The transmission by wireless methods of messages by means of morse-code signals and the teleprinter. Automatic methods of transmission and reception make it possible to conduct the exchange of such messages at very high speeds.
2. *Still Picture Transmissions.* The sending by wireless of the pictures which are often used to illustrate our newspapers over distances which may run to thousands of miles.
3. *Wireless Telephony.* This makes it now possible for a telephone subscriber to speak to another subscriber in almost any other country in the world.
4. *Broadcasting.* A development of wireless telephony by means of which the owner of a receiving set

can have news, entertainment and information from transmitting stations in his own and in other countries.

5. *Television.* The transmission and reception by wireless of moving pictures of events as they actually occur, or of film records of events which have occurred at some previous time.
6. *Radar.* A means of locating distant objects at ranges or in weather conditions which make them invisible to the naked eye, or to the eye aided by optical appliances.

This book is concerned mainly with wireless telephony, and in particular with that branch of it known as broadcasting. Still picture transmission and reception and television are dealt with in another book of mine.* A third book explains the working of Radar.†

The great difference between commercial wireless telephony and broadcasting is that the former seeks to convey a message to one particular person and to prevent others from eavesdropping, whilst the aim and object of the latter is to reach as large an audience as possible.

Commercial wireless telephony cannot prevent the sounds of its communications from reaching anyone who is within range of its transmitters and possesses a receiving set which can be tuned to the required wavelength; but it can and does make those sounds utterly unintelligible to anyone but the person for whose ear they are intended.

It is more than likely that when exploring the short waves with your wireless set you have come across transmissions which, though obviously those of speech, were yet not being made in any conceivable language. These are the " scrambled " transmissions of transatlantic and other long-distance wireless telephony services.

* " Television Simply Explained."
† " Radar: Radiolocation Simply Explained."

At the transmitting end an ingenious device, known as the scrambler, jumbles the sounds of speech in such a way that each undergoes an entire alteration. Just what that alteration is depends upon the particular adjustments of the scrambler that are in use at the time. The net result, though, is to turn all speech into a weird collection of sounds which can convey no intelligible message to the eavesdropper.

At the receiving end the deliberately distorted wireless signals pass into a de-scrambler, which restores their original form to the jumbled sounds and enables them to convey their message to the person for whom it is intended. The odds against the devising of an appropriate de-scrambler by anyone who wished to be able to understand a particular message are millions to one. When it is realised that the nature and degree of scrambling are almost infinitely variable and that changes can be made in the course of a single conversation, it will be seen that this method gives wireless telephony employing it a just claim to be called " narrow-casting "—a means of communication between a speaker and his chosen correspondent alone.

During the last war Mr. Churchill and President Roosevelt were in daily radio-telephonic communication across the Atlantic. They discussed, no doubt, the most important questions of policy and of strategy. It has been stated by lay journalists that Hitler regularly listened in to their talks; but it is impossible to believe this. Hitler's wireless experts may occasionally have been lucky in adjusting their de-scramblers to deal with part of a conversation; but that their success (if they had any successes) was no more than sporadic is shown by the way in which important moves on the part of the Allies so frequently caught the Germans napping. The Prime Minister and the President later used the teleprinter, whose signals can be made completely unintelligible except to those for whom they are intended.

Far from endeavouring to make its transmissions secret, broadcasting seeks every means of making them receivable by the greatest possible number of people. The only exception to this is where a broadcast is intended primarily for one particular part of the world. The B.B.C., for example, conducts broadcasts in a large number of languages, and if it is transmitting a talk or a news bulletin in Persian, it is clearly desirable to ensure that its message

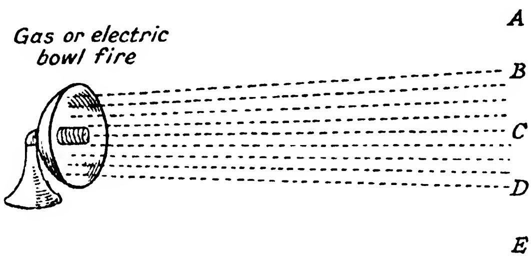


FIG. 2.—A thermometer held for a few moments at positions *A*, *B*, *C*, *D* and *E* successively indicates how the reflector focuses the heat radiated by a bowl fire into a narrow beam.

is best heard in countries where this language is understood.

Ordinary broadcast transmissions are radiated equally in all directions; a suitable receiver situated north, south, east or west of the transmitting station can pick them up, provided that it is within range. For transmissions intended to serve particular areas a different method, known as "beaming," is used. The radiation is focused into a beam, directed as required.

If you possess a bowl fire, either gas or electric, you have something which behaves very much as a beam wireless transmitter does. Bowl fires are designed to concentrate the radiation of heat (and we shall see presently that heat and wireless are very close relations) in one particular direction. In the case of heat radiation the part of the receiver may be played, as indicated in Fig. 2, by a thermometer. Hold a thermometer for a few seconds in various positions, each 10 feet from the bowl, and you will soon see how narrow is the beam into which the heat radiation is focused.

A beam wireless transmitter radiates its messages in a similar way, concentrating the available energy on to the places where it is required, and giving poor reception—or none at all—in others where it is not.

CHAPTER II

Air Waves and Sound

THE transmission by wireless of sounds of all kinds is accomplished by the agency of waves of two different kinds: air waves and ether waves. In a broadcasting studio the sound waves due to speech and music are transformed by the microphone into corresponding electrical impulses. These are passed to the transmitter, in which they are impressed on the wireless ether waves radiated from the aerial.

At the receiving end the wireless waves give rise in the aerial system to electrical impulses which are fed into a receiving set. In this the impulses due to sound waves are disentangled from those due to wireless waves by the process known as detection. The sound impulses then receive such magnification as may be needed and travel to the loudspeaker, by which they are re-converted into sound waves. These waves travel through the intervening air to our ear-drums and we hear (or, rather, we should hear, were wireless methods perfect) exactly the sounds which occurred in the studio.

That, quite literally, is all that there is in wireless telephony of any kind. It seems to be a simple and straightforward business and you may possibly wonder that it should contain sufficient material for the making of a book. I shall endeavour to give simple and straightforward explanations of the various processes involved; but when I mention that the subject-matter of this and each of the following chapters would require a book of its own (and in some cases several books) if it were to be dealt with at all fully, you will realise that my difficulty has been to decide not so much what to put in as what to leave out.

Wireless is, in fact, a vast subject—and it is becoming almost daily vaster, as new discoveries and developments are made. But we need not be dismayed by its huge scope. It is perfectly possible to obtain a good working idea of its general principles without wading through a formidable array of textbooks—and some of them can, indeed, be formidable! That is what we have set out to do, so let us now see something about waves.

Waves to most people mean the successions of crests and troughs which are seen when water is disturbed. The disturbing factor may be either wind blowing over the

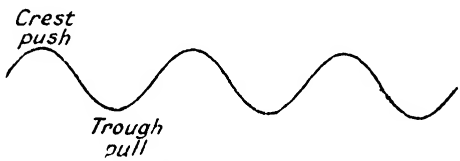


FIG. 3.—Water waves may be regarded as a succession of pushes (crests) followed by pulls (troughs).

surface of the sea, or the sudden entry of a stone into the placid surface of a calm pond. In either case the result is the same. The surface of the sheet of water is no longer smooth and even: it becomes rather like that of the corrugated cardboard used for packing bottles for safe transit through the post.

A stone, when it falls on to still water, makes a hollow, or depression, by displacing some of the water. The displaced water piles up into a ridge, displacing water in front of itself and forming a trough beyond. And so the process goes on. The impact of the stone on the surface of the water gives rise to a series of ridges and furrows—or crests and troughs—which move outwards in concentric circles from the point at which it first made contact.

A crest is formed by a pushing up of the water—a push; a trough occurs when the water is pulled down—a pull.

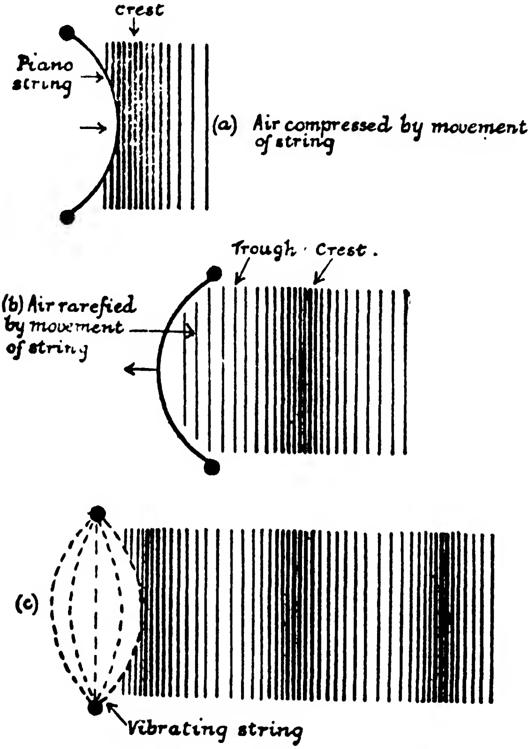


FIG. 4.—The movements of the vibrating string produce alternate compressions and rarefactions of the surrounding air—the crests and troughs of sound waves.

We can thus regard water waves as consisting of alternate pushes and pulls, as indicated in Fig. 3.

Water waves, or those occurring on any liquid, travel over the surface. Sound waves travel *through* air. The two processes, however, have much in common: each kind of wave consists of a push followed by a pull, or a crest and a trough.

What happens if we strike middle C of the piano, keeping the loud pedal depressed? Fig. 4 illustrates this diagrammatically. The string is adjusted by the piano-tuner (though he may not realise that he is doing this) to vibrate 256 times a second. The piano makers provide a string of such a length and weight that if it is properly

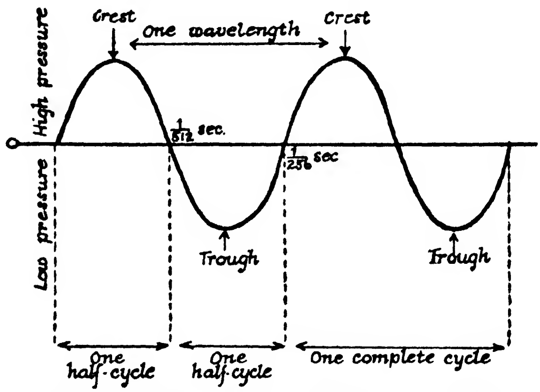


FIG. 5.—A wavelength is the distance between two consecutive crests or troughs. A cycle is the undulation from zero to crest, from crest to trough and from trough to zero which makes up one complete wave.

stretched it will move when struck, or twanged, 256 times in every second outward (to a crest) and inward (to a trough).*

When the string moves outward it compresses the air in front of it. Its inward movement has the opposite effect, leaving rarefied air behind. We can represent the

* A piano—or any other instrument—may be tuned to a particular pitch. Domestic pianos nowadays are actually tuned so that the vibration rate of their middle C is a little above (sharper than) 256 a second. Concert pitch is sharper still. In these pages 256 vibrations a second is used as a good round figure.

effect of one to-and-fro movement of the string on the surrounding air by the WAVEFORM seen in Fig. 5. In the crest the pressure rises from zero to maximum and then falls again to zero. In the trough the rarefaction increases from zero to maximum, returning again to zero.

A complete wave—crest and following trough—is known as a CYCLE; the crest and the trough are HALF-CYCLES. The crest, which we may think of as a push, is the POSITIVE HALF-CYCLE,

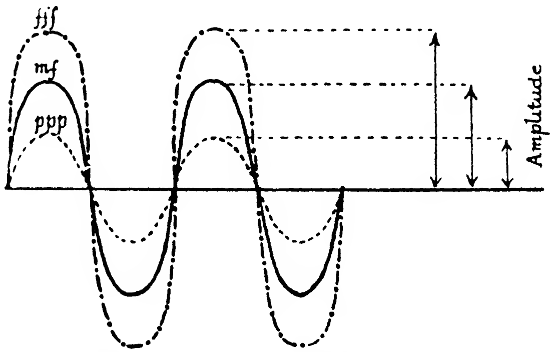


FIG. 6.—The energy conveyed by a wave depends upon its amplitude: the height to which the crests rise and the corresponding depth of the troughs.

and the trough, or pull, is the NEGATIVE HALF-CYCLE.

The number of complete waves or cycles occurring in each second is known as the FREQUENCY.

If the string is struck lightly it makes 256 inward and outward swings a second, but it does not move far in either direction: the AMPLITUDE of the resulting sound waves is small (Fig. 6). Striking the string hard does not alter the number of vibrations a second, or the frequency of the resulting waves. There are still 256 vibrations a second, and 256 cycles. But the swings of the string are greater in both directions and the amplitude of the sound waves produced is increased.

Taking stock of our investigation of waves, so far as it has now gone, we see—

(i) That a complete wave, or cycle, consists of a crest (push) followed by a trough (pull).
(ii) That the push and the pull are each half-cycles.
(iii) That the frequency is the number of complete waves which occur in a second.
(iv) That the amount of energy expended in producing a wave determines its amplitude. It is a corollary that the larger the amplitude of a wave, the greater is the amount of energy that it conveys: there is clearly more energy in a big push and a big pull than in a small push and a small pull.

So far we have considered one note only: middle C, which has a frequency of 256 cycles a second—256 c/s for short. Every musical note has its own particular frequency. The middle-C string could be tuned to produce C sharp by stretching it a little more tightly (higher frequency), or C flat (B) by reducing its tension and making it vibrate rather more slowly (lower frequency). Musical pitch, then, is purely a matter of sound-wave frequency. The faster the string of a piano, a violin or a harp vibrates, the higher the frequency of the resulting sound waves and the higher the pitch of the note produced. The same is true of the metal of a trumpet or of the column of air in an organ pipe. *Vice versa*, the slower the rate of vibration and the lower the frequency of the sound wave produced, the lower is the pitch of the note. Double the frequency and the note rises an octave in pitch; halve it, and the pitch falls by an octave.

We hear sounds because the vibrations of strings, or metal, or wood, or of the vocal cords, set up waves which travel through the air lying between the source of a sound and the drums of our ears. A wave-crest pushes the ear-drum inwards; the following trough allows it to spring outwards. The result is that the drum of the ear vibrates at the frequency of whatever it may be that gives rise to the sound wave. Impulses at this frequency are conveyed by the aural nerve to the brain, which translates them into the sensation of hearing.

You may wonder why middle C on the piano should sound quite different from middle C as produced by a violin, a flute, a banjo, a cornet or a xylophone. The same note clearly occurs in every case—one instrument can be tuned to the exact pitch of another. But each has its own characteristic *timbre*.

The reason is to be found in the *harmonics*. Strings, metal and wood do not make simply the vibrations corresponding to their natural frequency (that is, the frequency to which they are tuned), but make also a number of subsidiary vibrations. Suppose that a string is tuned to 256 c/s. When it is struck the string makes its FUNDAMENTAL vibrations at 256 c/s; but it also makes HARMONIC vibrations at $2 \times 256 = 512$ c/s (the second harmonic), $3 \times 256 = 768$ c/s (the third harmonic), $4 \times 256 = 1{,}024$ c/s (the fourth harmonic), and so on.

The relative strength of the fundamental and of the various harmonics varies according to the kind of sounding board provided, and it is that difference in the strength of the harmonics which makes the ear recognise the sounds produced by a plucked, scraped or struck string as those characteristic of the piano, the 'cello, the violin, the balalaika, the ukulele, or the harp.

All musical sounds consist of the fundamental plus a number of harmonic frequencies, and it is the balance of these which determines the *timbre*.

The sound wave produced by a simple fundamental vibration has the form seen in Fig. 7*a*. Suppose, now, that the second harmonic (Fig. 7*b*) is also present. The resulting wave may have the form seen in Fig. 7*c*. At one instant both sets of waves rise to a crest and the total energy is that of both added together; at another a fundamental crest coincides with a harmonic trough and the total energy is that of the one subtracted from that of the other; at other instants the two waves are neither in complete alliance nor in entire opposition. Taking all

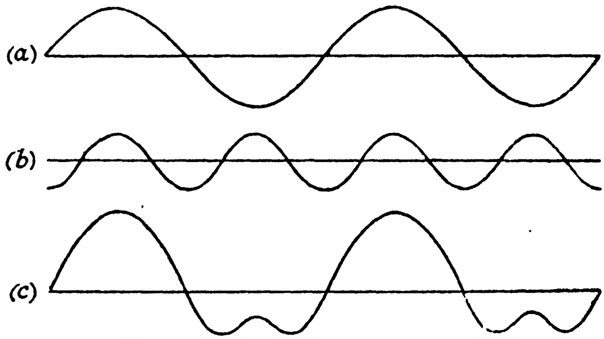


FIG. 7.—Illustrating the complex waveform produced by the combination of a fundamental frequency and its second harmonic. (*a*) Waveform of fundamental frequency; (*b*) waveform of second harmonic, with twice the fundamental frequency; (*c*) waveform produced by the combination of fundamental and second harmonic.

these instants together, the resulting waveform of a fundamental and a second harmonic may become that seen at Fig. 7*c*.

The simple, regular waves seen in Fig. 6 or 7 *a* and *b* are known as SINE WAVES.

You will realise that the waveform produced by a note consisting of a fundamental and many harmonics is a highly complicated one. But no matter how complicated it may be, it can always be simplified into a combination of different sets of sine waves.

The length of a wave and its frequency are interrelated in the closest possible way. Suppose that sound waves with a frequency of 112 c/s are set up at the point A in Fig. 8. They travel outward, we know, at 1,120 feet a second. One second after it leaves A the leading wave will arrive at B, 1,120 feet away. The entire space between A and B is now filled with waves. How many complete waves does it contain? Since B is one second's journey from A and 112 waves occur in a second, there must be 112 between the two points. And if 112 waves cover 1,120 feet, the length of each must be 1,120÷112, or 10 feet.

Thus the length of a wave can always be found if the frequency and the speed of travel or velocity are known.

FIG. 8.—The leading wave of a train of sound waves with a frequency of 112 c/s is at *A*. One second later it has reached point B, 1,120 feet away. The space between A and B is then filled by 112 complete waves. The length of each must be 1,120÷112; or 10 feet.

This is true both of sound waves in air and of the wireless waves which we shall discuss presently.

The symbol for WAVELENGTH is the Greek letter λ (lambda); that for frequency is *f*, and that for velocity *v*. We can now reduce our rule for finding the wavelength to the neat and tidy formula:

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

The calculation works both ways. If we know the wavelength we can find the frequency by dividing the wavelength into the velocity. Giving this a similar tidy form, we have:

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

Let us work out two examples. Middle C, we have said, has a frequency of 256 c/s. The length of the sound waves which produce it is:

$$\frac{1{,}120}{256}\text{ feet}$$
$$=4\tfrac{3}{8}\text{ feet}$$
$$=4\text{ feet }4\tfrac{1}{2}\text{ inches.}$$

What is the frequency of a sound wave whose length is 7 feet?

$$f=\frac{1{,}120}{7}$$
$$=160\text{ c/s.}$$

Conducting a further stocktaking, we can now add some further items about waves to the list of four already made:

(v) Doubling the frequency raises the pitch by an octave. Any increase in the frequency of a sound wave sharpens the note heard. Conversely, a decrease in the frequency makes it flatter.

(vi) A wave of the form seen in Fig. 6 or 7 *a* and *b* is known as a sine wave.

(vii) A harmonic is a multiple of the fundamental frequency.

(viii) A combination of fundamental and harmonic(s) produces a complex waveform.

(ix) If the frequency is known the wavelength can be found by dividing the velocity by the frequency. Conversely, the frequency is the velocity divided by the wavelength.

CHAPTER III

The Microphone

THE next step is to see how sound waves can be transformed into electrical impulses, as they are in both wired and wireless telephony.

The instrument used for the purpose is the MICROPHONE, a simple form of which is seen in Fig. 9. Its chief working part is a thin carbon or metal diaphragm, between the inner face of which and the metal case lies a mass of loosely packed grains of carbon. Carbon is one

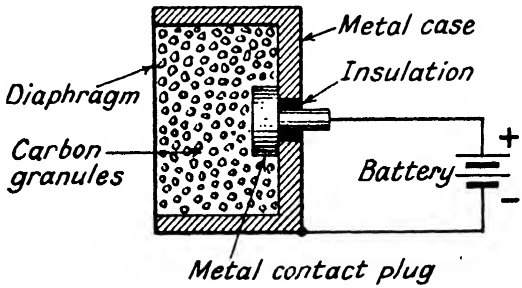


FIG. 9.—Simple form of microphone.

of the substances (the others are mostly metals) which allow an electric current to flow through them and do not offer great opposition to its passage. To understand how the microphone operates it is necessary to know something about an electric current.

An electric current consists of a flow of ELECTRONS, the smallest and lightest bodies known to exist. Each electron may be regarded as being a minute bundle, or "charge," of negative electricity. Electrons are made to flow by the immensely powerful attraction of PROTONS and POSITIVE IONS. The former may be regarded as bundles, or charges, of positive electricity. The positive charge of a proton exactly balances the negative charge of an electron; but a proton weighs nearly 2,000 times as much as an electron.

A normal atom of matter contains exactly as many protons as electrons. The two sets of charges just counterbalance one another and the atom as a whole has no electric charge. But an atom may lose one or more electrons temporarily. In this case the positive charges outnumber the negative, and the whole atom has a positive charge and is known as a positive ion: *a shortage or deficiency of electrons means a positive charge.*

It is also possible for an atom to acquire temporarily one or more extra electrons. When this happens the atom as a whole is negatively charged and is called a NEGATIVE ION: *a surplus of electrons constitutes a negative charge.*

Like charges repel like. A positive ion or a proton repels any other positive ion or proton with enormous force.

Unlike charges attract one another. A proton attracts an electron or a negative ion; a positive ion attracts an electron or a negative ion with the same enormous force.

To be able to flow an electric current must have a continuous conducting path out from the starting point and home again. Such a path is known as a CIRCUIT.

Since the proton and the positive ion are vastly heavier than the electron it is clear that the electrons, and not the much heavier bodies, must move under the force of mutual attraction. Hence an electric current flows from the negative pole of a battery, or other source of current, through the circuit to the positive pole. The idea of a positive current—from positive to negative—was proved to be erroneous many years ago, but it still appears in many school books and textbooks. I do not know why. for it makes the elements of electricity in general and of wireless in particular much more difficult to understand. In this book current is always assumed to flow in the proper way—from negative to positive.

Any reader who would like to read a rather fuller discussion of the electron theory of matter and electricity may find what he requires in my book "Television Simply Explained."

Substances which allow an electric current to flow through them are called CONDUCTORS. All of them offer *some* opposition under normal conditions. The property of opposing the flow of an electric current is termed RESISTIVITY (electrical terms denoting a quality end in -ivity) and the measurable amount of opposition is resistance (electrical terms denoting a measurable quantity end in -ance).

A good conductor has low resistivity: its resistance is small.

Substances which act as barriers to a flow of electric current are known as INSULATORS.

The ideal conductor would have zero resistance; the ideal insulator resistance of infinite value.

Outside the laboratory there are no perfect conductors and no perfect insulators. In practice all conductors present some resistance, tiny though it may be, and no insulator completely bars the flow of some minute amount of current. But the resistivity of a good conductor is very small, whilst that of a good insulator is enormously high.

The magnitude of the current flowing in a circuit is in direct proportion to the electrical pressure driving it and in inverse proportion to the amount of resistance encountered: that is the essence of Ohm's Law, the fundamental law of electric currents.

Electrical pressure is measured in VOLTS (symbol V);

resistance is measured in OHMS (symbol Ω),* and the rate of flow is measured in AMPERES (symbol A).

A pressure which drives a current is known as an ELECTRO-MOTIVE FORCE (E.M.F.)—a force which makes electrons move (symbol E). The symbol for current is I and that for resistance R.

Ohm's Law may be remembered very easily by writing:

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

If any two of the three quantities are known, the third can be found at once: cover up what you want to find and what remains shows you how to find it.

Suppose, for example, that a flashlamp battery with an E.M.F. of 4·5 volts causes 0·25 ampere to flow through the filament of the lamp. What is the resistance of the filament? Cover up R and we are left with $\frac{E}{I}$. Then $4{\cdot}5 \div 0{\cdot}25 = 18$ ohms.

What current flows in a circuit when E=6V and R=12Ω? What current will flow if R is decreased to 6Ω, or raised to 24Ω? In the first case we have $I=\frac{6}{12}=0{\cdot}5A$; in the second $I=\frac{6}{6}=1{\cdot}0A$; in the third $I=\frac{6}{24}=0{\cdot}25A$.

You will see that if the E.M.F. remains constant and the resistance varies, the current will vary proportionately. That is exactly what takes place when sound waves reach the microphone, to which we may now return after this rather long digression.

Examining Fig. 9, you will see that the path for current runs from the negative pole of the battery (note the way

* The Greek letter omega corresponding to a long "o" sound. Pronounced "ōhmĕga."

in which a battery is represented in diagrams) to the metal case of the microphone, with which the rim of the diaphragm makes electrical contact. The path continues from the diaphragm through the carbon grains to the plug, which is insulated from the metal case. From the plug a wire leads to the positive terminal of the battery, thus completing the circuit.

When the microphone is quiescent—that is, when no sound waves are reaching its diaphragm—the grains of carbon touch one another quite lightly. They make poor electrical contact, the resistance is high and the flow of current is small. The crest of a sound wave on reaching the diaphragm pushes it inwards. This causes the carbon grains to be pressed more tightly together. They make better electrical contact with each other, lowering the resistance of the circuit and allowing more current to flow.

The succeeding trough has just the opposite effect. The diaphragm is pulled outward, diminishing the pressure of the carbon grains against one another and making their electrical contact poor. Up goes the resistance and down goes the current.

Hence each crest causes a momentarily increased flow of current and each trough a similar decrease. If crests and troughs occur at a frequency of 256 c/s the current is varied at the same frequency and therefore forms an electrical copy of the sound of middle C. The diaphragm of a good microphone responds to complex sound waves containing fundamentals and harmonics and produces corresponding complex variations of current.

Further, the greater the amplitude of the sound wave the greater are the inward and outward movements of the diaphragm and the greater the variations of the current. The microphone thus gives rise to fluctuations of current which are electrical copies of both the frequency and the amplitude of the sound waves which reach it. Certain "snags," of which we shall see more later, prevent them from being quite perfect copies; but they can be made copies close enough to convey the sounds of speech and music without noticeable unfaithfulness.

The currents involved in microphone circuits are actually so small that the ampere would be an inconveniently large unit of measurement. Small currents are measured in milliamperes (thousandths of an ampere, symbol mA) or microamperes (millionths of an ampere, symbol μA). The letter μ is the Greek m and is pronounced "mew." We shall find the prefixes milli- and micro- used with the meanings "thousandth" and "millionth" respectively in many other units of electrical measurement.

The microphones used in telephones are similar to that shown diagrammatically in Fig. 9; but those in use in broadcasting studios have to handle far greater ranges of sound-wave frequencies and they are of considerably more complicated design.

CHAPTER IV

Telephone Receiver and Loudspeaker

THE microphone, as we have seen, translates sound waves into electrical impulses. The function of the telephone receiver and of the loudspeaker is to re-translate the electrical impulses into sound waves. Before we can see how each does its work we must see something of a subject closely allied with electricity: magnetism. Magnets are important working parts of both telephone receiver and loudspeaker.

Everyone is familiar with the permanent magnet in either " bar " or " horseshoe " form. It consists of a piece of hard steel or a special alloy. One of its peculiar

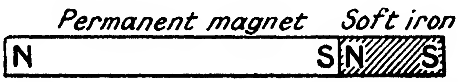


FIG. 10.—A piece of soft iron placed in contact with one pole of a permanent magnet becomes itself a magnet so long—but only so long—as the contact is maintained.

attributes is that, once magnetised, it retains the power of attracting iron, steel and certain other substances. Actually the term " permanent magnet " is almost as much a misnomer as " permanent wave." A permanent magnet is liable to lose some of its magnetism as time goes by and it can be quickly demagnetised by heating or hammering. For practical purposes, though, a permanent magnet retains its magnetism more or less indefinitely, unless it is subjected to ill treatment.

It is impossible to make a permanent magnet from a piece of soft iron. Place a piece of soft iron in contact (Fig. 10) with one pole of a permanent magnet and it becomes a magnet by INDUCTION—but only so long as the contact is preserved. Separate the two and the piece of soft iron is no longer a magnet.

The simplest way of determining whether or not a piece of metal is a magnet is to bring it near the needle of a compass. The latter is itself a magnet. It indicates, not true, but magnetic north (the geographic and magnetic north poles of the earth are a long way from one another), because one end of it is attracted by the earth's magnetic north pole. Every magnet has two POLES, which are termed north (really north-seeking) and south. A bar magnet, suspended by a fine thread, or kept afloat

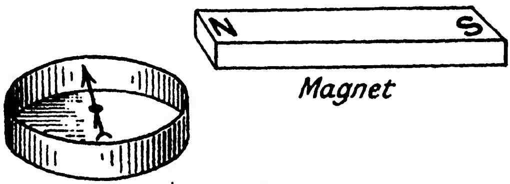


FIG. 11.—The N-pole of a compass needle is repelled by the N-pole of a magnet.

by corks on the surface of water, turns until its N-pole is pointing to magnetic north.

In magnetism, as in electricity, " unlikes " attract one another, whilst " likes " exert mutual repulsion. It is the repulsion between like poles which provides a means of knowing whether a piece of metal is or is not magnetised. That the N-pole of a compass needle is attracted by it is no test. Being itself a magnet, the needle attracts and is attracted by any piece of iron or steel in its neighbourhood; the needle is light and free to move on its pivot. It is therefore readily deflected *towards* any unmagnetised piece of iron or steel brought near it. If the piece of iron or steel is magnetised, one end of it (its N-pole) will drive the N-pole of the compass needle *away*, as shown in Fig. 11, whilst its other end will similarly *repel* the S-pole of the compass needle.

When an E.M.F. is applied to a conductor, current does not immediately reach its full, steady value. The delay may be very small—less, often, than a millionth of a second (microsecond)—but it is there all the same. First of all a MAGNETIC FIELD must be built up round the conductor. This field forms a kind of invisible sleeve (Fig. 12) round the conductor. It can be regarded as starting at the centre of the conductor and beginning to expand the instant current is switched on. Only when the field is completely developed is current free to flow at its full value.

When current is switched off the flow does not imme-

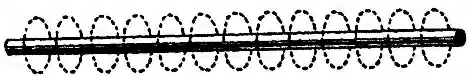


FIG. 12.—A conductor carrying current is surrounded by a magnetic field, which forms a kind of invisible sleeve round it.

diately fall to zero. The energy lent when the magnetic field is built up is repaid after switching off, and this repayment keeps a flow of current going for a short time whilst the magnetic field is collapsing.

An almost exact analogy is to be found in a canvas fire hose lying flat on the ground. When the hydrant to which it is connected is turned on water does not immediately spout from the nozzle at the other end. Before it can do so freely energy must be lent to expand the walls of the hose into the round. Turn off the hydrant and the water does not immediately cease to flow from the nozzle. The energy lent is repaid as the walls of the hose collapse and maintains some flow of water until they have fallen completely flat.

That there is a magnetic field surrounding a conductor such as a wire through which current is flowing is readily demonstrated by means of a compass, the needle of which is deflected as it is brought near the wire.

If the wire is wound into a coil (Fig. 13) the effect becomes much more marked. The compass shows that one end of the coil is a N-pole and the other a S-pole. A still more marked effect is produced if the coil is given a CORE of soft iron, which has the effect of concentrating the magnetic field and increasing its density. The strength of an ELECTRO-MAGNET depends on the number

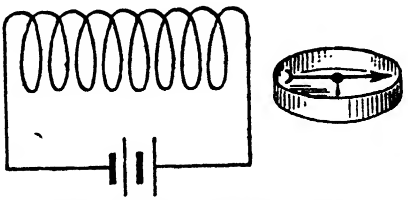


FIG. 13.—A coil carrying current becomes a magnet, with N and S poles.

of turns in the coil and the amount of current flowing through them.

An electro-magnet behaves like any other magnet so long as current is flowing through the turns of its coil; but switch off the current and it ceases to be a magnet. Increasing the current makes it a more powerful magnet; a decrease in the current reduces its magnetic power.

Just like a permanent magnet, an electro-magnet has its N and S-poles. Which end is the N and which the S depends upon the direction in which current is flowing round the turns of wire forming its coil. Reversing the direction of current reverses the polarity; that is, the end which was a N-pole with current flowing in one direction becomes a S-pole if the direction of the current is changed.

Fig. 14 shows some of the parts of the telephone receiver at *a* and *b*, and a section of the complete instrument at *c*. The ring-shaped permanent magnet *a* has soft iron L-shaped pole-pieces fixed to it. Magnetised by induction, these become themselves N- and S-poles. Over the pole-pieces two bobbins are slipped, each wound

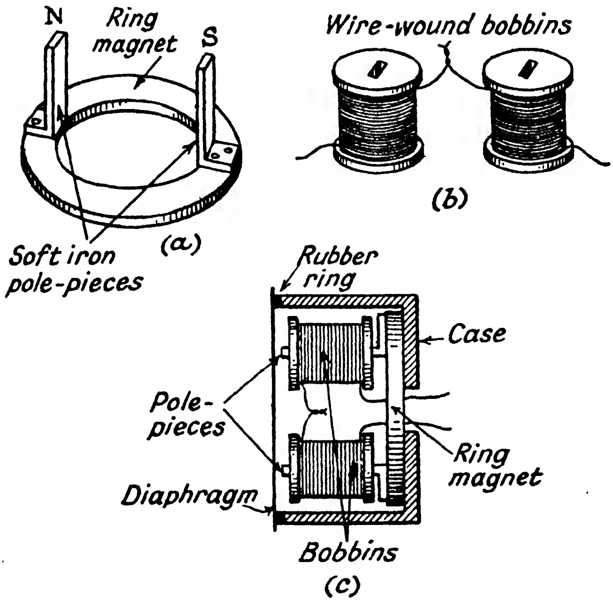


FIG. 14.—The telephone receiver—cap not shown.

with many turns of fine insulated wire. The two windings are connected together as shown at *b*. The ring magnet, carrying the pole-pieces and the bobbins, is attached to the base of the case. The front of the case is closed by a screw-on cap (not shown in the drawing) which clamps the rim of the metal diaphragm against the rubber cushioning ring.

The electrical impulses produced by the microphone are originally variations in the strength of a DIRECT CURRENT (abbreviation D.C.)—a current, that is, which flows always in the same direction. A sound wave crest reaching the diaphragm of the microphone gives rise, as we have seen, to an increase above the normal rate at which current flows through the microphone; a sound wave trough causes current to fall below its normal rate. A component called the TRANSFORMER, of which

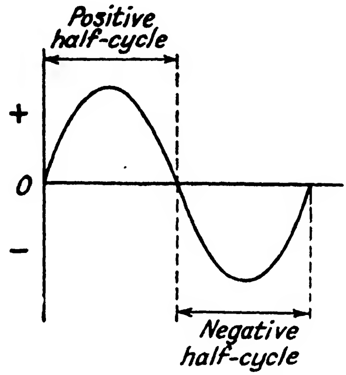


FIG. 15.—An alternating current increases in what we may call a positive direction, reaches its maximum and then falls to zero. This process forms the positive half-cycle. The negative half-cycle consists of a rise to maximum in the opposite (negative) direction, followed by a return to zero.

we shall see more presently, converts these rises and falls of current into true pushes and pulls.

Current in the transformer secondary circuit is zero so long as the microphone diaphragm is at rest. The change in the flow of current through the microphone produced by the arrival of the " push " half-cycle of a sound wave causes the current in the transformer circuit to rise from zero to a maximum value and then to fall back to zero. The rise and fall are rhythmic and we can represent them by a curve exactly similar to that which depicts the " push " half-cycle of the sound wave.

We have, in fact, the " push " half-cycle of a wave of electric current (Fig. 15), and we may conveniently call this a POSITIVE HALF-CYCLE.

Next instant the decrease in current in the microphone circuit causes the current in the transformer circuit to make a fresh start. It had reached zero. It can't go any further in the original direction, so it changes direction and increases to the maximum " pull " of a NEGATIVE HALF-CYCLE as shown in Fig. 15.

A current which changes in this way and consists of pushes followed by pulls, or of positive half-cycles followed by negative half-cycles, is known as an ALTERNATING CURRENT (abbreviation A.C.). We shall see a good deal about such currents a little later. Meantime it is enough to regard them as waves of electron flow. These waves have their frequencies and their wavelengths and obey the rules which we discussed in Chapter II. The standard frequency for A.C. mains supplies in this country is 50 c/s, and the average velocity of current through cables and wires may be taken as 200,000,000 yards a second. Remembering that $\lambda=\frac{v}{f}$, you may amuse yourself (and perhaps surprise yourself) by working out the approximate length of the waves of the current, supposing that it is A.C., 50 c/s, which lights your home.

Now consider what happens when a positive half-cycle of current reaches the bobbins of the telephone receiver illustrated in Fig. 14. The windings of the bobbins are so arranged that a flow of current through them in one direction makes the outer end (the end nearest the diaphragm) of the bobbin surrounding the north pole-piece a N-pole and the same end of the bobbin surrounding the south pole-piece a S-pole.

The result is that electro-magnetism is added to induced magnetism. The total magnetic force is increased and the diaphragm is pulled inwards.

When the direction of current is reversed in the following negative half-cycle the polarity of the electro-magnetism is also reversed. The bobbin on the N-pole-piece exerts a force in opposition to that of the pole-piece itself and the same happens with the second bobbin and the other pole-piece. The total magnetic force is thus reduced, with the result that the diaphragm is less strongly attracted and moves outwards by virtue of its own natural springiness.

The movements of the diaphragm of the receiver alternately compress and rarefy the air in contact with it. Sound waves are thus set up which travel to the ear of a listener and convey intelligence to him.

The whole series of operations may be summed up as follows:

(1) Sound wave crests and troughs alternately press the diaphragm of the microphone inwards and pull it outwards.
(2) The movements of this diaphragm cause the internal resistance of the microphone to vary.
(3) Fluctuations in the current flowing through the microphone thus occur which are electrical copies of the sound waves.
(4) In the transformer circuit, which delivers the current to the telephone line wires, the fluctuations of current are converted into A.C. with positive and negative half-cycles.
(5) In the receiver the arrival of a positive half-cycle causes an inward movement of the diaphragm; an outward movement results from the arrival of a negative half-cycle.

(6) The receiver diaphragm thus moves to and fro "in step" with that of the microphone.

(7) The movements of this diaphragm set up sound waves which are copies of those reaching the microphone.

They are not perfect copies, for, as has been hinted,

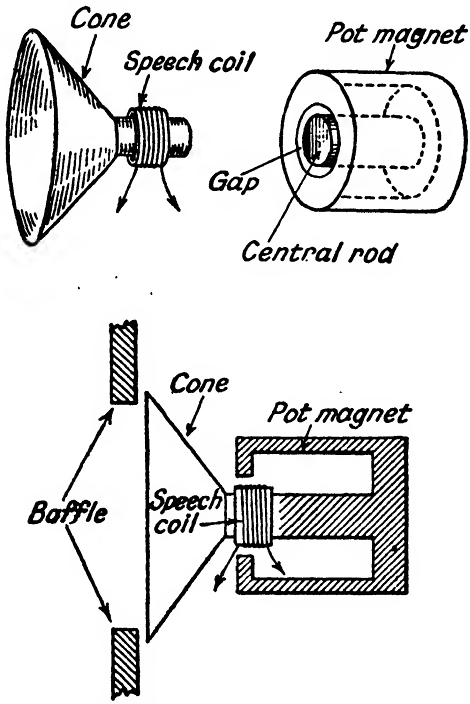


FIG. 16.—Illustrating the principle of the moving-coil loudspeaker.

there are certain snags; but they are sufficiently good to convey intelligible speech. The copies produced by the wireless loudspeaker are much better. Perfection is, so far as we now know, unattainable; but a really good wireless receiver used in conjunction with a first-rate loudspeaker can give reproduction of both speech and music which is so good that a critical ear finds little to cavil at in it.

The earliest loudspeakers were simply telephone receivers of the type illustrated in Fig. 14 with large and queerly shaped horns attached to them. To-day the moving-coil loudspeaker is used in the vast majority of wireless sets. Its principle is illustrated in Fig. 16.

A magnet is again employed, but this time it is of quite a different shape. It is made, as the drawings show, in the form of a pot with a central rod. The rim of the pot forms one pole of the magnet and the outer end of the rod the other. The magnet may be of the permanent type, as shown in the drawing, or it may be an electro-magnet. As the magnet is a powerful one there is an intense magnetic field across the gap. Into this gap fits the neck of a light cone, made of paper or other material, which carries the SPEECH-COIL. The cone is so centred that it is clear of the rod and the rim and is free to move to and fro in the gap.

The output current of the wireless receiver is fed to the speech-coil. This current consists of pushes, positive half-cycles and pulls, or negative half-cycle. You will remember that a coil through which a current passes becomes an electro-magnet, and that which end of it is the N-pole and which the S-pole depends on the direction of the current. As the current through the speech-coil changes direction each half-cycle the inner end of the coil is alternately a N-pole and a S-pole. Magnetic fields exercise attraction or repulsion on one another according to their directions. Hence during one half-cycle the speech coil, taking the cone with it, is pulled inwards and during the next it is pushed outwards.

Each complete cycle of current thus causes the cone to perform an outward and an inward movement. The one compresses and the other rarefies the surrounding air and the result is a sound wave. The frequency of the cone's movements is the same as that of the current reaching the speech coil. The distance which it moves inwards or outwards depends on the amplitude of the cycles of current in the speech-coil. The greater these movements, the greater the amplitude of the sound-waves produced.

The cone thus responds both to the frequency and to the amplitude of the actuating currents, and the sound waves set up by it are good copies of those occurring in the studio. They would be perfect copies were it not for the snags that have been hinted at previously.

A loudspeaker containing a moving cone requires what is known as a BAFFLE if it is to give reasonably good reproduction. This may be a board, a case, or the cabinet of the wireless set. Its purpose is to prevent sound waves from travelling round from the front to the back of the cone.

Think of what is happening as the cone moves outwards. In front of it is compressed air; behind it is rarefied air. Since nature abhors a vacuum, the compressed air in front would rush, if it were not prevented from doing so, round to the back to neutralise the semi-vacuum caused by the rarefaction there. In other words, the pushes in front of the cone would cancel out the pulls behind it and no sound waves would be set up. This effect will clearly be most complete if the movements of the cone are slow, as they are on low frequencies; for there is then plenty of time for the pressures in front to travel round and annul the rarefactions behind.

You can easily satisfy yourself of the truth of this by removing a receiving set with a built-in loudspeaker from its cabinet. Reproduction at once becomes " tinny," and there is an entire absence of bass owing to the cancellation of the low-frequency sound waves which produce the bass.

CHAPTER V

More About Waves: Alternating Currents

A DOUBLE-ACTING steam-engine, such as that seen in railway locomotives, does its work in the way shown in Fig. 17 *a* and *b*. During the outward stroke steam pressure forces the piston forwards and a push is applied

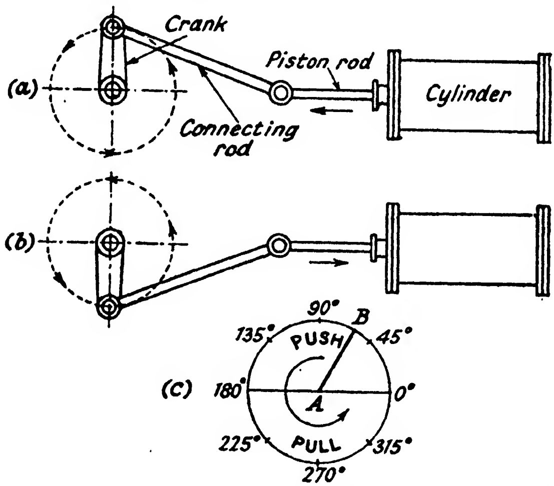


FIG. 17.—A double-acting steam-engine does its work by applying alternate pushes (*a*) and pulls (*b*) to the crank. The cycle of operations could be represented as at (*c*).

via piston-rod and connecting rod to the crank. Steam pressure forces the piston in the opposite direction during the inward stroke, causing a pull to be applied to the crank. The crank is thus given a rotary motion and the whole process is CYCLIC, being repeated over and over again.

We might represent the process diagrammatically, as in Fig. 17*c*, as the rotation of the radius (AB) of a circle. To make a complete revolution the radius travels through 360° of angle. We can say that in the position shown in Fig. 17*a* it has reached 90° and in Fig. 17*b* 270°. The position of the radius AB in Fig. 17*c* is at about 60°. Similarly, we can indicate any position of the crank as so many degrees from the starting point, or zero, which it is convenient to place at "three o'clock," as indicated in Fig. 17*c*.

To depict the cyclic succession of pushes and pulls in the way shown in Fig. 17*c* is a rather unsatisfactory business. Such a diagram, for instance, can show only one cycle. Worse than that, it gives no information at all about the strength of the push or the pull exerted at any instant on the crank in the course of a revolution.

Supposing that you wanted to exert the maximum possible power on a crank, such as the handle of a windlass or a crane, where would you arrange it to be before putting out your strength? Clearly at 90° (Fig. 17*a*) for a push, or at 270° (Fig. 17*b*) for a pull. If it was at either 0° or 180° no amount of pushing or pulling would have any effect at all. At 10° your push would be a little more productive of results and its effectiveness would be greater and greater as the angle of revolution increased to 90°.

At that point the maximum would be reached. Thereafter the effectiveness of the push would decline, until, at 180°, it became zero. The succeeding pull would have no effect at 180°, but would become more and more potent until the crank reached 270°, at which point it would exercise its greatest effect. After that it would grow less and less effective, sinking to zero as the crank completed its revolution by registering 360° of angular movement.

Similarly, sound waves, wireless waves and alternating currents are cyclic, repeating again and again the process of increasing from zero to maximum in one direction (which we may call positive), falling to zero, increasing

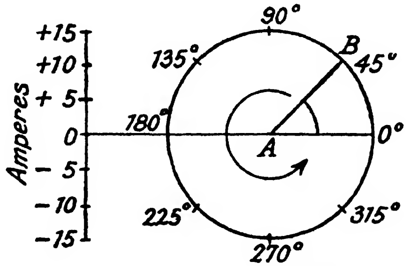


FIG. 18.—One cycle of an alternating current might be depicted in this way.

to maximum in the opposite (negative) direction, and returning to zero.

One cycle of an alternating current with a maximum or PEAK VALUE of 15 amperes could be depicted in the

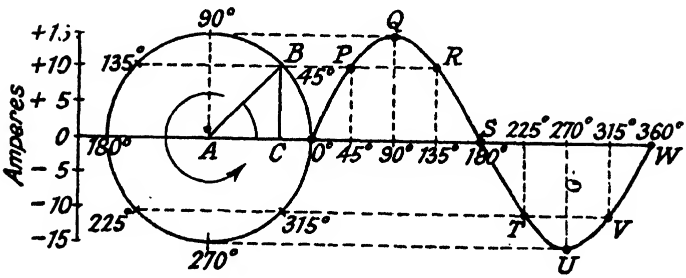


FIG. 19.—By drawing this curve we obtain a much better picture of what takes place.

way shown in Fig. 18. A much better way, however, of showing what happens is seen in Fig. 19. The diameter of the circle seen in Fig. 17 or Fig. 17*c* is produced to the right and marked off into 360 equal divisions representing degrees. A radius AB is again imagined to rotate anticlockwise. In the drawing AB has reached 45°. A horizontal straight line is ruled from this point, and at the point P, where a vertical straight line from the 45° mark on the produced diameter cuts it, a dot is made. Other dots are made corresponding to 90°, 135°, 180°, 225°, 270° and 315°. A curve drawn so as to pass through all the dots has the form seen in the drawing.

You will find it interesting to make a drawing of your own and, with the aid of a protractor, to make an accurate plot for each 5° of the complete cycle.

Similar curves give the best possible representation of events at any instant in a cycle, whether it be of an engine, of a sound wave, of a wireless wave or of an alternating current. That is why they are used to depict such things.

Fig. 19 represents one cycle of A.C. rising from zero to a positive peak of 15 amperes, falling to zero, reaching a negative peak of 15A, and coming back to zero. (This, by the way, is just a little more than the current that does flow from 200V A.C. mains through a two-bar electric fire.)

With the aid of a curve like that of Fig. 19 we can determine the value of the current at any moment. That value is the proportion (represented by the height BC in Fig. 19) of the maximum current (represented by the radius of the circle) reached at a particular moment. That moment may be indicated by the angle through which the imaginary radius has passed since it began its journey from zero.

If you have not forgotten your trigonometry* you will see that that proportion, or ratio, is the sine of the angle and

* *For mathematicians only.*

$$I_{inst} = I_{max} \sin \theta$$

where I_{inst} is the instantaneous current, I_{max} the maximum current, and θ the current angle (BAC in Fig. 19).

$$\text{And } \theta = \omega t$$

where $\omega = 2\pi f$, and t = time in seconds.

$$\text{Hence } I_{inst} = I_{max} \sin \omega t.$$

will realise at once why we speak of SINE WAVES or SINUSOIDAL CURRENTS. If you have forgotten what you knew of trigonometry it does not matter so long as you can recognise the curve representing a sine wave or a sinusoidal current.

Just one more point about these curves: whether they depict sound or wireless waves or alternating currents. The angle is simply a measure of the time that has elapsed at any instant since the wave or current started to rise from zero in a positive direction.

Take for example standard domestic A.C. with a frequency of 50 c/s. The whole cycle of 360° of angle occurs in $\frac{1}{50}$ second. Thus 45° represents one-eighth of a cycle, or $\frac{1}{400}$ sec.; 90°, one-quarter cycle, or $\frac{1}{200}$ sec.; 135°, three-eighths of a cycle, or $\frac{3}{400}$ sec.; 180°, one half-cycle, or $\frac{1}{100}$ sec.; 225°, five-eighths cycle, or $\frac{5}{400}=\frac{1}{80}$ sec.; 275°, three-quarters of a cycle, or $\frac{3}{200}$ sec.; and 315°, seven-eighths of a cycle, or $\frac{7}{400}$ sec. The cycle is completed in $\frac{8}{400}$, or $\frac{1}{50}$ sec.

You will find it instructive and useful to work out for yourself what similar angles represent in the way of time for sound waves with a frequency of 256 c/s and wireless waves of frequencies 400 kilocycles a second (a kilocycle, abbreviation kc/s, is 1,000 cycles a second) and 1,000 kc/s.

Wireless waves, like those of heat, light and X-rays, travel through the ether at the unvarying velocity of 186,200 miles a second.* The lengths of wireless waves are always expressed in metres or fractions of a metre, and their velocity is 300,000,000 metres a second. Hence for them the formulæ given in Chapter II become:

* This is a round figure, sufficiently accurate for general wireless purposes, though not for those of precision radar. Actually, there is a small difference between the velocity of wireless waves through a vacuum and that through air of average density.

$$\lambda = \frac{300,000,000}{f} \text{ metres}$$

$$\text{or,} \quad f = \frac{300,000,000}{\lambda} \text{ c/s}$$

To return to alternating currents, how are we going to find an effective value for a current which behaves like that depicted in Fig. 18? With D.C. matters are straightforward, for if the E.M.F. and the resistance remain steady, the current must have a constant value in accordance with Ohm's Law. But A.C. of the kind illustrated, varying from 0A to +15A and from 0A to − 15A in a fraction of a second, is a very different affair.

The best method of determining the effective value is to make A.C. and D.C. both do the same task, such as maintaining one element of an electric fire at a predetermined temperature. When this is done it is always found that to produce the same effect as D.C., the peak flow of A.C. must be 1·414 times as great. Thus to bring an electric fire to the temperature produced by 10A of D.C. a peak flow of 14·14A is required. In other words, the effective value of A.C. is $\frac{1}{1 \cdot 414}$, or 0·707 times its peak value. This is known as the ROOT MEAN SQUARE, or R.M.S. value,* and A.C. measuring instruments in general use record such values. We can put this concisely in the form:

* The effective A.C. voltage or current is found by squaring the peak value, taking the mean of this and then extracting the square root. Hence the term R.M.S.

$$\text{If } E_{max} = 325 \cdot 2\text{V}$$

$$E_{RMS} = \sqrt{\frac{325 \cdot 2^2}{2}}\ \text{V}$$

$$= 325 \cdot 2 \times \frac{1}{\sqrt{2}}\ \text{V}$$

$$= 325 \cdot 2 \times 0 \cdot 707\text{V}$$
$$= 230\text{V}$$

$$I_{RMS} = I_{MAX} \times 0{\cdot}707$$
$$\text{or, } I_{MAX} = I_{RMS} \times 1{\cdot}414$$

A.C. E.M.F.s have similar cyclic variation and their R.M.S. values are measured. Unless the contrary is expressly stated, the volts and amperes of A.C. always mean R.M.S. volts and R.M.S. amperes.

If two currents (or an E.M.F. and a current, or two

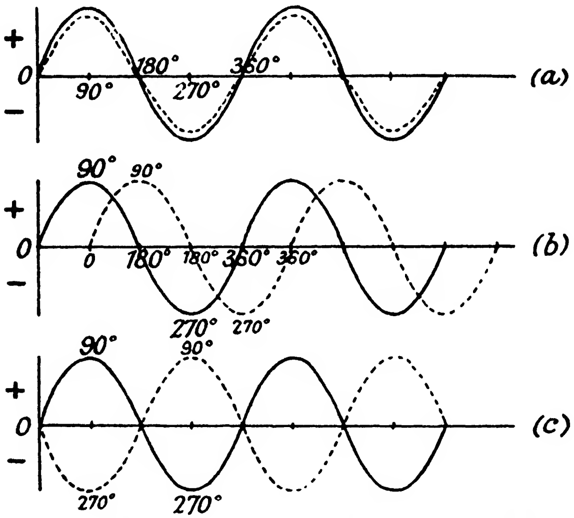


FIG. 20.—At (*a*) the two currents are "in step," or in phase. At (*b*) the current indicated by the heavy line is leading by 90° on that shown by the dotted line. The currents are 90° out of phase. At (*c*) the two currents, exactly "out of step," are said to be 180° out of phase.

sets of waves) rise and fall "in step" with one another, as seen in Fig. 20*a*, they are said to be IN PHASE. The two seen in Fig. 20*b* are not in phase. That indicated by the continuous line has reached 90° by the time that shown by the dotted line begins to rise. It is in fact always 90° ahead. The two are said to be 90° out of phase and that shown by the continuous line to be leading by 90°. At *c* the two are exactly " out of step ": at any instant the angle between them is 180° and they are said to be 180° out of phase.

When an alternating current is applied to a pure resistance, as it is in heating the wires of an electric fire or the filament of a lamp, the E.M.F. and the current are in phase, as might be expected, and the current obeys Ohm's Law. Thus 200 volts applied to an electric fire element with a resistance of 40 ohms drives $200 \div 40$, or 5, amperes of current through it. In the process work is done. The rate at which work is done is measured in WATTS (symbol W), and for D.C. it is found by multiplying volts by amperes. There is another way of finding the power dissipated in a circuit. We have seen that $W = E \times I$. By Ohm's Law $E = I \times R$.

Hence $$W = I \times I \times R.$$
$$= I^2R.$$

We shall see presently why $W = I^2R$ is always used for expressing the power expenditure in A.C. circuits. In the above example we have $W = 5^2 \times 40 = 1{,}000$W, or 1 kilowatt (kW).

But if we apply A.C. to a coil the state of affairs is very different. We have already seen that a direct current cannot reach its full rate of flow through a wire until the surrounding magnetic field has been built up. Nor can it cease to flow until the field has collapsed. The field opposes the start of a current flow and opposes its cessation. It opposes, in fact, any change in the rate of flow: the current cannot increase until an appropriate growth of the field has taken place; if it tries to decrease, energy repaid by the partial collapse of the field tends to maintain the rate of flow.

Thus, though the full E.M.F. is applied at the moment of switching on, there is a time-lag before the full current flow is reached. If the E.M.F. is reduced there is again a time-lag before current ceases. If any change is made in the E.M.F. the corresponding change in current occurs a little later.

The property of conductors which opposes any change in the rate of flow of current is called INDUCTIVITY; it is much more marked if the wire is wound into a coil and more marked still if the coil is given an iron core. The growth or collapse of the magnetic field when a current is changing in an inductive circuit opposes the change by what is in effect an induced counter-E.M.F. This E.M.F. is superimposed on that in the circuit, but is not in step with it. The greater the rate at which the current is changing, the stronger is the induced E.M.F. It depends also on the way in which the coil is wound, more turns causing a greater E.M.F., or giving the coil greater INDUCTANCE. An iron core also increases the inductance (symbol L). The unit of inductance is the henry (symbol H). When a coil has an inductance of one henry an E.M.F. of one volt is induced when the current changes at the rate of one ampere in one second. The induced E.M.F. opposes either an increase or a decrease in the rate of flow of current.

A coil designed to possess a given amount of inductance is properly known as an INDUCTOR, though in practice it is usually referred to as a tuning coil or as a choke.

If a D.C. E.M.F. is applied to an inductor no opposition is offered to the flow of current (except by the resistance of the wire of the turns) once the field has been built up and the rate of flow has reached its steady value. But A.C. has never a steady value; it is always changing—either rising or falling—and the inductance is always opposing those changes. We have seen that the current changes must lag behind the changes in E.M.F.; in an A.C. circuit containing inductance and negligible resistance the lag is 90°. In Fig. 20*b* the continuous line would represent the E.M.F. and the dotted line the current in such a circuit. Any resistance in the circuit tends to reduce the current lag: the higher the resistance, the smaller the lag.

An inductor, besides opposing any change in the rate of flow of alternating current, also opposes the effective, or R.M.S., rate of flow. This property of opposition is called REACTIVITY, and every inductor displays a definite amount of REACTANCE (symbol X), which is

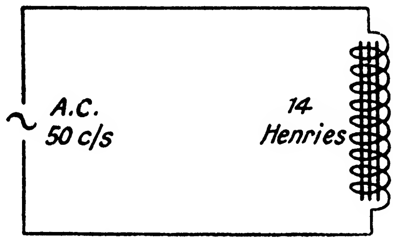


FIG. 21.—If A.C. at 50 c/s is applied to an inductor of 14 henries, the reactance is 4,400 ohms.

measured in ohms. The reactance of an inductor is $2\pi fL$, where π is a constant which, for practical purposes, may be taken as $\frac{22}{7}$; f is the frequency of the current, and L is the inductance of the circuit.

If A.C. 50 c/s is applied (Fig. 21) to an inductor of 14H, the reactance is:

$$2 \times \frac{22}{7} \times 50 \times 14 = 4{,}400\ \Omega$$

The current driven by an E.M.F. of 200V is:

$$\frac{200}{4{,}400} = \frac{1}{22}\ \text{A}$$

There is one great difference between A.C. or D.C. driven through a pure resistance and A.C. driven through a reactance. In the former case power is dissipated or spent; in the latter it is merely lent and paid back rhythmically: the energy put into building up the magnetic field whilst A.C. rises from zero to positive maximum is repaid during its fall from positive maximum to zero; there is a similar repayment of the energy put into building up the magnetic field whilst A.C. rises from zero to negative maximum. Thus if A.C. could be applied to a circuit containing pure reactance and no resistance there would be no dissipation of power whatever. Actually any conductor—and you cannot have a circuit without conductors—must contain some resistance, however small, and there must always be some expenditure of power when A.C. flows in a circuit. The work done in driving

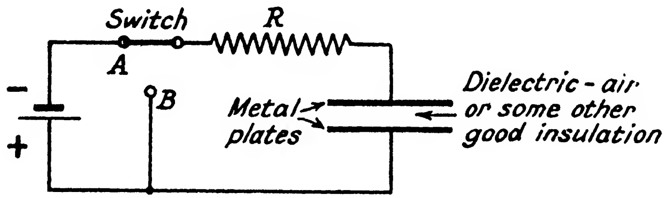


FIG. 22.—Illustrating the action of the capacitor, or condenser.

current through resistance constitutes the sole expenditure of power in an A.C. circuit—assuming, of course, that this includes nothing in the nature of a motor. You will see now why I^2R is used to express A.C. power expenditure.*

By now you will have become sufficiently familiar with the -or, -ivity, -ance series to realise that a component possessing the quality of reactivity must be a reactor. An inductor is one type of reactor. There is another, the component properly called a CAPACITOR, but perhaps better known by its older name of CONDENSER.

A capacitor (Fig. 22) may consist of two flat plates of

* See Appendix A.

metal, placed opposite one another and separated by air or some other good insulator. The insulating separator is known as the DIELECTRIC. Suppose that the switch is turned to position A in Fig. 22, connecting the cell through the resistor R to the capacitor. The applied E.M.F. of the cell causes electrons to flow to the upper plate and each electron arriving on this plate is counterbalanced by a positive ion on the lower. A stream of electrons is a flow of current. Hence current flows into the capacitor and continues to do so until the attraction between the increasing numbers of electrons and positive ions—surplus of electrons on the upper plate, electron deficiency on the lower—has built up an E.M.F. equal to that of the cell. Current then ceases to flow and the condenser is said to be charged.

In this state the dielectric is under strain owing to the attraction between the surplus of electrons on one plate and the surplus of positive ions on the other: an ELECTRIC FIELD, or area of strain, exists between the two plates. If the difference of potential between the two plates is made sufficiently great the dielectric may break down under the strain. Electrons rush through it from the negative to the positive plate. This may not ruin the capacitor if the dielectric consists of a self-repairing material, such as air or oil; but if the dielectric is a solid, such as paper or mica, a breakdown causes punctures which end the useful life of the component.

Now throw the switch to position B. The cell is put out of action and a path is provided from the upper plate with its electron surplus to the lower with its electron deficiency. There is a rush of electrons through R and the conductors to the lower plate, where they neutralise the positive ions. When this process is complete the condenser is discharged—there is no longer any E.M.F. between its plates.

Next, imagine the filament of a lamp connected, as in Fig. 23, to a source of A.C. with a capacitor in circuit. The successive positive and negative half-cycles have the effect of alternately charging the condenser in one direction, discharging it, charging it in the opposite direction, and again discharging it. At one instant electrons travel towards the plate marked *b* and build up a surplus there; at the next they rush from *b* to *a*, as discharge takes place. Then *a* develops an electron surplus, followed by a rush of electrons in the opposite direction during discharge. All these electrons travel through the filament of the lamp,

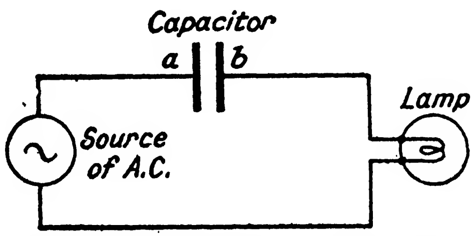


FIG. 23.—If a source of A.C. is connected through a capacitor to a lamp, the filament lights up.

and the passage of the current which they form causes it to become so hot that it glows brightly.

The net result is that the lamp lights up and continues to glow so long as A.C. is applied to the circuit. The current does not in fact pass through the capacitor, but the results are exactly the same as if it did. Hence it is convenient to regard A.C. as actually passing through capacitors in any circuit to which it is applied.

The unit of capacitance or of the electrical "size" of capacitors is the farad (symbol F); this, however, is far too large for practical purposes, and in wireless we always use the microfarad (symbol $\mu F) = \frac{1}{1,000,000}$ F, or the micro-microfarad (symbol $\mu\mu F$) $= \frac{1}{1,000,000,000,000}$ F.

The term picofarad (symbol pF) is often used nowadays instead of micro-microfarad.

Remember that in all formulæ C (the symbol for capacitance) is in farads unless the contrary is expressly stated.

We have seen that current must flow into a capacitor before a difference of potential can exist between its plates. Hence, when A.C. is applied to a capacitor, the current leads on the E.M.F. The lead, if resistance in the circuit is negligible, is 90°. This is precisely the opposite of what happens in a circuit containing an inductor with negligible resistance, where, as we have seen, the current lags by 90° on the E.M.F.

The reactance of a capacitor is $\frac{1}{2\pi fC}$. Suppose that A.C. at 50 c/s is applied to a condenser of 1 μF, the reactance is:

$$\frac{1}{2 \times \frac{22}{7} \times 50 \times \frac{1}{1,000,000}}\Omega$$

$$= \frac{7 \times 1,000,000}{2 \times 22 \times 50}\ \Omega$$

$$= 3,182\Omega$$

Again there is no expenditure of power, provided that the resistance of the conductors is negligible. The energy lent for building up the electric field during the rise to maximum of a positive half-cycle is repaid during the subsequent fall to zero. In the negative half-cycle events are similar. If there is resistance, the power expended is again I^2R.

You will see that there are two kinds of reactance: inductive, where the current lags 90° on the E.M.F., and capacitative, where the current leads 90° on the

E.M.F. Inductive reactance is usually indicated by the symbol X_L, and capacitative reactance by the symbol X_C.

Every circuit must actually contain resistance, inductance and capacitance. Any conductor must display *some* resistance to the passage of A.C., and, no matter how short or how nearly straight it may be, it must exhibit in *some degree the phenomenon of inductance, for, however feeble the current it carries, the surrounding magnetic field is there to oppose any change in its rate of flow.* Again, electric fields are bound to exist between any two parts of a circuit (such as the "out" and "home" conductors) across which there is a difference of electric potential or pressure. The net opposition to the passage of A.C. is a combination of resistance, inductance and capacitance which constitutes IMPEDANCE, symbol Z.

A little thought will show that with a given value of inductance, the higher the frequency, the greater is the reactance. Thus if in the example given on page 47 the frequency is 1,000 c/s instead of 50 c/s, the calculation becomes:

$$X_L = 2 \times \frac{22}{7} \times 1{,}000 \times 14\Omega$$
$$= 88{,}000\Omega.$$

At 10,000 c/s X_L is 880,000Ω; at 1,000,000 c/s (or 1 megacycle a second, symbol Mc/s), 88,000,000Ω, or 88 megohms (symbol MΩ). Such an inductor would offer to D.C. no more opposition than that of the actual resistance of its windings. An inductor may thus be used to offer trifling opposition to the passage of D.C. and enormous opposition to the passage of A.C. An inductor used in this way is called a CHOKE. It may be, and often is, used in the wireless set to sort out D.C. from A.C. by offering an easy path to the former and an almost insuperable barrier to the latter.

On the other hand, X_C decreases as the frequency rises. If in the example on page 52 the frequency is 1,000 c/s instead of 50 c/s, X_C drops from 3,182Ω to 159·1Ω. At 10,000 c/s it is 15·91Ω, and at 1,000,000 c/s 0·1591Ω.

A capacitor may also be used to sort out D.C. from A.C. After the short-lived charging current there can

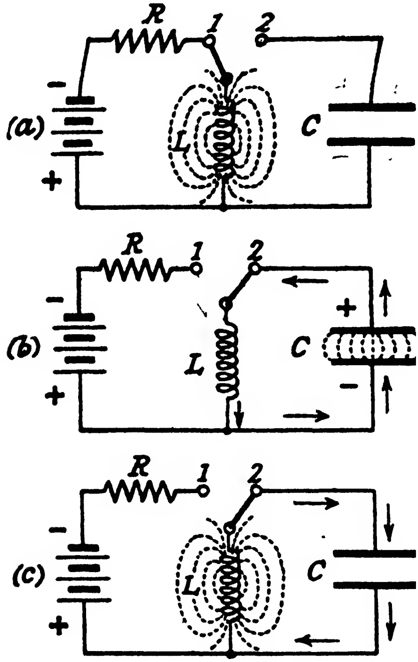


FIG. 24.—Illustrating the development of magnetic and electric fields.

be no further flow of D.C. into a condenser and there is none through it. A.C., though, does behave exactly as if it passed through a condenser, opposed only by X_C. Thus, if a condenser is placed in a conductor carrying both A.C. and D.C.—one and the same conductor can and often does carry both—it acts as an absolute barrier to D.C. but allows A.C. to pass. Such a capacitor, known as a BLOCKING CAPACITOR (or blocking condenser), has its place in the wireless set.

Now examine the arrangement shown in Fig. 24. A little imagination is required, for the inductor L is to be regarded as having no resistance, and it must, further, be considered possible to move the switch from position 1*a* to position 2 *b* and *c* with lightning rapidity.

With the switch in position 1 (Fig. 24*a*) current is driven through L and a magnetic field is built up round the inductor. Turn the switch to position 2. What now happens is seen at *b*. The collapse of the field keeps the current going in its original direction and it charges the capacitor. At the instant depicted in Fig. 24*b* all the energy in the circuit is momentarily stored in the electric field. Next moment (Fig. 24*c*) C discharges, producing a flow of current in the opposite direction through L. The magnetic field is built up round L and now the energy in the circuit is stored in this field.

If there were no resistance in the circuit these swings of current would continue indefinitely, the magnetic and electric fields alternately borrowing and repaying the energy. Such a condition is known as oscillation. Every circuit must contain resistance; but, as we shall discover presently, we have means of annulling the effects of resistance and of making circuits oscillate indefinitely.

It is by means of oscillatory circuits that the wireless transmitter generates the waves which convey the energy radiated from its aerial. Such circuits have also important parts to play in the receiving set.

When an E.M.F. is applied to a capacitor (as seen in Fig. 25*a* with the switch in position A) through a certain amount of resistance—and we have seen that there must be resistance, however small, in any circuit—the difference of potential between the plates of the condenser increases as current flows in until it reaches very nearly the value of the applied E.M.F. The time required for the completion of this process depends on the value of the resistance and the capacity of the condenser. The rise in the potential difference between the plates is not, however, a steady, regular increase.

An almost exact analogy is furnished by the inflation of a bicycle tyre by means of a hand pump. Anyone who

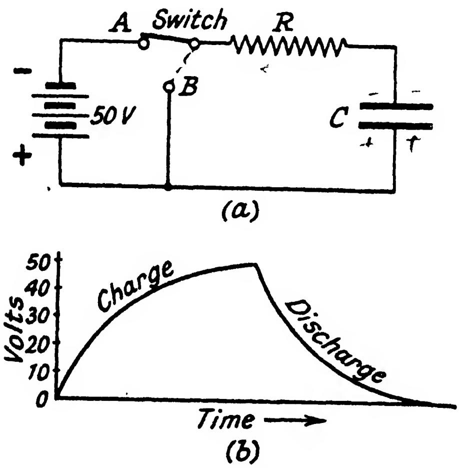


FIG. 25.—The charge and discharge of a capacitor.

performed this task for the first time would think during, say, the initial 15 seconds that it was the lightest of light work. When the inner tube is empty, there is no pressure within to oppose the entry of air driven by the pump. As air flows in the counter-pressure increases and the work becomes harder: after a short while the tyre pumper would probably revise his opinion about the nature of the work involved—particularly if the day were hot! Owing to the growing opposition of the pressure within the tube the work becomes rapidly harder and harder after the first deceptively easy spell.

Substituting pounds to the square inch for volts, a curve representing the increase of pressure plotted against time would have much the same shape as the rising curve seen in Fig. 25*b*.

So with the charge of a capacitor. At first there is nothing to oppose the inward flow of current. Electrons stream in and the difference of potential between the plates rises rapidly. Then this electrical pressure begins to make itself more and more strongly felt. It opposes the influx of electrons with growing force and this influx falls off, becoming smaller and smaller as time goes on.

The charging curve of a capacitor is, in fact, similar to that seen in the ascending curve of Fig. 25*b*. Mathematicians will recognise the shape as exponential; but if you are not a mathematician, there is no need to trouble about that. The thing to remember is that any capacitor to which an E.M.F. is applied charges to approximately 63 per cent. of the applied voltage in a time in seconds equal to the capacitance in microfarads multiplied by the resistance in megohms. This product is called the TIME-CONSTANT of the circuit.

Suppose that in Fig. 25*a* R has a value of 100,000 ohms and C a value of 0·003 μF. Expressed in megohms, 100,000 ohms = 0·1. Then the time constant

0·1 × 0·003 second
= 0·0003 second
= 300 millionths of a second, or 300 microseconds, written as 300μsec.

No matter what the applied E.M.F., a capacitor of 0·003 microfarad will charge to 63 per cent. of it through 100,000 ohms of resistance in 300μsec. That is the time constant of any circuit similar to Fig. 25*a* with these values of resistance and capacitance.

If the switch in Fig. 25*a* is turned to position B, the capacitor discharges through the conducting path provided. The nature of the discharge is seen in the descending curve in Fig. 25*b*. At first the large pressure, or E.M.F., drives current from the capacitor at a rapid rate; but as the pressure tails off the rate of flow of current out of the capacitor falls off.

The bicycle tyre analogy again holds good. If the valve is loosened in its seating the high inner pressure drives air out very fast to begin with; but as the pressure

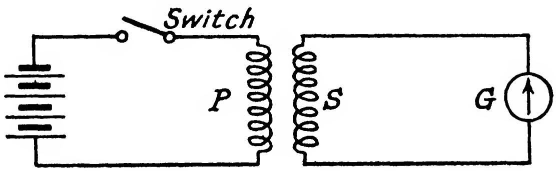


FIG. 26.—Closing the switch in the primary circuit causes a momentary flow of current in one direction in the secondary. Opening the switch gives rise to a spurt of current in the opposite direction.

falls and has less driving power the outward flow of air takes place at a lower and lower rate.

One of the greatest discoveries made by that remarkable genius Michael Faraday was that an electric current flowing in one circuit can induce a flow of current in a neighbouring circuit though there is no physical connection between the two.

If two circuits like those shown in Fig. 26 are made up, it is found that the needle of a centre-zero galvanometer (that is, a current-indicating instrument with the zero mark in the middle of its scale) is momentarily deflected in one direction when the switch is closed and exhibits a similar deflection in the opposite direction when the switch is subsequently opened.

When the switch is closed the magnetic field round the coil marked P (primary) in Fig. 26 expands. During this expansion the lines of force of the field " cut " the turns of the secondary coil (S). Before the switch is closed current in the secondary circuit is zero. As the magnetic field round P expands after the closing of the switch the current in the secondary circuit increases so long as the outward-moving lines of force cut S. When the field round P is fully built up, the outward movement of the lines of force ceases. S is no longer being cut by moving lines of force and current in the secondary circuit falls to zero.

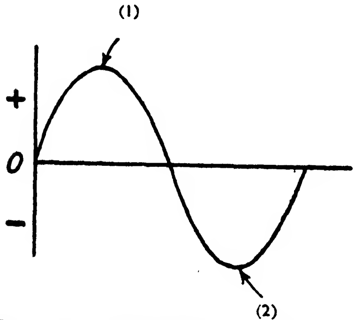
Now open the switch. The needle of the galvanometer gives a " kick " in the opposite direction. See if you can discover why before reading the explanation which follows.

If you considered what happens to the magnetic field when the switch is opened you probably arrived at the right answer. With the switch closed and current flowing in the primary the magnetic field surrounding P continues unaltered in its fully developed state. The opening of the switch causes the field to collapse and its lines of force, falling inwards, cut S in a direction opposite to that of their outward movement. Current in the secondary now rises to maximum in the opposite direction, falling to zero when the completion of the collapse of the field brings the inward movement of the lines of force to an end.

The current resulting in the secondary from a rapid closing and opening of the switch has the form illustrated in Fig. 27*a*; it alternates in the way with which we are now familiar from zero to maximum in one direction and then from zero to maximum in the other.

Such a current is said to be induced. An induced alternating current in the secondary could also be produced in the way shown in Fig. 27*b*. Here a variable resistor R enables the primary current to be increased or reduced. An increase causes an expansion of the magnetic field round P and a cutting of S by outward-moving lines of force. A decrease makes the magnetic field round P fall in to some extent and S is cut by inward-moving lines of force.

A component containing primary and secondary coils,



(1) Switch closed—current in S rises from zero to maximum and then falls to zero.

(2) Switch opened—the collapse of the magnetic field causes the lines of force to cut S in the opposite direction as the field falls in. Current rises to maximum in the opposite direction, falling to zero when the collapse is complete.

FIG. 27*a*.—Illustrating the induction of current in the secondary as the switch is closed and opened.

with the two circuits COUPLED, is called a TRANSFORMER.

You can see now how a fluctuating direct current through the constantly changing resistance of the micro-

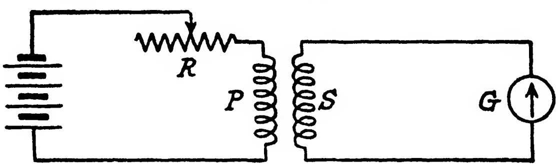


FIG. 27*b*.—Increasing or decreasing the resistance in the primary circuit causes induced currents to occur in the secondary.

phone is turned by the transformer into a speech-frequency, or audio-frequency, alternating current with corresponding fluctuations in amplitude and frequency.

Next, suppose that, as in Fig. 28, a source of A.C. is applied to the primary of a transformer. The magnetic field round P rises and falls in one direction during each positive half-cycle and does the same in the opposite direction in the course of each negative half-cycle. The consequent cuttings of S by the moving lines of force give rise to an alternating current in the secondary circuit.

One of the great boons conferred by the transformer is that it enables us to step up, or step down, a primary E.M.F. to any required degree. The relation of the secondary to the primary E.M.F. is, in fact, determined by the ratio of the secondary to the primary wiring turns of the transformer.

Suppose, for example, that the primary input in Fig. 28

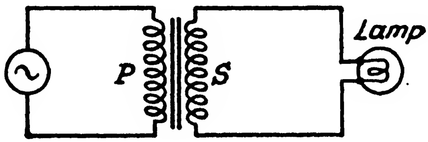


Fig. 28.—When a source of A.C. is applied to the primary of a transformer, alternating current is produced in the secondary.

is 5A at 10V, and that there are four times as many turns in the secondary as in the primary. Then the secondary E.M.F. is $4 \times 10 = 40$V.

Are we then getting something for nothing, if we can increase the E.M.F. at will in this fashion? We are not. As is the way with everything in this world, we have to pay for what we receive. If this particular transformer were 100 per cent. efficient the greatest secondary current that we could expect with a 5A input to the primary would be one fourth of 5A. What is gained on the swings is lost on the roundabouts; but in the wireless transmitter and receiver the volts are often more important than the milli-amperes or micro-amperes of current, and the ability to increase (or decrease) an E.M.F. by means of a transformer is of very great value. There are times, too, when we wish to increase or decrease the available current. This also can be done by the transformer; but any increase in the secondary amperes can take place only at the expense of the volts. We cannot have it both ways.

CHAPTER VI

Series and Parallel

TWO or more components are said to be connected in SERIES when, like the resistors in Fig. 29, they are so arranged that between them they offer a single path for current, which must traverse them one after another. If you think over the circuit of Fig. 29 for a moment you will see that as the current must be driven first through 6 and then through 4 ohms the total resistance encountered is $6+4=10\Omega$. Exactly the same amount would flow if a

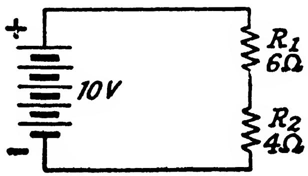


FIG. 29.—The two resistors, R_1 and R_2, are here in series and the total resistance is equal to R_1+R_2.

single resistor were used with a value equal to that of the two added together.

When, therefore, resistors are in series the total resistance offered by them is the sum of their individual resistances.

But a very different state of affairs occurs if the same two resistors are connected as in Fig. 30. They are then said to be in PARALLEL. Components are connected in parallel when each offers a separate path for current, which divides and traverses these different paths simultaneously.

In the Fig. 30 circuit the E.M.F. applied to R_1 is 10V and the current through it must by Ohm's Law be

$\frac{10}{6}=1\frac{2}{3}$A. Similarly, the current through R_2 is $\frac{10}{4}=2\frac{1}{2}$A. The total current is thus $4\frac{1}{6}$A. From this we can work out the effective resistance R of the combination, again using Ohm's Law. Here $R=\frac{E}{I}=\frac{10}{4\frac{1}{6}}=2\frac{2}{5}\,\Omega$, which is less than the resistance of either of the individual resistors. Had there been three or more resistors in parallel in the Fig. 30

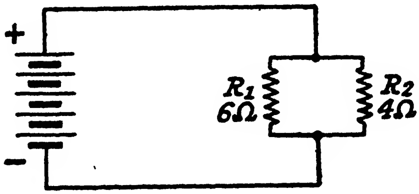


FIG. 30.—When resistors are connected in parallel the total resistance is less than that of any individual resistor.

circuit, calculations on the same lines would have shown a total resistance less than that of any one of them.

The rule for resistors in parallel is:

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

Taking the Fig. 30 case, we have:

$$\frac{1}{R}=\frac{1}{6}+\frac{1}{4}\,\Omega$$

$$\therefore \frac{1}{R}=\frac{5}{12}\,\Omega$$

$$\therefore R=\frac{12}{5}\,\Omega$$

$$=2\frac{2}{5}\,\Omega$$

The rules for the capacitance of condensers in series and parallel are precisely the opposite of those for resistors. A glance at Fig. 31 will show that the charging current flowing into the parallel capacitors C_1 and C_2 at *b* is

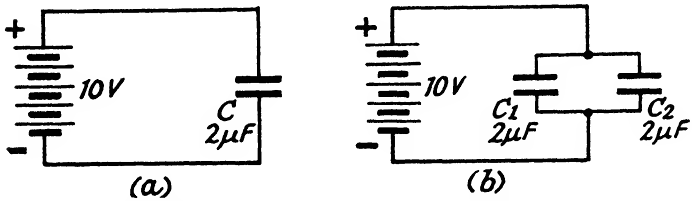


FIG. 31.—The charging current flowing into C_1 and C_2 at *b* is twice that flowing into C at *a*.

twice that flowing into the single condenser of the same capacitance at *a*. Similarly, if discharge paths are provided, the current from C_1 and C_2 at *b* will be twice that of C at *a*.

The capacitance at Fig. 31*b* is $2+2=4\mu F$.

When capacitors are in parallel the total capacitance is the sum of the individual capacitances.

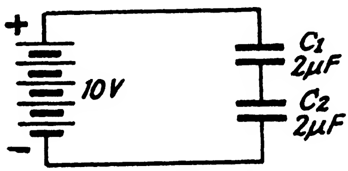


FIG. 32.—When capacitors are connected in series the total capacitance is less than that of any of them: $\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}$

For capacitors in series, as in Fig. 32, the rule is:

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

Here
$$\frac{1}{C}=\frac{1}{2}+\frac{1}{2}\mu F$$
$$\therefore C=1\mu F$$

Next consider how the available E.M.F. of 10V is used up in driving current through the resistors seen in Fig. 33. We have seen that the total resistance in the circuit is 10Ω. It follows that the current is $\frac{10}{10}=1A$. In R_1 1 ampere of current is flowing through 6Ω of resistance. By Ohm's Law the E.M.F. needed to drive this

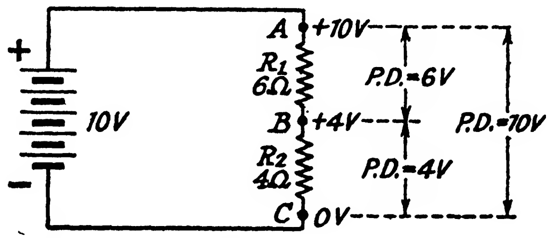


FIG. 33.—Of the available E.M.F. a proportion is used up in driving current through each resistor.

current is $I \times R=1 \times 6=6V$. Through R_2 also flows 1A, and here the required E.M.F. is $1 \times 4=4V$. Thus of the original 10V available 6V are used in driving the 1A of current through R_1 and 4V in driving the 4A through R_2.

Across R_1 there is a fall in voltage, known as a POTENTIAL DIFFERENCE, or P.D., of 6V, and the P.D. across R_2 is 4V. Notice carefully the difference between an E.M.F. and a P.D. An E.M.F. is the voltage which causes a current to flow; a P.D. is the result of a flow of current or of the displacement of electric charges. The P.D. across a resistance is always $I \times R$. If 2A were driven through the 6Ω of R_1 the P.D. would be $2 \times 6=12V$.

If we wish to "tap off" any portion of the total voltage available from a battery or other source of E.M.F. we can do so by means of a network of resistors. Thus in the Fig. 33 circuit we can obtain a potential of 10V from point A or 4V from point B relative to C. The arrangement shown in Fig. 34*a* shows how any whole number of volts from 1 to 10 could be tapped off from a 10V source.

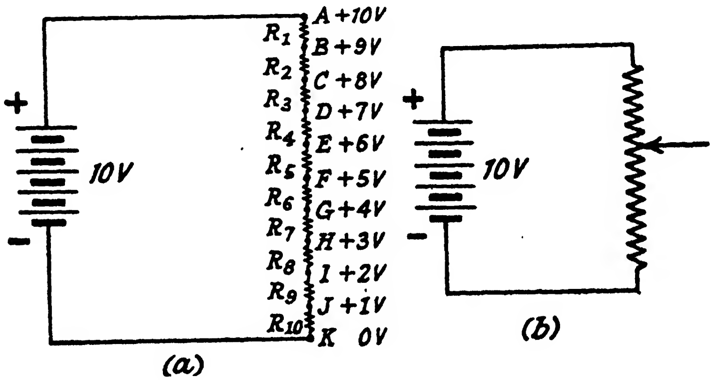


FIG. 34.—By using as at *a* 10 resistors all of the same value, a potential of any whole number of volts from 1 to 10 can be tapped off. The arrangement at *b*, where a sliding contact is used, enables minute adjustments of the voltage to be made. The arrangement at *a* is a potential divider; that at *b* is a potentiometer.

Such an arrangement is known as a POTENTIAL DIVIDER.

At *b* in Fig. 34 a single resistor is used, but it is provided with a sliding contact. In this way very fine gradations can be made in the proportion tapped off from the total available voltage. This arrangement is known as a POTENTIOMETER.

The potential divider is an important part of most wireless receivers. The application of the potentiometer most commonly seen is the typical volume control.

CHAPTER VII

Tuning and Tuned Circuits

WHEN we turn the tuning control knob in order to make a wireless receiving set bring in a particular station we do electrically inside the set very much what a piano-tuner does mechanically as he works on a string. We saw in an earlier chapter that the frequency at which a string of given length vibrates depends on its weight and its tension. The piano-tuner cannot alter the weight, or *mass*, of the string, but he can and does adjust its tension by tightening or loosening it with his key.

What, exactly, do we mean when we say that a string is tuned to middle C? We imply (*a*) that if the string is plucked or scraped or struck it will vibrate 256 times a second, and (*b*) that if it is "excited" by the arrival of sound waves with a frequency of 256 c/s, it will respond by vibrating at that frequency: a middle C tuning fork, struck and held near the middle C string of a piano, will cause the latter to vibrate strongly if the damper is not touching it owing to its response to the sound waves which reach it.

A B or a D tuning fork would produce little response from the C string. It responds feebly, if at all, to any waves but those of its RESONANT or NATURAL FREQUENCY—256 c/s.

Like each string of a piano, every wireless transmitting station has its own natural frequency: the frequency to which its aerial and the associated circuits are tuned. To receive a particular station clear of interference from others we must tune the wireless receiving aerial and the set connected to it so that they are in resonance with this frequency. The transmitter then acts as the tuning fork and the receiver as the piano string. Transmitters on neighbouring frequencies evoke some response from the receiver. If its selectivity is poor we hear them as a background (and sometimes even as a foreground !) to the desired signal; but when the selectivity is as it should be the receiver responds so much more strongly to a transmission at its natural frequency that nothing is heard of others.

The electrical counterpart of mass is inductance. It is owing to its mass that a body such as a piano string or a railway truck resists any attempt to set it in motion. And once its inertia has been overcome and it is in motion mass causes it to oppose any speeding up or slowing down of that motion. You will see the likeness between the effects of mass on the starting, stopping, speeding up, or slowing down of a railway truck and the effects of inductance in opposing the starting, stopping or changing of an electric current in a circuit.

Capacitance is, similarly, the electrical counterpart of tension or springiness. A taut string, pulled one way and released, flies in the opposite direction and then returns almost to the original point of release. The return would be complete and the string would go on swinging to and fro indefinitely but for friction. In overcoming this friction the string continually loses a little of its store of energy, which goes to produce heat in the air. The result is that the amplitude of the string gradually dies down. Similarly the electric field of the capacitor in the Fig. 24 circuit gives back on discharge almost all that was put into it during the charging period. Charging and discharging would go on indefinitely were it not for resistance, which DAMPS the current, causing each swing to be of slightly smaller amplitude than the one before it. Some of the energy of the current is being turned into heat in overcoming the resistance of the circuit.

In many (though by no means all) wireless tuned circuits the inductance is fixed and, like the piano-tuner, we obtain resonance by adjusting the springiness or capacitance until the required natural frequency is obtained. This is done by means of a variable condenser the capacitance of which is altered by moving the tuning control knob. The variable condenser has two sets of intermeshed plates, one fixed and one moving. The latter are mounted on the spindle, turned, directly or through

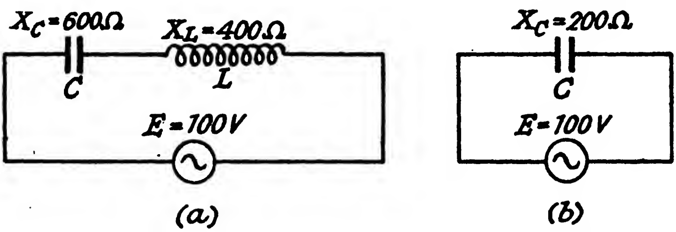


FIG. 35.—(*a*) A.C. is here applied to a circuit containing capacitance and inductance in series. The net reactance is the difference between X_L and X_C, the smaller value being subtracted from the greater. Here the difference is 200Ω, and X_C is the greater. The circuit is equivalent as regards reactance to that shown at (*b*).

gearing, by the control knob. The capacitance is at maximum when the moving plates are completely meshed with the fixed, and at minimum when the two sets of plates are disengaged from one another. Any value of capacitance between the minimum and maximum available can be obtained by adjusting the position of the moving plates.

Fig. 35*a* shows a circuit containing inductance and capacitance in series. In such a circuit the two reactances X_L and X_C have precisely opposite effects: X_L makes the E.M.F. lead the current by 90°, whilst X_C makes the current lead the E.M.F. by 90°. The net reactance of the circuit is the difference between X_L and X_C, the smaller being subtracted from the greater. Here $X_C=600\Omega$ and $X_L=400\Omega$. The net reactance is thus $600-400=200\Omega$, and as X_C is the greater the net reactance is capacitative. If the applied alternating E.M.F. is 100V the current is $\frac{100}{200}=0{\cdot}5$A. Exactly the same result would be produced if the E.M.F. were applied to the Fig. 35*b* circuit. In both cases the current is 0·5A, and as the reactance is capacitative the current leads the voltage by 90°.

We know that a circuit cannot contain inductance and capacitance but no resistance at all. There must be

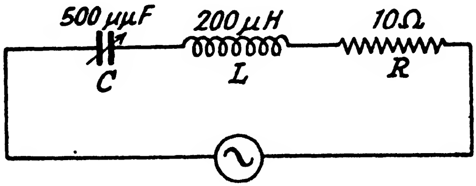


FIG. 36.—Any circuit must contain some resistance, which may be represented by R.

resistance in all parts of the circuit—in the coil, in the condenser and in the leads. But no matter how the resistance is distributed, we can " lump " it all together and represent it by a series resistance, such as R in Fig. 36. We now have inductance, capacitance and resistance all in series, and the opposition which they offer to an alternating current is impedance, symbol Z, which was mentioned in a previous chapter. In a series circuit such as Fig. 36, $Z=\sqrt{X^2+R^2}$; and X, we know, is the net reactance, the difference between X_L and X_C.

So far the mathematicians have had several footnotes dedicated to them and there has been nothing for the special benefit of the non-mathematical reader. At this point the latter may cease to feel neglected, for the whole of Appendix B is for him and him alone. We have, when dealing with the frequencies of wireless, to make calculations involving very large numbers. If these are written down in "longhand," calculations, though they are usually simple enough, become very tedious—and are apt to occupy a great deal of paper. Appendix B gives an account of a useful mathematical "shorthand" which will be found handy for calculations of all kinds—not just those of wireless—in which large numbers are concerned. We shall make use of it from now onwards.

A combination of a variable capacitor, an inductor, and the incidental resistance such as that seen in Fig. 36, constitutes a SERIES TUNED CIRCUIT. In the drawing the maximum capacitance of the variable condenser in 500 μμF. For reasons which we shall come to later the capacitance in the circuit will not be zero when the condenser is set at minimum, with its plates completely unmeshed. Its knob will, however, enable us to adjust the capacitance to any value between about 60-80 μμF and rather more than 500 μμF.

Let us find the impedance of the circuit if $f=700$ kc/s (700×10^3 c/s), L=200μH (200×10^{-6}H), R=10Ω, and C has values of (*a*) 150, (*b*) 500 and (*c*) 258 μμF (150×10^{-12}, 400×10^{-12} and 258×10^{-12}F).

$$X_L = 2\pi f L$$

$$= 2 \times \frac{22}{7} \times 700 \times 10^3 \times 200 \times 10^{-6} \text{ ohms}$$

$$= 880\Omega$$

In case (*a*)

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

$$=\frac{1}{2\times\frac{22}{7}\times700\times10^{3}\times150\times10^{-12}}\text{ ohms}$$

$$=\frac{10^{6}}{2\times22\times15}\Omega$$

$$=1{,}515\Omega$$

$$X=X_C-X_L=1{,}515-880=635\Omega$$

$$Z=\sqrt{10^2+635^2}$$

$$=\text{approx. }635\cdot1\Omega$$

Here X_C is greater. The impedance is therefore capacitative and the current leads on the E.M.F.

In case (*b*)

$$X_C=\frac{1}{2\times\frac{22}{7}\times700\times10^{3}\times400\times10^{-12}}\Omega$$

$$=568\cdot2\Omega$$

$$X=X_L-X_C=880-568\cdot2=311\cdot8\Omega$$

$$Z=\sqrt{10^2+311\cdot8^2}$$

$$=\text{approx. }312\Omega$$

Here X_L is the greater. The impedance is inductive and the E.M.F. leads on the current.

In case (*c*)

$$X_C=\frac{1}{2\times\frac{22}{7}\times700\times10^{3}\times258\times10^{-12}}\Omega$$

$$=880\Omega$$

$$X_L-X_C=880-880=0.$$

The two reactances exactly cancel out and the only opposition offered by the circuit to a frequency of 700 kc/s is that of resistance, which is only 10Ω, and the current neither lags nor leads, but is in step with the applied E.M.F.

In this condition the circuit is tuned to 700 kc/s and 700 kc/s is its RESONANT or NATURAL FRE-

QUENCY. By means of the variable condenser the circuit can be tuned, or brought to resonance, at frequencies within a wide range. At 1,000 kc/s, for instance, X_L for a coil of 200μH is 1,257Ω. Adjust the condenser so that the capacitance is 126·5 μμF; X_C becomes 1,257Ω and the circuit is now tuned to 1,000 kc/s.

The resonant frequency f_o can be found for any tuned circuit by means of the formula:

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

In the last example we had L=200μH and C=126·5 μμF.

$$f_o = \frac{1}{\frac{44}{7} \times \sqrt{200 \times 10^{-6} \times 126{\cdot}5 \times 10^{-12}}}$$

$$= \frac{44}{7} \times \frac{1}{14{\cdot}14 \times 11{\cdot}247 \times 10^{-9}}$$

$$= \frac{10^9}{10^3}$$

$$= 1{,}000{,}000 \text{ c/s, or } 1{,}000 \text{ kc/s.}$$

A.C. presents at times some big surprises, when it appears to behave in an altogether irrational manner. These effects are often due to the borrowings and repayments of energy by the magnetic field of an inductor and the electric field of a capacitor, such borrowings and repayments—electrical swings and roundabouts—being 90° out of phase.

Fig. 37 shows a series tuned circuit to which an E.M.F. of 2 millivolts (two thousandths of a volt$=2 \times 10^{-3}$V) is applied at 700 kc/s, the resonant frequency of the circuit. At f_o the reactances of L and C exactly cancel out and the impedance of the circuit is simply the resistance

$=10\Omega$. The current through the whole circuit is therefore $2\times10^{-3}\div10=2\times10^{-4}$A, or 0·2 milliampere (mA).

If this current flows, as flow it must and does, through the whole circuit, how many volts are required to drive it through the 880Ω reactance of L whilst it is passing through the coil, or the 880Ω reactance of C whilst it is passing through the condenser? By Ohm's Law E=I×R $=0{\cdot}2\times10^{-3}\times880\Omega=176$ millivolts, or 88 times the applied voltage.

In this tuned circuit there is thus a voltage magnifica-

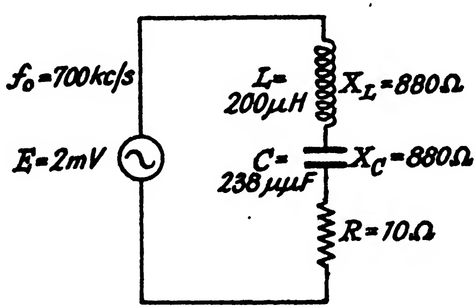


FIG. 37.—As explained in the text, the voltage across L is 88 times that across R, and the Q of the circuit is 88.

tion of 88 times across the coil or the condenser at the resonant frequency.

You will see that this voltage magnification, or Q as it is called, is directly dependent upon the resistance: double R and you have Q; halve R and twice the Q is obtained. Now R is the high-frequency or H.F. resistance of the circuit—H.F. resistance will be dealt with in a moment—which is due far more to the windings of the inductor than to any other part of the circuit. In fact H.F. resistance in the rest of the circuit is negligible in comparison with that due to the coil. Hence Q is for practical purposes the ratio of the reactance of the coil to its resistance:

$$Q = \frac{X_L}{R}$$

Since $X_L = 2\pi f L$, it follows that the voltage magnification obtainable at any frequency depends entirely on the ratio of L to R, or $\frac{L}{R}$.

It is the voltage magnification that takes place at resonance in tuned circuits which makes wireless possible; but for Q, for example, no broadcasting station on the medium-wave or long-wave bands could be received free from interference by other transmitters. Its Q may be termed

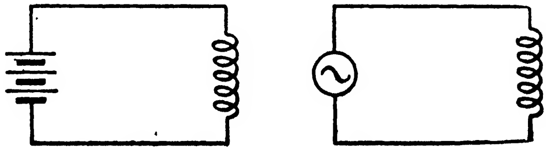


FIG. 38.—Though its D.C. resistance may be very small indeed, the A.C. resistance of the same coil can be considerable.

the efficiency factor of a coil. Good coil design is founded upon keeping the resistance low in comparison with the inductance.

The resistance R of Figs. 36 and 37 is not quite the same thing as resistance in a D.C. circuit. If, for example, D.C. and A.C. are applied in turn to the same coil, as in Fig. 38, the A.C., or high-frequency, resistance may turn out to be many times as great as the D.C.

We are not, remember, comparing the reactance of the coil with its D.C. resistance. Resistance is the property in a circuit which causes energy to be expended and work to be done when current flows. Current does no work in negotiating pure reactance; but work is done when H.F. resistance is encountered.

Since the turns of a coil lie close to one another there is interaction between the magnetic fields surrounding them, which means that the energy put into the magnetic field as it is built up is not fully returned when it collapses. There is a small underpayment of each borrowing. That slight expenditure of energy must be made good by the current and work is done. As the underpayment takes place once in each half-cycle, you will realise that it can mount up to something considerable at high frequencies.

Though the windings of the coil are the main source of high-frequency resistance (R_{hf}) in a tuned circuit, they are by no means the only ones. The coil current may, for instance, induce currents in neighbouring conductors. These meet with resistance and the energy needed to overcome this is drawn from the original current.

The capacitor, again, may play a part in introducing R_{hf}, though this is usually small in comparison with that of the inductor. The perfect dielectric would possess "springiness" such that all the energy used for the build-up of the electric field was returned during its collapse. There are, unfortunately, no perfect dielectrics and some small losses inevitably occur. Once more, energy is expended and work done. Nor is the capacitor the only place in the circuit where electric fields, all in more or less imperfect dielectrics, can occur. There is capacitance between any two points of a circuit which are at different potentials, and what are known as "stray capacitances" cannot be left out of the R_{hf} picture.

Designers of tuned circuits and those of the components which go to make them up strive to keep R_{hf} low. The Q of a tuned circuit is determined by the H.F. resistance, and the SELECTIVITY of the circuit depends on its Q.

One of the most important attributes of a wireless transmitter or receiver is selectivity. A transmitter must be tunable sharply to its assigned frequency if it is not to interfere with others. A receiver must be just as sharply tunable, in order that it may select the wanted transmission and exclude those that are not wanted.

Fig. 39 shows how coils of high, medium and low Q behave in a series circuit tuned to 700 kc/s. Such a curve is known as a response curve, since it indicates the response of the circuit to f_0 and to neighbouring frequencies. With

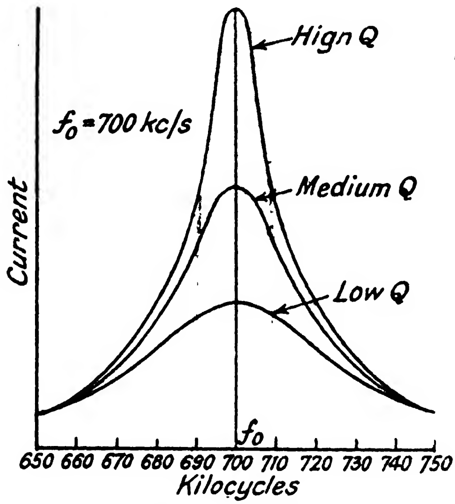


FIG. 39.—Typical response curves for series acceptor circuits with coils of high, medium and low Q at a resonance frequency of 700 kc/s.

the high-Q coil the resonant frequency causes a large current to flow, whilst frequencies 10 kc/s above or below f_0 give rise to a current which is only a fraction of this. In other words, were this circuit part of a receiving set tuned to receive a transmitter working on 700 kc/s it would *accept* the desired transmission more strongly than others working on frequencies 10 kc/s above or below and would show a negligible response to those 50 kc/s away from f_0.

The medium-Q curve shows a response at f_0 which is not nearly so much greater than those at f_0+10 kc/s and $f_0 - 10$ kc/s. The selectivity of the circuit would thus be smaller, for it could not distinguish so markedly between wanted and unwanted transmissions. The low-Q curve indicates still poorer selectivity, for the current at f_0 is only three times as great as that 40 kc/s above or below the resonant frequency.

The Q of the coil, then, is the determining factor of the selectivity in a tuned circuit of this kind.

The series, or acceptor, circuit is not much used in

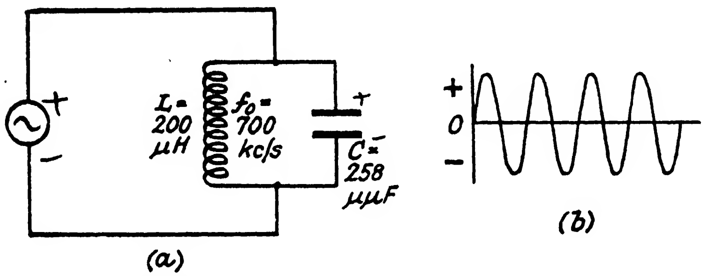


FIG. 40.—The parallel tuned circuit. The circuit here depicted respresents an imaginary condition, since it contains no resistance.

wireless sets to-day. They usually incorporate a number of parallel tuned circuits of the type illustrated in Fig. 40*a*.

Suppose that, as Fig. 40*a* suggests, a tuned circuit contains no resistance. The current through the inductor L lags by 90° on the E.M.F. and that through the capacitor C leads by 90° on the E.M.F. At 700 kc/s X_L and X_C are equal. The currents through L and C are therefore of equal magnitude. Since one current leads on the E.M.F. by 90° and the other lags on it by the same amount the two currents are 180° out of phase and we have the condition of affairs illustrated in Fig. 20*c*. Being equal and opposite, the coil current and the condenser current exactly cancel one another out and the net current taken from the source of A.C. is nil.

Were there no resistance in the circuit, an interesting state of affairs would be found when it was connected to a generator, as in Fig. 40*a*. A charging current would flow into the circuit only for a brief instant; the circuit would then offer infinite impedance and no more would enter. The generator might now be cut out and current would continue to " oscillate " in the circuit for ever. At one moment, when C was charged, all the energy would be in the electric field of the capacitor; at the next C would discharge through L and all the energy would be

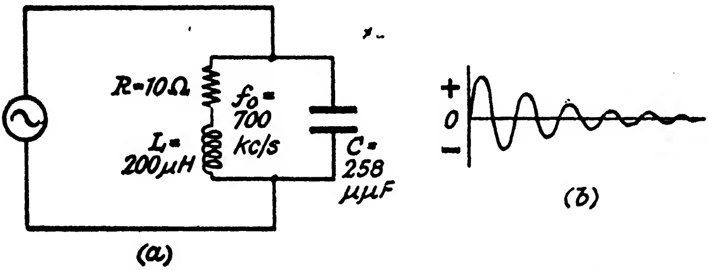


FIG. 41.—The circuit of Fig. 40 redrawn so as to include resistance.

in the magnetic field of the coil. Charge and discharge of C in the opposite direction would follow . . . and so on *ad infinitum.* The oscillations would be all of the same amplitude, as shown in Fig. 40*b*. Such oscillations are said to be undamped, or continuous.

In practice there must of course always be a certain amount of resistance, and to remove it from the realms of imagination to those of reality the circuit may be redrawn as in Fig. 41*a*, where R represents the sum of the high-frequency resistance present in the circuit.

The presence of resistance makes a considerable difference to the performance of the circuit. To cancel out completely the two currents must be both equal and exactly opposite in phase. Now, the current through a resistor is exactly in phase with the E.M.F. driving it, whilst that through a capacitor or inductor displaying reactance but no resistance is just 90° out of phase with the E.M.F. When an inductor or a capacitor contains a combination of resistance and reactance the phase difference is no longer 90°.

A picture of what takes place in such circumstances can be formed by thinking of the resistance as striving to pull E.M.F. and current into phase and of the reactance as striving to pull them 90° out of phase with one another. The result of these mutually opposed influences is a current less than 90° out of phase with the E.M.F. The amount by which the phase difference is less than 90° depends upon the relative values of resistance and reactance in the circuit; in any such circuit the higher the resistance present the smaller is the phase difference between E.M.F. and current.*

Were the generator cut out, the damping due to the presence of resistance would cause the current to die out very rapidly, each half-cycle being of less amplitude than its predecessor as shown in Fig. 41*b*. Oscillations which die out in this way are said to be damped. Damping in a circuit is due to the presence of resistance or to something which produces effects equivalent to those caused by adding resistance.

Owing to the presence in it of some resistance the parallel tuned circuit is not a complete barrier to current at the resonant frequency. Some current is taken from the source of A.C.

This brings us to a rather curious point. The smaller the R_{hf}, the greater the opposition offered at resonance by a parallel tuned circuit. As energy is expended and work

* See Appendix C.

done by the current in passing through a parallel tuned circuit the opposition offered to its passage must be resistance. It is a strange kind of resistance, for it increases if the R_{hf} of the circuit is reduced and falls if R_{hf} is increased. Still, it is resistance and the name given to it is DYNAMIC RESISTANCE—R_d.

Just as a series tuned circuit, which in the absence of

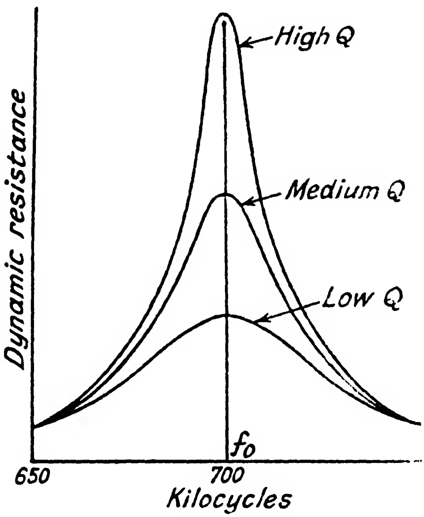


FIG. 42.—Response curve of parallel-tuned rejector circuit.

R_{hf} would offer no opposition to current at the resonant frequency, is known as an ACCEPTOR, so the parallel tuned circuit, which would have infinite dynamic resistance but for R_{hf}, is called a REJECTOR. The measure of the efficiency of a rejector circuit is its dynamic resistance, which depends upon the Q: at resonance

$$R_d = 2\pi f_o L \times Q$$

This formula may be simplified in the following way:

4

$$Q = \frac{2\pi f_o L}{R_{hf}}$$

$$\therefore R_d = \frac{2\pi f_o L \times 2\pi f_o L}{R_{hf}}$$

But at resonance $2\pi f_o L = \frac{1}{2\pi f_o C}$

$$\therefore R_d = \frac{2\pi f_o L}{2\pi f_o C \times R_h}$$

$$= \frac{L}{CR_{hf}}$$

Taking the values in the Fig. 41 circuit, we have:

$$R_d = \frac{200 \times 10^{-6}}{258 \times 10^{-12} \times 10}$$

$$= 77{,}500\Omega$$

Fig. 42 shows typical response curves for rejector circuit with coils of different Q's. Except that they show the dynamic resistance and not the current plotted against the frequency, they are very similar to those for an acceptor circuit seen in Fig. 39. The selectivity again depends upon the Q.

CHAPTER VIII

The Principles of Radiation, Transmission and Reception

BEFORE we go on to deal in some detail with the receiving set and the circuits and components which it contains it may be well to make a general survey of the processes of transmission and reception.

The key component of both transmitter and receiver is the thermionic valve, with which the chapters which immediately follow this are concerned. Meantime it will suffice to know that the valve can be made to perform any one of three important functions:

(1) *The valve can be used as an oscillator*

Employed in this way and yoked to a parallel tuned circuit the valve acts as a generator of oscillations (very rapidly alternating currents are said to oscillate) at the resonant frequency of the circuit. When fed into a transmitting aerial, these waves of current give rise to electromagnetic waves which are radiated through the ether.

(2) *The valve can be used as an amplifier*

Oscillations so feeble that their E.M.F.s are measured in microvolts are sufficient to actuate a valve amplifier. A minute input to an amplifying valve results in an output of much greater amplitude. Amplifying valves may be used " in cascade," the output of the first being made the input to the second and so on. In this way oscillations may be magnified a million times or more in amplitude.

(3) *The valve can be used as a rectifier*

Rectification in electrical parlance means the conversion of alternating or oscillating current into direct current.

In order that the receiving set may be able to "translate" the signals received by the aerial to which it is attached into intelligible sounds a process known as "detection" must take place. Rectification is an essential part of detection, and the valve is a first-rate detector of wireless signals by virtue of its qualities as a rectifier.

Fig. 43 shows a "block diagram" of a typical wireless speech transmitter. The oscillator stage is closely tuned to the frequency on which the station works. Its output

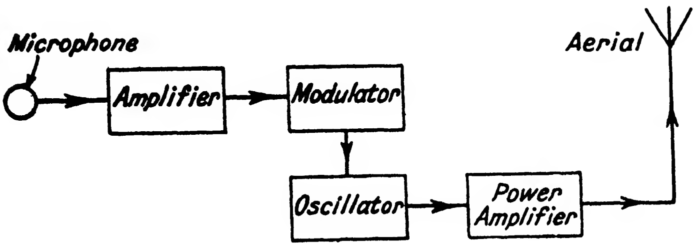


FIG. 43.—Simplified block diagram of a typical speech transmitter.

is an oscillating current of sine-wave form and constant amplitude which is fed to the aerial.

The aerials of the older broadcasting stations* consist of a "roof" of one or more wires suspended horizontally between masts and a vertical portion running straight downwards from the roof. It will come as a surprise to many to learn that the aerial proper is the vertical portion and that the main function of the roof (besides acting as a support for the vertical portion) is to decrease the frequency (or increase the wavelength) of the aerial proper by adding capacitance. The roof and the ground beneath it form a condenser of large physical proportions but comparatively small capacitance.

* See p. 95.

Since the transmitting aerial contains both inductance and capacitance, magnetic and electric fields are built up round it during each half-cycle of the current flowing in it. A good mental picture of the process of radiation from an aerial can be formed in the following way. Think of the fields as starting from within the aerial and expanding outwards from it during the rise of current from zero to maximum in each half-cycle. At the maximum of one half-cycle, which we may call a positive, the position is as indicated in Fig. 44*a*. There is a vertical electric field

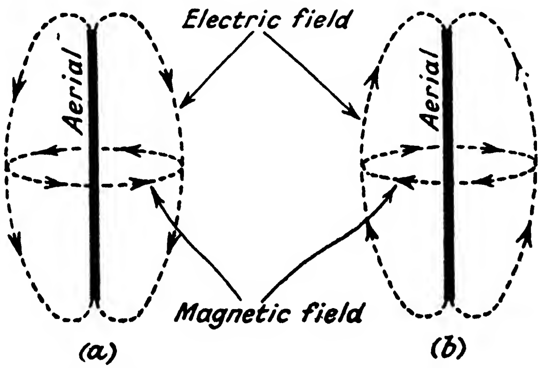


FIG. 44.—Showing diagrammatically the magnetic and electric fields built up round a vertical aerial during a positive (*a*) and a negative half-cycle (*b*).

with a downward direction and a horizontal magnetic field the direction of which is anti-clockwise as viewed from above. The following half-cycle with its negative maximum builds fields, like those seen in Fig. 44*b*, whose directions are opposite: the electric field is now upwards and the magnetic field clockwise.

Imagine these fields as forming, collapsing, forming in the opposite direction, and again collapsing, thousands or even millions of times a second.

During each collapse the lines of force which form the fields try to return into the aerial. But many of them have not time to do so before those of the next half-cycle start moving outwards. The lines of force which are, so to speak, left behind may be regarded as "looping off" as radiation in the way seen in Fig. 45.

Each loop of radiation has fields opposite in direction to those of the loops before and behind it. Note that the lines of force in the forward surface of one loop and the rear surface of the next are in the same direction. Like

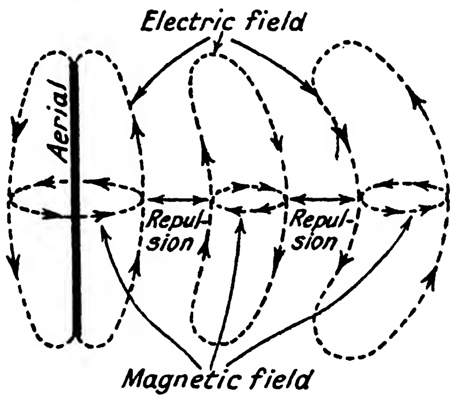


FIG. 45.—As the fields collapse some of the lines of force have not time to return to the aerial and "loop-off" as radiation.

repels like. There is repulsion between the loops and radiation is, so to speak, driven outwards from the aerial. The result is the formation of a train of electro-magnetic waves with positive and negative half-cycles.

One word about Figs. 44 and 45. They are drawn for the sake of clearness in two dimensions only. Both the electric and the magnetic fields should really be shown in three-dimensional "solid" form. The fields surround the aerial, and the looping off from a simple vertical aerial is not just in one direction, as Fig. 45 rather seems to suggest, but in all directions equally. The same qualifications apply to Fig. 46, which is the next to be considered.

The looped-off radiation consists of electric and magnetic fields at right angles to one another. These fields reach their maximum density in one direction at a crest and their maximum density in the other direction at a trough, as indicated in Fig. 46. The electric maximum and the magnetic maximum coincide. The expanding and collapsing fields form two sets of sine waves at right angles to one another. It is exceedingly difficult to make a drawing which renders this clear. I have never yet

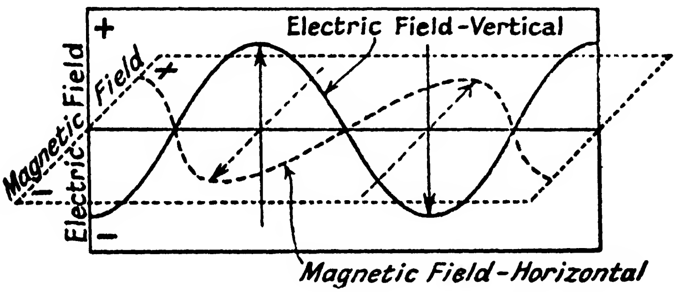


Fig. 46.—The wave formed by the electric field (solid line) is vertical—up and down the page. That formed by the magnetic field is horizontal and must be imagined as going into and out of the page.

come across a completely successful one in any textbook, and I can only hope that Fig. 46, which is the result of much thought and the spoiling of a good deal of paper, may convey the idea.

For reception with the ordinary type of outdoor aerial we are concerned with the electric portion of the wave. The electric field due to a vertical transmitting aerial is vertical and the wave is said to be vertically polarised. A vertical aerial transmits (or receives) a vertically polarised wave. It is a convention to use the electric field as the criterion of polarisation.

The frame aerial used in portable receivers is quite different from the " open " type of receiving aerial. The open aerial, consisting of a vertical wire and a " roof," used in conjunction with an earth connection, forms a capacitor of large physical dimensions but small capacitance—0·0002 μF to 0·0003 μF is the average capacitance of the usual " broadcast " receiving aerial.

The frame aerial is an inductor. It consists of a narrow coil of comparatively large diameter. The magnetic field induces currents in it. It acts, in fact, as the secondary of a transformer of which the primary is the transmitting aerial. Since the turns of a coil must be cut by the magnetic field for a current to be induced in them, it follows that the frame aerial used for broadcast reception must be arranged vertically, so that its turns may be cut by the horizontally polarised magnetic field of the incoming wave. Current is induced in a frame aerial because the incoming wave reaches its nearer edge a short time before it arrives at the farther edge. There is thus a difference of potential in the vertical sides of the frame forming the nearer and farther edges and a current is set up in the windings. It is in this way that the frame derives its directional properties. No signal is obtained if the frame is arranged so that its turns are not cut by the magnetic field of the incoming wave: try the effect of operating a portable set with its frame horizontal. No signal, again, appears if the frame is so arranged that the magnetic field cuts both vertical edges of its windings simultaneously. You can prove this by turning the frame of a portable set so that it lies at right angles to an imaginary line between your house and a transmitting station. The nearer the frame to this position, the weaker are the received signals.

To return to the transmitter of Fig. 43. When the microphone is switched off, or when no sound waves are reaching it, the oscillator generates an oscillating current at the frequency to which it is tuned, all waves being of the same amplitude. Magnified by the power amplifier, these currents are fed to the aerial, which is thus caused to radiate electro-magnetic waves of the kind seen in Fig. 47*a*.

Such waves, of constant amplitude and frequency, are known as continuous.

Now let the microphone be switched on and let a sound wave of 1,000 c/s reach it. Corresponding current fluctuations are set up in the microphone circuit and these are

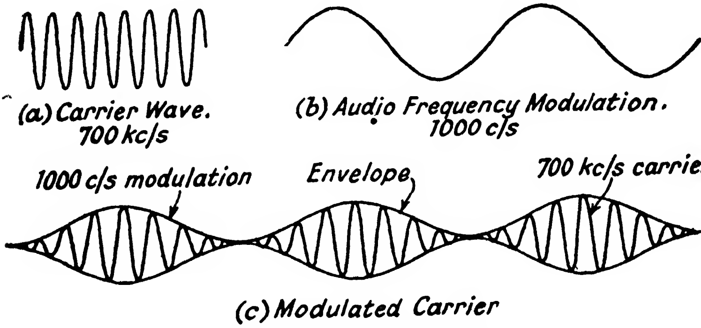


FIG. 47.—Illustrating the modulation of a 700 kc/s carrier by a 1,000 c/s note.

magnified to any required degree by the microphone amplifier. The output of this amplifier passes to the MODULATOR, which mingles it with that of the oscillator.

Audible sounds have frequencies between about 16 and 20,000 c/s, though the response of individual human ears varies very greatly. Every ear has its own response curve. Young people can hear sounds of much higher frequency than can the middle-aged or the old. Generally speaking the sound-wave frequencies which are normally audible by mankind range between about 16 and 15,000 c/s.

Many animals—dogs, for instance—have ears which respond to far higher frequencies; they can hear sounds produced by waves whose frequencies are too high to convey anything to us.

Take it that the sound wave reaching the microphone in this case is devoid of harmonics and has a frequency of 1,000 c/s (Fig. 47*b*). The effect of the modulation of the oscillator's output is to modify in the way shown in Fig. 47*c* the amplitude of the waves radiated from the aerial. The drawing is merely diagrammatic. The 700 kc/s oscillations sent out by the aerial are known as the CARRIER WAVE, since they carry the modulation imposed upon them. The crests and troughs of the carrier trace out the form of the modulating wave, which forms the "envelope." Were Fig. 47*c* drawn to scale it would show 350 cycles of the 700 kc/s carrier building up each half-cycle of the 1,000 c/s envelope.

The results of modulating a carrier wave in this way (there are other ways of doing it) are interesting and important. The unmodulated carrier (Fig. 47*a*) is radiated at a single frequency: $f_o = 700$ kc/s. But when a 1,000 c/s modulation is applied radiation from the aerial is no longer on a single frequency: it is on a band of frequencies between 700,000 c/s + 1,000 c/s (= 701 kc/s) and 700,000 c/s − 1,000 c/s (= 699 kc/s). Thus to transmit even a pure 1,000-cycle note the transmitter requires not one frequency of 700 kc/s, but a channel, 2 kc/s in width, ranging from 699 to 701 kc/s.

Certain sounds, such as the beat of a drum, the noise of a handclap or the sound of a pistol shot, produce sound waves which rise suddenly to maximum amplitude and as suddenly die away to zero. They are known as TRANSIENTS. They are a mixture of many frequencies ranging from a few hundred to perhaps 20,000 c/s. To reproduce them perfectly the wireless transmitter would have to send out and the receiver would have, in theory, to be able to deal with sound-frequency modulations up to 20,000 c/s or more. Actually, acceptable reproduction of these and all other sounds of speech and music is obtained with a far smaller range of frequencies. So many stations have to be crowded into the band (1,500 – 550 kc/s, 200 – 550 metres) allotted to medium-wave broadcasting that each channel has to be limited to 9 kc/s, or 9,000 c/s. This means that each station cannot be modulated by a range of sound-frequencies going above 4,500 c/s. A 700 kc/s station modulated in this way occupies a channel between 700+4·5 kc/s=704·5 kc/s to 700 – 4·5 kc/s= 695·5 k/cs. The channel thus ranges from 695·5 to 704·5 kc/s and is 9 k/cs in width.

The modulation frequencies applied to the carrier give rise to what are known as the SIDEBANDS. In the case discussed the upper sideband extends up to 704·5 kc/s and the lower sideband down to 695·5 kc/s.

The waves radiated from a transmitting aerial induce currents in any receiving aerial that they encounter. If the receiving aerial is tuned to the carrier frequency these currents are of respectable strength and suffice to operate the receiving set. When you switch on your set hundreds of transmitting stations are causing minute currents to be induced in the aerial; but if the Q of your tuned circuits is sufficiently good, and if there are enough of them to provide adequate filtering, the set will respond so much more strongly to the frequency to which it is tuned than to other frequencies that the desired station alone is heard.

Modulated electro-magnetic waves like those seen in Fig. 47 set up corresponding electrical oscillations of appreciable strength in a receiving aerial tuned to the carrier frequency (Fig. 48). These oscillations, which correspond in form to the modulated carrier, are magnified by the signal frequency amplifier.* Just how much amplification at signal frequency is needed depends on the amplitude of the incoming oscillations.

The signal-frequency part of the set such as that shown in Fig. 48 determines the selectivity of the apparatus. The selectivity of signal-frequency stages is cumulative. That is, if at resonance one tuned circuit reduces the response to the unwanted signal to 0·047 of that to the wanted signal, a second similar tuned circuit properly used in cascade will reduce it to $0{\cdot}047 \times 0{\cdot}047$, or 0·0022. A

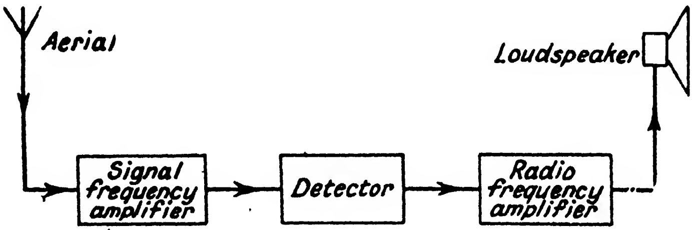


FIG. 48.—Block diagram of simple receiving set.

third will bring it down to $0{\cdot}047 \times 0{\cdot}047 \times 0{\cdot}047 = 0{\cdot}0001$, or $\frac{1}{10,000}$.

The output of the signal-frequency stage of the receiving set is shown diagrammatically in Fig. 49*a*. It consists of

* *Note on Frequencies.*—A good deal of difficulty is caused to the reader by the rather loose use in many textbooks of terms such as "radio-frequency," "high-frequency" and "low-frequency." In this book, to avoid all confusion, I shall henceforward use "signal-frequency" to indicate the frequency of the waves reaching the receiving aerial and "audio-frequency" to indicate the frequencies of speech and music. The high-pitched sounds of speech and music will be referred to as "upper audio-frequencies" and the corresponding low-pitched sounds as "lower audio-frequencies." In this way such absurdities as high and low high-frequencies and high and low low-frequencies will be avoided. Where the term "high-frequency" is used in this book it refers to the rapid alternations of voltage or current occurring in the wireless set and serves to distinguish them from the more sedate 50-c/s alternations of the domestic lighting and power supply.

an oscillating voltage whose swings are electrical copies of the carrier wave with its sideband modulation. To enable this to be translated into intelligible signals a double process is necessary.

This is known as DETECTION or demodulation. You will see that if we applied current in the form shown

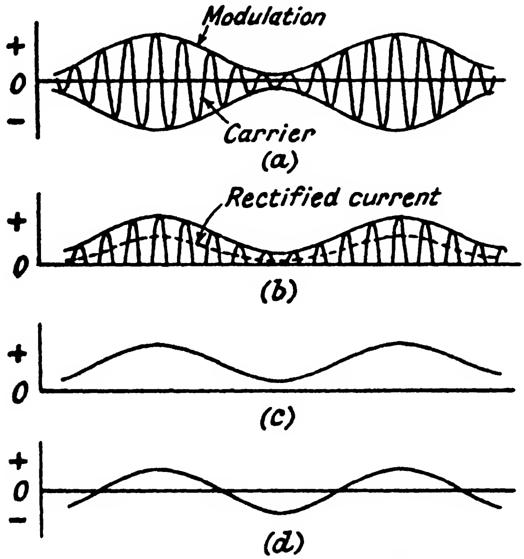


FIG. 49.—The output (*a*) of the signal-frequency stages consists of electrical oscillations which are close copies of the carrier wave and its sidebands. To obtain a current which will operate telephones or loudspeaker, rectification (*b*) is necessary. The carrier wave must also be filtered out (*c*). Reconversion to A.C. takes place in the A.F. amplifier.

in Fig. 49*a* to a pair of telephones or to a loudspeaker, nothing would happen. The upper and lower halves of the signal are equal and opposite; pushes and pulls of the same strength would take place simultaneously and the diaphragm or cone would remain stationary.

One half of the signal is got rid of by rectifying it, or converting it into D.C. The rectified current does not reach the peak value of the original signal; it has a lower value as indicated by the dotted line in Fig. 49*b*.

Something else remains to be done: the carrier frequency must be eliminated, for it is only the audio-frequency modulation that is now required. How this is done will be explained in the chapter on detectors. When this process has taken place the detected signal is as seen in Fig. 49*c*. The signal is now in the form of a fluctuating D.C. voltage. It has its cycles and half-cycles, but as it fluctuates between zero and maximum positive and never goes negative it is D.C.

Reconversion to A.C. takes place in the first audio-frequency stage (Fig. 49*d*). In the A.F. amplifier the signal can again be amplified to any required extent. It continues to be in the form of voltage swings until it has passed through the final, or output, valve. The loudspeaker is, as we have seen, a current-operated device, requiring the expenditure of power to make it work. The output of the last valve in the receiver, then, is in the form of current oscillations, which are delivered to the speech coil of the loudspeaker.

And so the sound waves which reach the microphone at the transmitting station reappear as sound waves in our homes owing to the compressions and rarefactions of the surrounding air by movements of the loudspeaker cone.

The whole process of wireless transmission and reception may be summarised in the following way. Sound waves reaching the microphone give rise to fluctuating direct currents which are electrical copies of them. Transformed into A.C. and amplified, these are made to modulate the output of the oscillator. After amplification, these modulated oscillating currents are fed to the aerial, where they give rise to the radiation of electro-magnetic waves.

The radiated waves are in the form of a carrier with the modulation superimposed upon it.

Nearly all medium-wave transmitting stations erected in recent years have aerials which ensure a better " service area " than those of the older type described on page 84. These aerials, which are known as vertical radiators, are steel lattice towers, half a wavelength in height, standing on huge insulating bases. As the wavelength of a station may be altered from time to time, arrangements for retuning the aerial have to be incorporated. These may consist of a coil of variable inductance in the middle of the tower and at its top an array of telescopic horizontal arms (rather like the ribs of an umbrella) which enable the capicitance to be varied as required.

On reaching a receiving aerial tuned to their carrier frequency the waves induce currents which are electrical copies of the modulated carrier. The corresponding voltages are amplified by the signal-frequency stages of the receiver. Then, after demodulation by the detector, they are further amplified and finally delivered by the output valve as current oscillations to the loudspeaker. The loudspeaker converts them into sound waves which are reasonably good copies of the sound waves reaching the microphone in the studio.

CHAPTER IX

The Valve: (1) Detectors

THE electric glow lamp, by the light of which you may be reading this, works in the following way. The E.M.F. supplied by the mains drives a current, or stream of electrons, through its filament. The magnitude of the current depends on the E.M.F. and the resistance

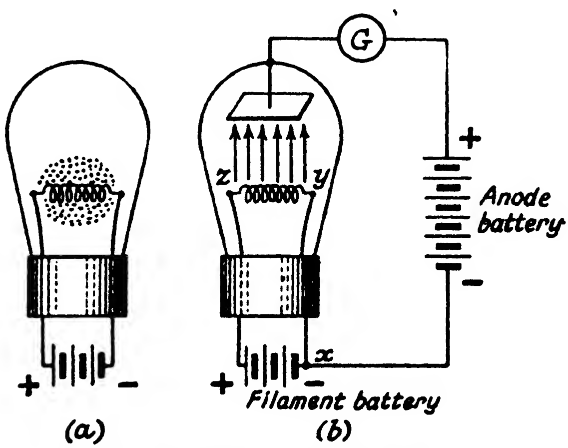


FIG. 50.—Round a glowing filament in an evacuated bulb (*a*) there is a swarm of dancing electrons. If a metal plate is sealed into the bulb and given a positive potential (*b*), electrons are drawn across the vacuum and the galvanometer G registers a current.

of the filament. Such is the energy expended in the process that the filament becomes white hot and emits light.

The electrons are in a state of terrific activity. Many of them actually leave the filament and, after brief excursions into the surrounding vacuum, return to it again. At any instant the glowing filament of an electric lamp is surrounded (Fig. 50*a*) by a cloud of ejected electrons, some just leaving it, some in the course of their gyrations, others on their way back to it.

In the 1880's Edison, who was trying to discover the reason why the bulbs of his early lamps, fitted with carbon filaments, became blackened on the inside after a short period of use, found that if a metal plate (Fig. 50*b*) were sealed into the bulb and given a positive potential, a current appeared to flow across the vacuum of the bulb. No use could then be found for this discovery, which remained for many years nothing more than an interesting laboratory curiosity known as the Edison Effect.

When wireless had come into being Sir Ambrose Fleming perceived that the Edison Effect had a useful rôle to play. The FLEMING DIODE was the first wireless valve, the direct ancestor of every one of the numerous types that we now have. In the valve the filament or other starting point of electrons is known as the CATHODE, whilst the plate, their destination, or point of arrival, after their journey through the vacuum, is called the ANODE.

It is well worth while to consider Fig. 50*b* for a short time. The negative electrons are drawn across the vacuum because of the pull exercised on them by the positive ions on the anode. The traffic is entirely one way. Were the anode battery reversed so as to make the anode negative a force of repulsion would be exerted on the electrons dancing round the filament. Electrons, then, can flow in one direction only: from the cathode to a positively charged anode.

Fig. 51*a* indicates how the Fleming diode* was used as

* The -ode suffix of diode, anode, cathode, etc., is derived from the Greek word *hodos* meaning a path. The various conductors inside the valve are called electrodes, or paths for electrons. A valve containing two electrodes is a diode; one with three electrodes, a triode; one with four electrodes, a tetrode; one with five electrodes, a pentode; one with six electrodes, a hexode; one with seven electrodes, a heptode; one with eight electrodes, an octode.

a detector. At (*b*) is seen the crystal detector, which the diode replaced for certain purposes.

Let us consider the action of the crystal detector first. The junctions of certain crystals, such as those of galena and carborundum, and a metal have the property of offering a comparatively low resistance to current passing through them in one direction and a very high resistance indeed to current passing through them in the opposite direction. If, therefore, an alternating or oscillating current is applied to such a combination, little opposition

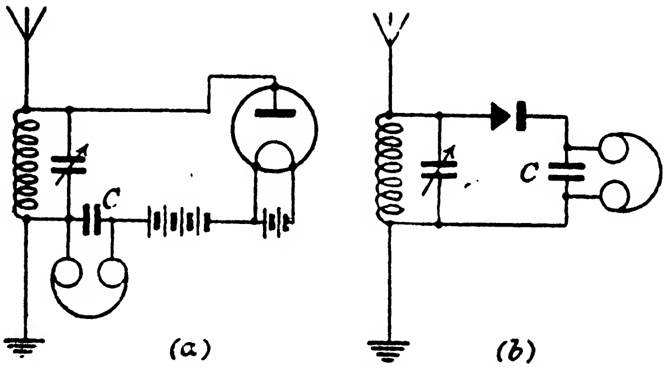


FIG. 51.—The diode valve (*a*) and the crystal (*b*) as detectors.

is offered to, say, the positive half-cycles, during which current flows readily. During the other half-cycles, opposition is so great that the flow of current is minute. Thus there is a one-way current, flowing during the positive half-cycles only, and the net result is that RECTIFICATION, the conversion of A.C. to D.C., takes place.

Fig. 52 illustrates diagrammatically what happens. At *a* are seen the voltage oscillations, corresponding to the carrier and its sidebands, applied to the detector. The resulting spurts of uni-directional current are seen at *b*. These currents charge up the condenser C in Fig. 51, which acts as a kind of reservoir for them, " ironing out " the signal-frequency swings into audio-frequency swings as seen at *c*, corresponding to those of the modulation envelope. These last pass from the condenser through the telephones and actuate the diaphragms.

The operation of the diode valve is similar. The valve, like the crystal, rectifies and the condenser C smooths

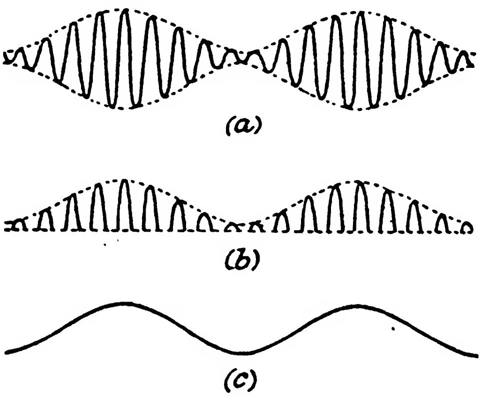


FIG. 52.—(*a*) E.M.F.s applied to crystal; (*b*) the resulting spurts of current; (*c*) the charges produced in the condenser C.

out the rapid surges of current into a copy of the A.F. modulation envelope.

In crystal sets the condenser C may sometimes be removed without making much difference to results. This simply means that a sufficient reservoir effect is produced by the stray capacitances of the wiring and of the telephones themselves.

The diode valve as detector is little if any better than the crystal as regards sensitiveness, for it does not amplify. Its main advantages are that it does not need the delicate adjustment required by the crystal detector of the "catwhisker" type and that it is far more stable. The diode is used to-day to a considerable extent as detector (with signal-frequency and audio-frequency amplification), and it plays an important part in the power packs of A.C. mains receivers, in which it is used as a rectifier.

The diode's historical importance is that it was the first kind of thermionic wireless valve and that it paved the way first for the three-electrode valve and then for more complex types, whose uses are legion.

The term "thermionic," by the way, comes from the Greek words *thermos*, hot, and *ion*, something making a journey. It is used of apparatus in which electrons are ejected from a heated cathode. Another term often used nowadays is "electronic." This is used of any kind of apparatus in which a stream of electrons is drawn across a vacuum from a cathode by means of a positively charged anode. "Electronics" is the department of electricity which deals theoretically and practically with apparatus of this kind.

There is one point which had better be cleared up before we go any further, for I know that it presents a difficulty to some people. In Fig. 50*b* both the electrons from the anode battery and those from the filament battery must pass through the conductor marked *x*, *y*. Many cannot at first see how one wire can carry simultaneously two different currents. How, again, do those two currents sort themselves out on reaching the point *y*? Some of the electrons are supplied by one battery, some by the other; why don't they get mixed up?

Think of it in this way. A flow of current, or a stream of electrons, is caused by the attraction of positive ions. Suppose that on the anode, which is connected to the positive terminal of the anode battery, there are 1,000 positive ions (actually the number might run to billions of billions, but we will stick to small figures). Then 1,000 electrons are attracted from the negative terminal of the anode battery and make their way to *y*. If there are 1,000 positive ions also at *z*, which is connected to the positive terminal of the filament battery, 1,000 electrons are attracted from the negative terminal of that battery and make their way to *y* also.

Thus 2,000 electrons travel from *x* to *y*, and when they arrive at *y* they find a " demand " for one thousand by the anode and for a second thousand by the point *z*. And so 1,000 of them travel from the point *y* through the filament to *z* and the other thousand cross the vacuum to the anode. One cannot say which path an individual electron will choose; it is all a question of the supply and demand of the moment. But in the case discussed each battery supplies 1,000 electrons from its negative terminal and 1,000—not necessarily the same electrons—are returned to it at its positive terminal.

One of the most important of all wireless inventions was made by an American physicist, Dr. Lee de Forest. At first sight there appears to be nothing very startling about it, for it consisted simply in placing a helical* coil of fine wire between the filament and the anode of Fleming's diode. That little coil of wire has had effects which not even the most fertile imagination could have foreseen at the time of its invention.

Prior to the introduction of the GRID, as this coil of wire is called, the valve could do no more than rectify A.C., or detect wireless signals without amplifying them. The grid made the valve able to oscillate and to amplify

* The terms helix, helical and spiral are often misused—even in scientific textbooks ! A helix is a cylindrical coil, all of whose turns have the same diameter but do not overlap. A spiral has turns of constantly diminishing diameter. The " spiral staircase " of which one hears and reads is nearly always helical.

as well as to rectify. Without it there could have been no broadcasting, no satisfactory long-distance radio telephone services, no television and no radar.

Fig. 53 illustrates the internal arrangements of a three-electrode valve. Supports for the filament, grid and anode are sealed into a glass FOOT, or "PINCH," which is itself sealed into the base of the evacuated glass bulb.

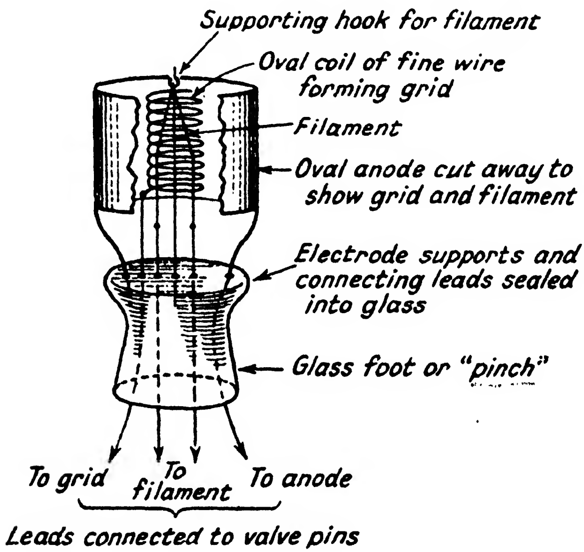


FIG. 53.—The electrodes of a triode valve mounted on the glass foot or "pinch," which is sealed into the evacuated bulb.

Leads to filament, grid and anode are brought out through the foot and connected to the metal pins fixed into the cap of the valve. The type of construction illustrated in Fig. 53 applies only to the directly heated valve used in battery-operated receiving sets. The cathode is here a filament, heated by the passage of current through it.

Remember that it does not matter how the cathode is heated—a bunsen burner might be used if it could be fitted in !—so long as it is brought to a temperature high enough to cause electron emission. In valves used in mains-operated sets the cathode is indirectly heated. The heating current passes through a heater, consisting of turns of wire, which perform on a smaller scale the same function as those of the familiar electric fire. The cathode is insulated from the heater. It starts to emit electrons when the heater has raised its temperature sufficiently—

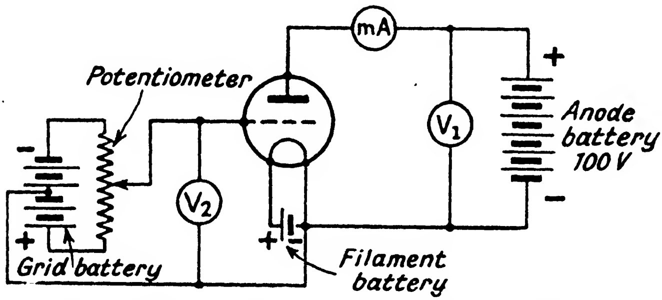


Fig. 54.—Simple circuit for taking the characteristic curves of a triode.

hence the " warming-up time " that follows the switching on of a mains set before anything is heard.

For the present we will consider battery valves with directly heated filament cathodes, since these introduce less complications than do valves with indirectly heated cathodes.

We shall see a good deal in the pages which follow of grid and anode potentials or voltages. These are always measured with respect to the negative end of the filament in a battery valve and to the cathode in an indirectly heated valve. Thus $E_a = 100V$, $E_g = -4V$ means that the anode is 100 volts more positive than the negative end of the filament (or the cathode) and that the grid is 4 volts more negative than the negative end of the filament (or cathode).

Fig. 54 shows a simple circuit which may be used for finding out a good deal about the characteristics of any particular triode. A 100-V battery with tappings allows the anode to be made anything from, say, 50V to 100V positive. The voltmeter V_1 records the anode voltage and the milliammeter mA the anode current. By means of the potentiometer the grid may be given a positive, negative

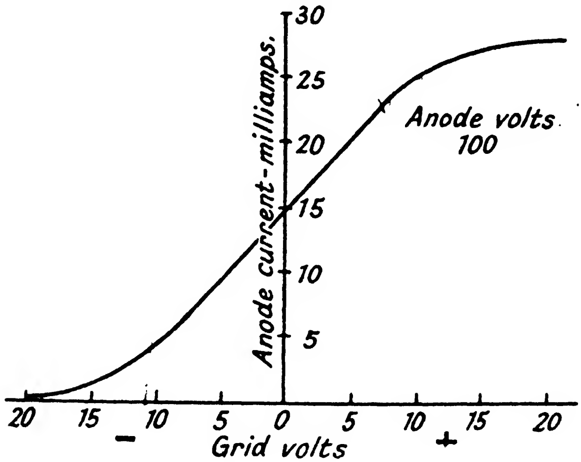


FIG. 55.—Typical curve obtained with the Fig. 54 circuit.

or zero potential, the amount of which is measured by the second voltmeter V_2.

Keeping the anode volts at 100 and raising the grid potential one volt at a time from, say, − 20V to +20, the anode current, recorded by the milliammeter mA, is plotted step by step against the grid volts. The resulting curve might have the kind of shape shown in Fig. 55.

As the grid is so much nearer to the filament than is the anode, positive or negative voltages upon it have even stronger attractive or repulsive effects on the emitted electrons. To put it in another way, a comparatively small negative voltage on the grid is sufficient to neutralise the pull of a considerable positive voltage on the anode. A small positive voltage on the grid has the same pulling effect on electrons as a much larger voltage on the anode.

This is what is seen in Fig. 55 when the grid is made 20V negative: the electrons shot out of the filament are so strongly repelled by the grid that the 100V on the anode cannot draw any of them across the vacuum. No anode current flows and this particular valve is said to have a CUT-OFF at −20V on the grid, or $E_g = -20V$.

As the grid voltage is made steadily less negative, anode current begins to flow. Its rise is slow in this particular case until about −12V is reached and the early portion of the characteristic is markedly curved. After that the rise of anode current is regular and rapid as the grid becomes less negative, and the next portion of the characteristic is nearly a straight line. Lastly, when the grid has reached a certain positive potential (+10V in this case) the anode current tails off and the characteristic again becomes curved.

The three parts of the grid-volts anode-current CHARACTERISTIC, or CURVE, are known as the LOWER or BOTTOM BEND, the STRAIGHT PORTION, and the UPPER BEND.

The lower bend is brought about by the interaction of the electrons in the cloud dancing round the filament. These electrons are called the SPACE-CHARGE and they all repel one another; the outer electrons drive back those nearer the filament. Not until the grid potential has been made considerably less negative than cut-off can the positive anode potential exercise sufficient pull to overcome the space-charge effect. After that reducing the negative grid potential—making the grid more positive—results in a steady increase in the anode current.

So long as the grid is negative it attracts no electrons to itself; all that are drawn across the vacuum go to the anode. But when the grid reaches zero potential some of the electrons are caught by the grid and there is a current from filament to grid. This current rises as the

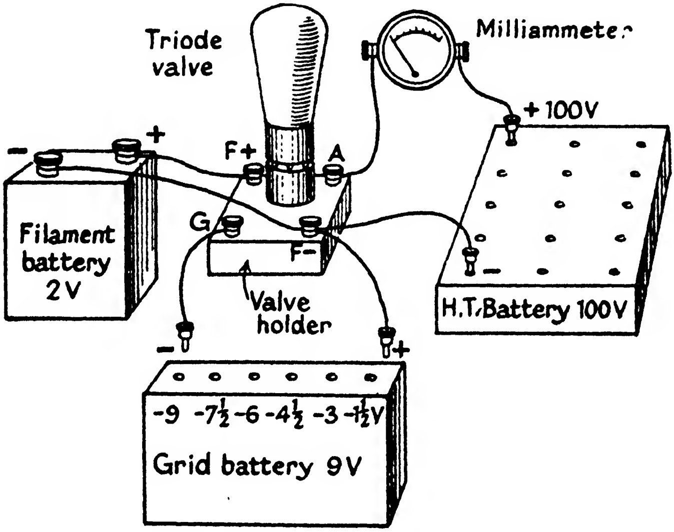


FIG. 56.—A " hook-up " with which triode characteristics may be plotted roughly.

grid is made more and more positive. The upper bend is reached when all the available emitted electrons are being drawn from the region of the filament, but so large a proportion is going to the grid that the anode current tails off. Finally the SATURATION POINT is reached when no further increase in the positive grid potential causes any rise in the anode current.

I recommend you to plot one or two grid-volts anode-current characteristics of battery triodes for yourself, even if they are roughly made with the kind of " hook-up " illustrated in Fig. 56. If you have, or can borrow, one or two battery triodes (not of the power valve type), a milliammeter reading 0-25mA, a filament accumulator and dry H.T. and tapped grid batteries, the process is quite simple.

On a sheet of paper (graph paper for choice) rule out a frame like that of Fig. 55, showing single milliampere divisions on the upright and 1½ volt divisions on the horizontal. Find the cut-off by making the grid so negative that the milliammeter records no current; then make the grid progressively less and less negative by moving the wander-plug one socket at a time. Plot in each reading of current.

When you have plotted " grid volts zero " (grid wander-plug held against F – terminal) reverse the grid battery: that is, put the F – wander-plug into the grid battery – 9V socket and insert the grid wander-plug successively into the – 7½, – 6 sockets, and so on. The – 7½V socket now represents + 1½V, and so on.

Your results will not be accurate; but I think that you will find them interesting and instructive.

The important points about valves to note so far are these:

(1) A comparatively small grid voltage is able to control the flow of anode current.

(2) So long as the grid is negative no current flows in the grid circuit and there is therefore no expenditure of energy there.

(3) Thus, if it is kept negative, the grid controls the current in the anode circuit without expending any energy in so doing. That is the real secret of the valve's efficiency.

Now let us see how a three-electrode valve may be used as a detector. Fig. 57 shows one possible circuit for the purpose. The voltages due to oscillating currents induced in the aerial, which is tuned by the circuit LC_1, are fed to the grid of the triode via the capacitor C_2. When the valve is employed as a detector in the way shown its filament-grid portion functions as a diode.

Positive half-cycles of voltage make the grid positive and there is a flow of GRID CURRENT. This, remember, is a stream of electrons from the cathode to the grid. During the negative half-cycles either no grid

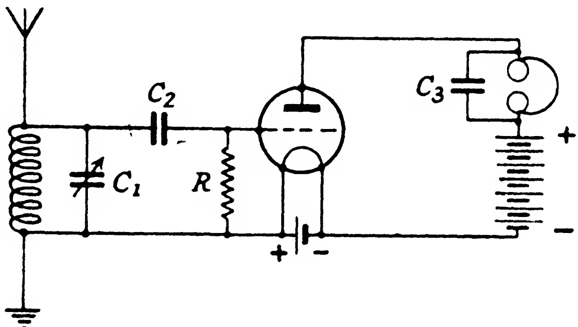


FIG. 57.—The triode used as gridleak and condenser detector.

current at all passes, or the flow is very much reduced. The net result is a flow of current into the capacitor C_2, the plate nearest the grid acquiring a negative potential.

The potential between the plates of the capacitor C_2, in fact, rises and falls in accordance with the amplitude of the incoming oscillations and has very much the "shape" seen in Fig. 52*b*. Owing to the presence of the resistor R in Fig. 57, the capacitor is able to charge and discharge in such a way that the potential difference between its plates follows the amplitude of the applied oscillations. But for the discharge path provided by R, current would continue to flow into C_2 during every positive half-cycle and the effect would be to continue charging up C_2.

Since one plate of C_2 is connected directly to the grid of the valve, the grid must be at the same potential as this plate. The voltage variations on the grid consist of the symmetrical S.F. swings of varying amplitude of the incoming signal. Superimposed on these are A.F. rises and falls of voltage, corresponding to the modulation envelope of the S.F. signal. Since the grid voltage controls the anode current this current is affected by both these series of voltage changes. The anode current has thus three components: (1) the D.C. from the source of H.T. supply; (2) the A.C. of varying amplitude at S.F. corresponding to the carrier of the incoming signal; (3) the A.C. of varying amplitude at A.F. corresponding to the modulation envelope.

The S.F. component of the current, which is of no use for working the 'phones, is by-passed by the capacitor C_3, whose reactance to such frequencies is very small. This capacitor, however, offers a high reactance to the A.F. current, which is made to pass through the 'phones along with the D.C. component. These two currents together constitute (Fig. 52*c*) a pulsating D.C. which results in the emission of audible sounds by the 'phones.

But for R, which forms a leak-away for C_2, a greater and greater negative charge would build up on the grid until cut-off was reached and no current of any kind could pass through the valve. The valve would become choked or paralysed by the increasing negative grid potential.

That this does happen can easily be verified if you make up the Fig. 57 circuit and remove or disconnect R when it has been working for some time. For a moment signals continue to come through; then they fade away and there is complete silence when the increasing negative voltage on the grid has choked the valve by taking it to cut-off and beyond. The time constant of C_2 and R must be such that the charges and discharges of C_2 can follow the modulation envelope.

C_2 is known as the GRID CONDENSER and R is the GRIDLEAK. This kind of detection is called grid-leak-and-condenser, or leaky grid condenser, detection.

Another way in which the triode can be used as detector is illustrated in Figs. 58 and 59. By means of the grid battery G.B. the grid of the valve is given a sufficient

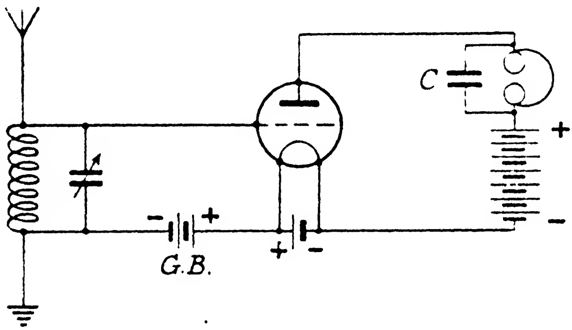


FIG. 58.—The triode as bottom-bend detector.

standing negative potential, or BIAS, to bring the working point to X in Fig. 59. The working point, you will see, is at the top of the lower bend of the characteristic. In the case of the valve whose characteristic is seen in Fig. 59 the negative bias required to do this is 3 volts when the anode voltage is 100. When an alternating voltage swinging between $+2\frac{1}{2}$V in the positive half-cycles and $-2\frac{1}{2}$V in the negative is applied to the grid the results are as seen in Fig. 59.

A positive peak of $2\frac{1}{2}$V takes the grid up to $+2\frac{1}{2} - 3V = -\frac{1}{2}V$; a negative peak takes it to $-2\frac{1}{2} - 3V = -5\frac{1}{2}V$.

In the positive half-cycles the anode current rises from a little over $\frac{1}{2}$mA to 4mA, whilst in the negative half-cycles it falls by only $\frac{1}{2}$mA. Rectification thus takes place as indicated in the drawings and the capacitor C again irons out the rectified current, separating the S.F. component from the A.F. component.

The lower-bend detector is not much used nowadays,

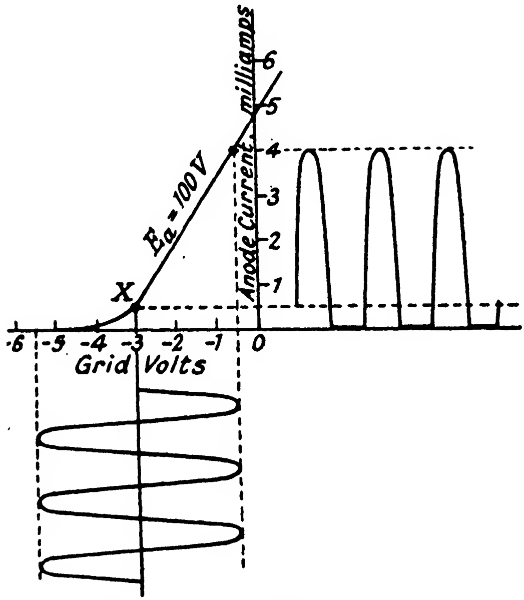


FIG. 59.—Bottom-bend rectification.

for it has one very bad fault. The voltage swing shown in Fig. 59 between $+2\frac{1}{2}$V and $-2\frac{1}{2}$V peak is comparatively large. What would happen if the grid volts swung only from $+\frac{1}{2}$V to $-\frac{1}{2}$ at the peaks? Plot this yourself and you will see that there is hardly any rectification. This kind of detector, in a word, is more effective with large amplitudes than with small; hence it deals unevenly with a broadcast transmission, where the amplitudes are continually varying, and introduces distortion to an undesirable degree.

The outstanding points about detection may be summarised as follows:

(1) The currents induced in a receiving aerial and passed on by it to a receiving set correspond to the carrier wave with its envelope of modulation sidebands.

(2) To enable telephones or loudspeaker to translate these currents into intelligible sounds the carrier wave and one-half of the modulation envelope must be eliminated.

(3) This is done by the detector, which gets rid of one half of the sideband envelope by rectifying the signal applied to it. The carrier wave is "ironed out" by the use of a reservoir capacitor.

(4) This capacitor is charged up by the rectified currents reaching it. It is enabled to discharge by the provision of a leak in the form of a path of high impedance or resistance. The difference of potential between its places thus varies in accordance with the varying voltages of the remaining sideband envelope.

(5) The crystal and the diode valve rectify without amplifying.

(6) When the triode is used as a detector of the gridleak-and-condenser type the voltages between the plates of the leaky capacitor are applied to its grid. Such voltages, as the next chapter shows, control the anode current and amplification takes place.

(7) Amplification also takes place when the triode is used as a bottom-bend detector.

CHAPTER X

The Valve : (2) Amplifiers

IN the last chapter we saw that rectification is brought about in either of the two systems described by adjusting the triode so that its response to two consecutive half-cycles of an oscillating voltage applied to its grid is uneven. In the gridleak and condenser method the valve is adjusted so that the working point (Fig. 57) is with the grid biased slightly positively. In that drawing the grid is connected through the gridleak to the positive terminal of the filament battery. Since the reference point for all potentials in the battery valve is the negative end of the filament the grid in Fig. 57 has a positive bias; it is more positive than the negative end of the filament. Different valves of battery and mains types require slightly different adjustments for the best results; detectors of this kind may operate with working points ranging from grid potential zero to *plus* two volts or more with respect to the negative end of the filament or the cathode.

The important point is that the valve must be so biased that it discriminates between the positive and negative voltage half-cycles reaching its grid. To be a good detector of this class the valve must "favour" the positive half-cycles by passing grid current so long as each lasts and must show antagonism to the negative half-cycles by cutting off the grid current during their presence.

It may be taken that any normal triode will show this discrimination to some extent if its working point is near zero grid volts. That is, grid current will flow if the peak of a positive half-cycle of applied voltage takes the grid to zero volts or to some positive value.

The bottom-bend detector exercises discrimination when the negative half-cycle of voltage on the grid takes the working point for a moment down on to the curved part at the lower end of the grid volts anode-current characteristic.

Hence discrimination against one part of the voltage cycle reaching the grid is going to occur either if the positive half-cycle makes the grid so positive that grid current flows, or if the negative half-cycle makes the grid so negative that the working point is taken for an instant down on to the lower bend.

In the process of detection we want such discrimination to occur. We want the valve to make full response to only one half of each cycle. We want the distortion caused by the partial or complete suppression of response to one half of each voltage cycle arriving on the grid. But our requirements from the valve used as an amplifier are very different. Here we need the valve to respond equally to both halves of each cycle. There must be no distortion, for the duty of an amplifying valve is to magnify truthfully. The output in its anode circuit must be an enlarged but otherwise unaltered copy of the input to its grid circuit.

From what has been said it will be realised that for a valve to amplify faithfully and without distortion its normal working point must be so adjusted that the peak of no positive voltage half-cycle on the grid takes it up even for an instant into the grid current area and the peak of no negative half-cycle takes it down into the lower bend of the characteristic.

Fig. 60 gives an indication of the way in which this is done—it is not quite the whole story, as we shall see presently. The grid battery G.B. enables the valve to be so biased by means of a standing negative potential applied to its grid that the normal working point is in the middle of the straight portion of the characteristic lying to the left of the vertical straight line representing zero grid volts. In the case illustrated a negative bias of 3 volts produces the desired effect. It will be seen that this

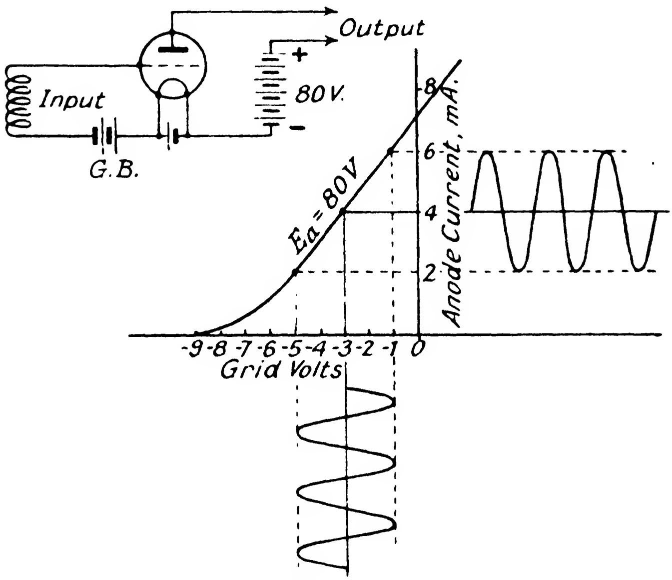


FIG. 60.—The triode as amplifier. By means of negative bias the normal working point X is adjusted so that it is in the middle of the straight portion of the characteristic to the left of the vertical zero grid-volts line.

particular valve with 80 volts in its anode can handle without distortion a voltage applied to its grid which swings from +2V at the positive peak to – 2V at the negative peak.

The anode current output is a magnified copy of the grid voltage input.

Fig. 61 shows what is known as a FAMILY of grid-volts anode-current characteristic curves for the same valve, made by increasing the anode volts 10 volts at a time from 60V to 100V. It will be gathered from them (1) that the effect of raising the anode volts is not to alter the shape of the characteristic but to shift it bodily to the left; (2) that the result of this is to increase the length of

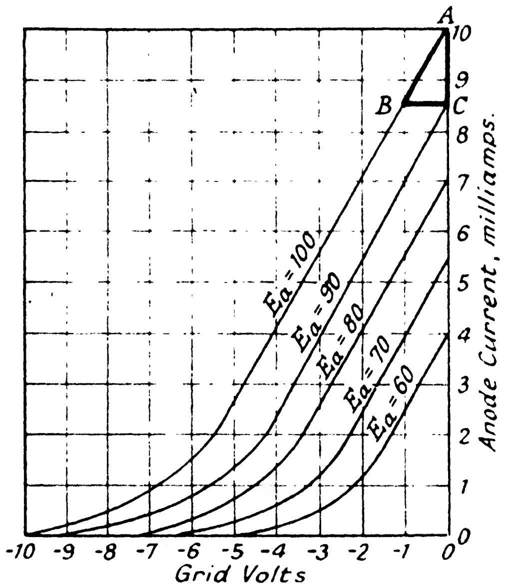


FIG. 61.—A family of grid-volts anode-current curves.

the useful straight portion (and therefore the extent of the grid voltage swing which the valve can handle without distortion) as the anode voltage is raised.

From such a family of curves much useful information about the valve and its performance can be gained. First of all we can obtain a measure of the valve's efficiency. Look at the triangle ABC at the top of the diagram. With the grid at zero volts and 100V on the anode (point A) the anode current is 10mA. If we make the grid bias − 1V with the same anode voltage (point B), the anode current is reduced to 8·5mA (point C). In other words, changing the grid voltage by 1V changes the anode current by 1·5mA. Just as we can describe the slope of a hill as 1 in 10, or $\frac{1}{10}$, so we can describe the slope of the straight portion of the characteristic, using the symbol *d* to mean " change of," as

$$\frac{dI_a}{dE_g} = \frac{1 \cdot 5}{1}$$

or one and a half milliamperes per volt—1·5mA/V. This is known as the MUTUAL CONDUCTANCE or SLOPE (symbol g_m) of the valve. It is a measure of the control exercised by the grid and therefore a measure of the efficiency of the valve.

Remember that any particular value of g_m is true for only one small part of the characteristics; we are concerned with *changes* in anode current and grid volts and not with average values. The slope might be different were triangles drawn in other places. It is conventional in the case of receiving valves to measure the mutual conductance with anode volts 100 and grid volts zero—that is, from point A in the diagram.

Next we can discover from the family the amount of amplification of which the valve is capable. Starting again with grid volts zero, anode volts 100 (point A), we find that there are two ways in which the anode current can be reduced from 10mA (point A) to 8·5mA (point C). The first is to change the grid bias by making it one volt less positive (point B); the second is to change the anode volts by 10, making the anode 10 volts less positive. Thus a change in grid volts of 1V has the same effect on the anode current as a change in anode volts of 10V:

$$\frac{dE_a}{dE_g}=10$$

This is the AMPLIFICATION FACTOR of the valve (symbol μ, pronounced " mew ").

Raising or lowering the anode volts without altering the grid potential has the effect of increasing or decreasing the anode current. Since the business of an E.M.F. is to drive current through resistance, and the amount of current driven through a given resistance varies according to the E.M.F. applied, this suggests that we are dealing with some kind of resistance in the valve. We are; but as we are concerned with oscillating and changing E.M.F.s driving an oscillating and changing current, this is another of those special kinds of resistance (we have already come across high-frequency resistance and dynamic resistance) which manifest themselves under such conditions.

Starting again from point A, we find that a change of 10 volts on the anode causes a change of 1·5mA in anode current. In this case we must work in volts and amperes, and we have:

$$\frac{dE_a}{dI_a}=\frac{10}{0{\cdot}0015}=6{,}666\Omega$$

This is the ANODE RESISTANCE (symbol R_a) of the valve. It is sometimes called the A.C. resistance or the impedance of the valve; anode resistance, however, is the proper term.

R_a, μ and g_m are all interdependent. If you know any two of them you can find the missing one from:

$$\frac{\mu}{g_m \times R_a}=1$$

Cover up what you want to find and what is left shows you how to find it. Remember that g_m for this purpose must always be expressed in amperes per volt.

Many beginners in the study of wireless find themselves, as I know from experience, confronted by one special point of difficulty. Here it is. In Fig. 60 we see *current* in the anode circuit. But what is going to happen if we have two or more valve amplifiers in cascade? Surely we must apply to the grid of valve No. 2 amplified *voltages* from valve No. 1, and to the grid of valve No. 3 amplified voltages from valve No. 2; it would be of no use to apply current changes in milliamperes to the grid of the valve which, as you will realise, is a voltage operated device.

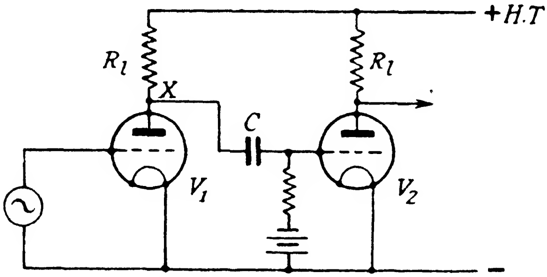


FIG. 62.—The anode load here takes the form of a resistance R_l. Current variations through R_l cause the voltage at the point X to vary accordingly. The varying voltages at X are an amplified copy of the voltage variations reaching the grid of V_1. They are passed on via C to the grid of V_2.

How are the current variations in the anode circuit of one valve made to appear as voltage variations for applications to the grid of the next? This is a point which, almost without exception, the textbooks do not make clear.

The answer is that there is always a LOAD in the anode circuit. This load may be either an impedance or a pure resistance through which current is driven. It is simplest for the moment to consider the case of the resistive load as shown in Fig. 62, in which two resistance-coupled amplifying valves are seen. The anode current flowing through the load R_l gives rise to a potential difference, or voltage drop, across the resistor.

If 3mA flow through a load of 20,000Ω the volts used up in forcing the current to pass are, by Ohm's Law,

$$\frac{3}{1{,}000} \times 20{,}000 = 60.$$

As the current in the anode circuit of a valve is continually varying it follows that there is a similarly varying voltage drop across the load.

A simple method of seeing what happens is to take a characteristic of a valve with a resistor as the load in its anode circuit. Fig. 63 shows the result of doing this with the valve used for Fig. 61, but this time with an available

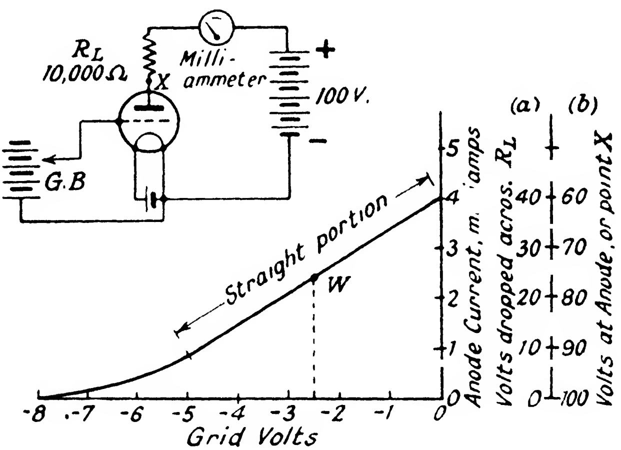


FIG. 63.—The grid-volts anode-current characteristic of the Fig. 61 valve taken with a load resistance R_l of 10,000Ω in the anode circuit. The volts dropped across R_l and the actual volts on the anode are shown at (*a*) and (*b*).

E.M.F. of 100V and with a load resistance (R_l) of 10,000Ω in the anode circuit.

Starting with grid volts zero, we find the milliammeter reading 4mA. A current of 4mA through 10,000Ω means a voltage drop of 40 in the load; the actual volts on the anode are therefore 100 – 40=60V. As the grid is made volt by volt more negative the anode current falls and with it the volts expended in R_l (scale *a*, Fig. 63): the actual volts on the anode therefore increase (scale *b*, Fig. 63) as the grid goes more and more negative.

At grid volts – 5 we reach the lower end of the straight part of the characteristic. The useful portion for amplification purposes thus lies between $E_g=0$ and $E_g=-5V$. Whilst the grid is made progressively 1 volt more negative from 0V to – 5V, the volts at the anode change from 60 to 90. A change of 4V on the grid results in a change of 30V on the anode—a voltage amplification of six times.

You will notice that the voltage changes produced at the anode are exactly opposite in phase to those at the grid: when the grid goes more positive the anode goes less positive and *vice versa*. In other words, a positive half-cycle on the grid gives rise to a negative half-cycle of anode voltage. This is one of the features of the valve: the voltage applied to its grid appears in its output with a phase change of 180°. Thus any odd number of valves in cascade turn a signal " upside down." If the number of valves is even the output voltage is in the same phase as the input: a positive half-cycle on the first grid appears as a positive half-cycle at the last anode.

But, you may exclaim at this point, we saw that the valve whose characteristics appear in Figs. 61 and 63 had a μ of 10; why then isn't the voltage amplification ten times? Why does a change of grid volts of 0 to – 5 not result in a 50-volt change in anode current?

The reason is that the STAGE GAIN (that is, the amplification provided by the valve and its circuits) could be equal to μ only if R_l were infinitely large. But if the resistance of R_l were infinitely large the anode current would be reduced to zero. It follows that R_l must have a value less than infinity and that the stage gain (symbol A) must always be less than the μ of the valve. Actually:

$$A=\mu\times\frac{R_l}{R_l+R_a}$$

In this case $\mu=10$, $R_l=10{,}000\Omega$ and $R_a=6{,}666\Omega$. Thus:

$$A=10\times\frac{10{,}000}{10{,}000+6{,}666}$$

$$=\frac{100{,}000}{16{,}666}=6$$

In practice the highest satisfactory value for R_l is usually taken as four times R_a. The greatest stage gain obtainable with a resistive anode load is thus:

$$A=\mu\times\frac{4}{4+1}=\frac{4}{5}\mu$$

With the valve under discussion the highest stage gain with this form of coupling would be:

$$\frac{4}{5}\times10=8$$

Looking again at Fig. 63 we note that the useful straight portion of the characteristic extends from $E_g=0V$ to $E_g=-5V$. The valve with 100V H.T. can therefore handle without distortion a grid voltage making a total swing of 5V from positive peak to negative peak. This voltage will swing from 0 to $+2\frac{1}{2}V$ in the positive half-cycles and from 0 to $-2\frac{1}{2}V$ in the negative. The working point will therefore be half-way along the straight portion (W in Fig. 63) at $E_g=-2\frac{1}{2}V$, and this is the bias required.

Fig. 64 shows a family of characteristic curves of another kind. To make such a family the grid is first adjusted to zero potential; the anode voltage is then raised by regular steps—say 10 volts at a time—and the anode current plotted against the anode voltage. The next curve is made with the grid kept at 1 volt negative, the third with the grid 2 volts negative, and so on until the family is complete.

These curves are perhaps the most generally useful of all kinds, for they enable us to find out almost everything

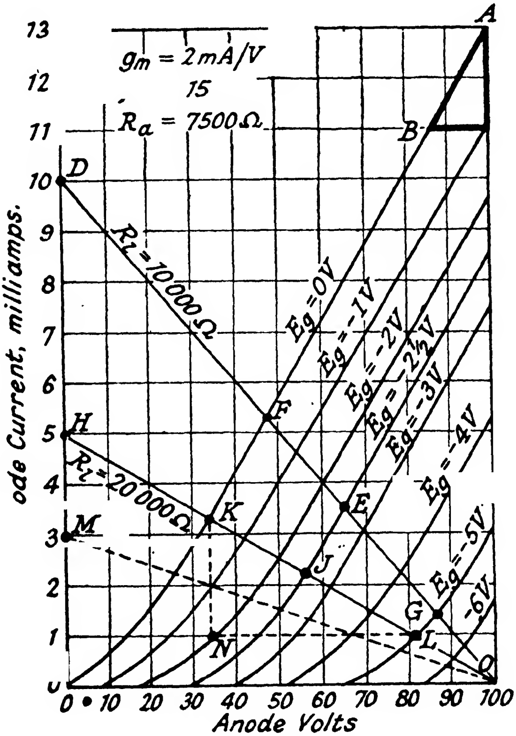


FIG. 64.—A family of anode-volts anode-current curves, with "load-lines."

that we want to know about the valve under working conditions.

From the triangle ABC we can discover g_m, μ and R_a at once. Changing the grid volts by one (B to C) changes the anode current by 2mA: g_m=2mA/V. Changing the grid volts by one from 0V to -1V (B to C) reduces the anode current by 2mA (A to C); to produce the same effect the anode volts must be changed from 100 to 85 (A to B): μ is $\frac{15}{1}=15$. A change in anode volts of 15 (A to B) changes the anode current by 2mA or 0·002A (A to C): R_a is $\frac{15}{0{\cdot}002}=7{,}500\Omega$.

How will this valve behave as an amplifier if a load resistance of 10,000Ω is used in its anode circuit with the 100V of H.T. available? The anode-volts anode-current family will tell us. We know that every milliampere flowing through 10,000Ω will mean a voltage drop of 10 in the resistor. Therefore a change of 1mA in the anode load R_l means a change of 10V in the anode volts E_a. If the anode current I_a changed from zero to 10 mA, E_a would change from 100V to zero. Rule in the line DFEO joining the 100V mark on the diagram and the 10mA mark. This line, which is called a load-line, shows us every possible change that can occur in the anode voltage for grid voltages between zero and -6 with $R_l = 10{,}000\Omega$.

Suppose that we want the valve to handle an oscillating grid potential of 2½V—that is, an applied voltage with positive and negative peaks of +2½V and $-$2½V respectively. From the load-line it seems that $-$2½V would be a suitable standing negative bias on the grid, and this brings the working point to E when no signal is coming in. When a positive peak arrives it makes the grid potential $-2\frac{1}{2}+2\frac{1}{2}=0$V. The working point slides, so to speak, along the load-line from E to F. It slides from E to G when the following negative peak makes the grid potential $-2\frac{1}{2}-2\frac{1}{2}=-5$V. And so the working point may be thought of as gliding rapidly backwards and forwards between F and G so long as an oscillating voltage of $2\frac{1}{2}$V is applied to the grid.

Will the valve amplify faithfully the voltage reaching its grid? The load-line will give the answer. For amplification to be absolutely faithful the halves of each cycle of anode voltage must be equal. Are they here? At E the anode voltage is 65. At F it drops to 48, changing by 17. At G it rises to 88, changing by 23 from the voltage at E. It thus changes in its negative-going half-cycle by 17V and in its positive-going half-cycle by 23V. This means that the negative peak of grid voltage is amplified 6·8 times and the positive peak 9·2 times. The anode circuit voltage cycle is lopsided, or distorted.

The kind of distortion introduced is known as harmonic. The second harmonic of the frequency of the applied voltage is strongly brought out. You can see what a wave may look like when this has happened to it by turning back to Fig. 7. You can hear what sort of sounds it produces by allowing an amplifier to operate in the condition FEG of Fig. 64!

Actually the load-line tells its story far more rapidly than all this might suggest. All that is necessary is to measure the lengths of EF and EG. Provided that the ratio of the longer to the shorter (that is, the greater length divided by the smaller) does not come to more than 1·22 all is well.

Harmonic distortion is measured as a percentage, the percentage which the amplitude of the harmonic represents of the amplitude of the fundamental. If there is not more than 5 per cent. second harmonic it is relatively harmless. That condition is satisfied so long as $\frac{EF}{EG}$ does not exceed 1·22.

Let us try again with a higher anode load. OH is the load-line for 20,000Ω (5mA through 20,000Ω means a voltage drop of 100V), and with J as "no-signal" working point and an oscillating grid potential of $2\frac{1}{2}$V, JK and JL are nearly equal.

To make sure that you have grasped how a load-line is drawn work out for yourself to what anode load OM corresponds.

There is a great deal more than can be learnt about the working of a valve from its anode-volts anode-current characteristic family. Much of this is too advanced and of too mathematical a nature to be within the scope of this book. If you wish to go more deeply into the subject you will find all the information that you require in the chapter on the amplifying stage in "The Technique of Radio Design."*

One further point may, however, be mentioned here. From the curves the output power obtainable from a valve used in the last stage of a receiver can be ascertained. To find it multiply the whole change in anode volts (N-L in Fig. 64) by the whole change in anode current (K-N) and divide the result by 8. Here we have changes of 50 volts and 2·4mA=0·0024A.

$$\frac{50 \times 0{\cdot}0024}{8} = 0{\cdot}015 \text{ watt.}$$

It is plain that the subject of Fig. 64 is *not* a power valve !

Why divide by 8 in the above calculation ? Because we took the peak values of the whole anode voltage cycle and of the whole anode current cycle. To bring the answer to R.M.S. watts we find the average values of positive and negative voltage peaks by dividing the whole change by 2; we then find the R.M.S. volts by dividing by $\sqrt{2}$: we must do the same things with the current. Thus we

* "The Technique of Radio Design," by E. E. Zepler, Ph.D.

have to divide the product of volts and current by $2 \times \sqrt{2} \times 2 \times \sqrt{2} = 8$.

Though we speak of the straight portions of valve characteristics, there is actually no portion of them which is perfectly straight. There is always a slight curve, a continuation of the lower bend. This is one of the reasons why valve amplification falls a little short of perfection: owing to the curvature of the characteristic some distortion is inevitable. But the departure from the true straight line is very small in good amplifying valves and, provided that the rest of the circuit is well designed, the distortion should be insufficient to cause unpleasing results.

Summing up the most important points about valves as simple amplifiers of the type described, we have:

(1) The valve must be so used that the biggest voltage peaks reaching its grid do not take the working point up into the area where grid current flows, or down to the bottom bend.

(2) This is accomplished by the use of a negative grid biasing voltage such that the normal working point when no signal is being received is in the middle of the straight portion of the characteristic to the left of the zero grid volts line.

(3) Voltage changes on the grid control the anode current and produce similar changes in it.

(4) By means of the anode load these current changes are caused to produce voltage changes at the anode.

(5) These voltage changes are amplified copies of the changing voltages on the grid.

(6) The mutual conductance of a valve is the measure of the control exercised by the grid without expenditure of power. It is the efficiency factor of the valve.

(7) The amplification factor is the measure of the amount of voltage magnification of which a valve is theoretically capable.

(8) The anode resistance is the internal A.C. resistance of the valve.

(9) The voltage amplification obtainable from a valve and its associated circuits (the stage gain) depends upon the anode resistance and the anode load. In practice the optimum anode load for a triode is usually not less than twice the anode resistance. The maximum stage gain normally obtainable in a resistance-coupled circuit is four-fifths the amplification factor. It is, however, possible, as we shall see presently, to "step up" the amplified voltage by means of a transformer.

CHAPTER XI

The Valve : (3) Reaction Circuits and Oscillators

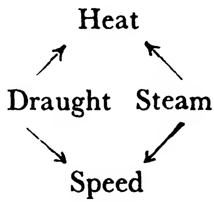
EVERYONE who has watched a railway locomotive in action—and who has not?—must have noticed that, except when it is stationary and inactive, there issues from the funnel a mixture of smoke and steam. Even when the locomotive is standing still the same thing may be seen if the driver finds the head of steam insufficient and turns on the " blower."

To maintain a good pressure of steam a strong draught of air through the furnace is necessary. This is obtained by directing the exhaust steam from the cylinders up the funnel. The steam, which still has considerable remaining pressure, moves up the funnel leaving a vacuum behind it. To fill this vacuum air is drawn through the furnace, thus supplying a draught. The blower is simply a jet of steam up the funnel which can be turned on when the cylinders are idle.

The greater the speed of a train, the larger is the amount of steam used by the cylinders of the engine and therefore the more copious the amount from the exhausts moving up the funnel. Hence, the higher the speed, the greater is the draught through the furnace, the greater its heat and the greater the volume of steam generated in the boiler.

At first sight it might seem that the build-up could continue *ad infinitum*; but commonsense and practical experience indicate that it cannot. There is a limit to the process somewhere.

We may think of the process as taking place in two circuits, which interact with one another. In the engine circuit we have heat⟶steam⟶speed. In the boiler circuit: draught⟶heat⟶steam. The interaction of the two circuits may be shown in the form:



In all cases the arrows represent an idea such as "produces" or "increases."

The build-up is limited because the available energy must come eventually from the far from unlimited amount of coal (or oil) fed to the furnace.

Analogous electrical processes are to be found in the REACTION circuits used in some wireless receivers and in the circuits of the valve oscillators which are an important part of transmitters and of certain receiving sets.

We will consider reaction first. Fig. 65 shows it employed in a type of single-valve receiver which was once commonly used for broadcast reception. Nowadays, fortunately, this kind of receiver has fallen into disuse for broadcast reception. The reason for the "fortunately" will appear in a moment.

When we discussed tuned circuits we saw, if you remember, that the Q of such a circuit and the voltage magnification of which it is capable depend entirely on R_{hf}, the high-frequency resistance. The more R_{hf} is reduced, the greater becomes the voltage magnification. Note that as point No. 1 in considering Fig. 65, in which the tuned circuit is C, L_1.

Next, we have seen that the larger the swings of the oscillating voltage applied to the grid of the valve, the larger are the current changes in the anode circuit. Point No. 2.

In the anode circuit here we have the coil L_2, which is coupled to L_1. Changes in the current through L_2 cause expansions or contractions of the magnetic field surrounding the coil. The lines of force of these fields cut the turns of L_1 and induce E.M.F.s and corresponding currents in that coil. Point No. 3.

The valve amplifies: voltage changes on the grid appear as larger voltage changes at the anode. Point No. 4.

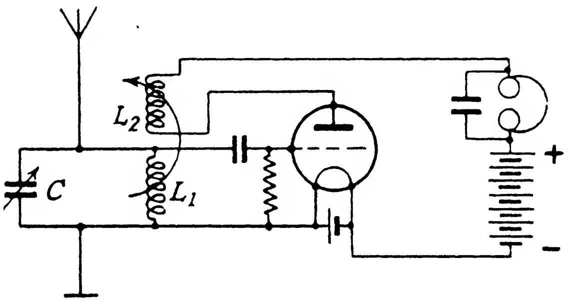


FIG. 65.—A single-valve receiver employing reaction between the anode coil L_1 and the grid coil L_2. The arrow through the coils indicates that the coupling between them is variable.

The currents through L_2 corresponding to the amplified voltage changes at the anode induce amplified E.M.F.s in L_1. Point No. 5.

These amplified E.M.F.s appear as larger voltage changes on the grid of the valve. Point No. 6.

And so the process continues. There is a build-up owing to the interaction between the anode and grid circuits. A larger voltage change on the grid causes a larger voltage change at the anode. There is an increased oscillating current through L_2, an increase in the expansions and contractions of the magnetic field round L_2, an increase in the transference of energy from anode to grid circuit, an increase in the amplitude of the voltage changes applied to the grid.

Now let us see why the build-up of the voltages on the grid takes place. In a tuned circuit such as C, L_1, in Fig. 65, there is an expenditure of power owing to the presence of R_{hf}. This expenditure, instead of being a dead loss, is made good in a reacting circuit by the transfer of energy from L_2 to L_1. R_{hf} limits the Q of a circuit simply because in the ordinary way it causes losses. If these losses are partly made good by energy transferred from the anode circuit, the Q improves. The extent to which it improves depends upon the proportion of the R_{hf} losses made good by energy transferred from L_2 to L_1, by way of the coupling between these two coils. If the degree of coupling between L_1 and L_2 is variable, as it is in receivers of the kind illustrated in Fig. 65, the Q of the tuned circuit is directly controllable: it can be increased or decreased as circumstances demand.

Transference of energy from anode circuit to grid circuit in this way is known as POSITIVE FEED-BACK. For it to be fully effective L_1 and L_2 must be so arranged that the voltages induced by L_2 in L_1 are in phase with the voltage swings on the grid of the valve. The amplitude of the latter is then increased.

It is sometimes stated that the result of the transference of energy from the anode circuit to the grid circuit is to annul the R_{hf} of the latter. This is not so. The R_{hf} of the circuit is still there, but its damping *effects* are cancelled to a greater or less extent by tightening or loosening the coupling between L_1 and L_2. It is the losses due to the work done in overcoming resistance that are made good and annulled by energy from the feed-back current.

Using a single-valve set of this kind is an interesting and instructive experience. Start with L_2 so placed that the coupling between the coils is zero and there is no positive feed-back. The performance of the set is then similar to that of the receiver illustrated in Fig. 57. The sensitivity is poor, only big stations at comparatively short range being strongly received; the selectivity is so inadequate that it may be impossible to separate strong transmissions of widely different frequencies.

Slowly tighten the coupling and a big change becomes more and more evident. The signal strength of a " wanted " transmission increases and it becomes less and less difficult to tune out those that are not wanted. The Q is going up, increasing both sensitiveness and selectivity.

There comes a point at which you begin to notice a woolliness in speech, a lack of brilliance in music. Both are due to the same cause. The Q is now so high that the set is too selective to pass the carrier and the complete sidebands of the transmission. As we have seen, any transmission on the medium-wave or long-wave bands occupies a channel of frequencies extending to some 4,500 c/s above and below the carrier frequency. When the Q is very high the response to f_0, the carrier frequency, is most marked and the tuning is extremely sharp. In such circumstances the response to frequencies above or below f_0 falls off rapidly and the upper audio-frequencies near the outer fringes of the sidebands are attenuated. " Sideband cutting " takes place and the quality of reproduction suffers accordingly. The balance of high-pitched and low-pitched sounds of treble and bass is upset. The lower audio-frequencies are strongly amplified, whilst the upper audio-frequencies are partially or wholly suppressed. What is called FREQUENCY DISTORTION occurs because the balance of the frequencies present in the original sound waves is upset in the reproduction.

It will be realised that in any wireless receiver used for the reception of speech and music as entertainment selectivity must not be of so high an order that it results in sideband cutting. In other words, high selectivity and good quality of reproduction do not go hand in hand. We shall see more about this later.

If the coupling of the coils L_1 and L_2 is still further tightened a rustling noise is heard: the set is on the threshold of OSCILLATION. Another small move of L_2 and it passes into oscillation.

What is now happening is that the feed-back is sufficient completely to annul the effects of R_{hf} in the tuned circuit by removing the effects of damping. The magnetic field of L_1 and the electric field of C build up and collapse alternately without attenuation, all losses being made good by the feed-back from the anode circuit. They are, in fact, rather more than made good, for the energy fed back now exceeds that required to overcome resistance. The tuned circuit becomes a generator of power. Undamped oscillating currents flow in the aerial-earth circuit and radiation of continuous waves takes place from the aerial.

You will now see why such a receiver was unpopular with neighbouring users of wireless sets in the early days of broadcasting. If it was allowed to oscillate (as it not infrequently was by beginners and by older hands who ought to have known better !) the radiations from its associated aerial gave rise to interference which might affect reception over a surprisingly wide area. It became, in fact, a small transmitter.

The power generated in the tuned circuit comes ultimately from the high-tension battery or other source of anode current supply. Either supplies D.C. to the anode and, owing to the control exercised by the oscillating voltages on the grid, the valve in its anode circuit converts this D.C. into alternating or oscillating current. It is this conversion which makes possible the feed-back by induction from L_2 to L_1. The amount of current available from the anode supply definitely limits the power which can be generated by an oscillating valve.

Positive feed-back can occur without there being induction effects between two separate coupled coils as in Fig. 65. Fig. 66 shows a form of Hartley oscillator, in which one coil, L_1, common to both anode and grid circuits, provides the necessary coupling for the feed-back.

At the point W in the anode circuit the direct battery

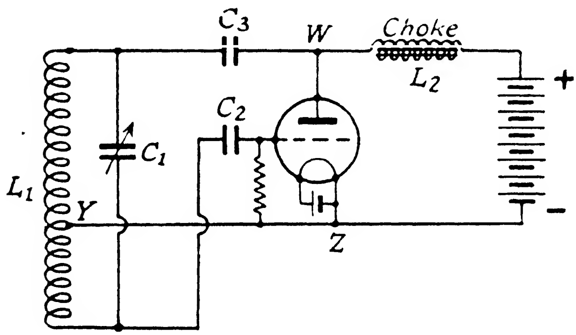


FIG. 66.—The Hartley oscillator.

current finds no appreciable opposition to its flow offered by the inductor L_2 and a complete barrier to its passage in the capacitor C_3. It therefore flows only to the positive terminal of the anode battery and cannot take the path WC_3X.

On the other hand the oscillating portion of the anode current finds the reactance of L_2 a bar to progress and is offered an easy path through C_3.

Remember that the reactance of an inductor increases as the frequency increases, whilst that of a capacitor is less to high frequencies than to low. The coil L_2 is designed to have so high a reactance at the working frequency of the oscillator that it is a barrier to the oscillating current. Such an inductor—a coil designed to prevent the passage of an oscillating current—is called a CHOKE. C_3 is known as a BLOCKING CONDENSER. It bars the passage of D.C.; but its capacitance is such that it has very small reactance at the working frequency of the oscillator.

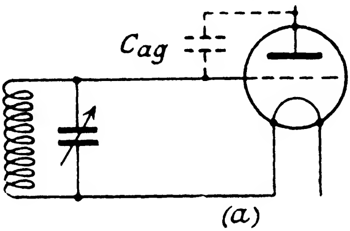
L_2 and C_3 in Fig. 66 are a good example of the use of chokes and blocking condensers as traffic controllers in wireless circuits. Such a combination of correctly chosen inductance and capacitance values sorts out D.C. from A.C. and makes each take the right path.

In the Hartley oscillator of the type seen in Fig. 66 the oscillating part of the anode current takes the path WC_3XYZ, passing through the upper portion of L_1. The magnetic field of this part of the coil cuts the turns of the other part, inducing voltages in it. There is thus a positive feed-back.

Positive feed-back may also take place by capacity coupling between anode and grid circuits. A capacitor, remember, provides a path for oscillating currents. In the triode valve itself we have three electrodes, the anode, the grid and the cathode, all at different potentials, and we have seen that there is capacitance between any two conductors between which there is a difference of potential. For the moment we will consider only the stray capacitance between anode and grid, which is one of the greatest causes of headaches to designers of wireless receiving sets.

This stray capacitance is the sum of that between the actual grid and anode inside the bulb, that between their metal supports, that between their connections in the valve-holder, and that between the wires in the circuit running to anode and grid respectively. It may be represented by the dotted lines of Fig. 67*a*. This anode-grid stray capacitance is known as C_{ag} and for the average triode it may amount to 5 μμF. But the triode is an amplifier and one of the results of its amplifying powers is that the effective value of C_{ag} is increased in proportion to the stage gain A. This is known as the MILLER EFFECT.

The effective value of C_{ag} is $C_{ag} \times (1 + A)$. If the stage



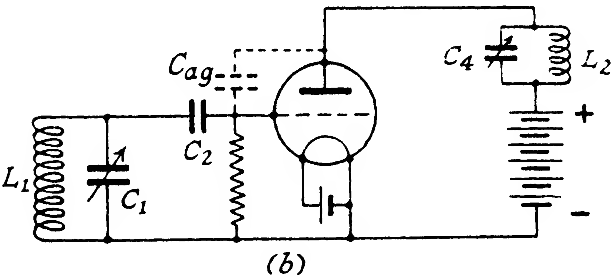


FIG. 67.—C_{ag} represents the total capacitance between the anode and the grid of the valve and their associated wiring connections. At (*b*) this capacitance is seen providing a path for positive feed-back. The circuit here shown will function as a tuned-anode tuned-grid oscillator.

gain is 20 and the anode-grid capacitance of the valve 5 μμF, the effective C_{ag} is $(1 + 20) \times 5$ μμF $= 105$ μμF.

Now suppose that we have high-Q tuned circuits for both anode and grid, as in Fig. 67*b*. C_{ag} provides a path for positive feed-back and the valve oscillates at the resonance frequency. This is fine—provided that we want it to function as an oscillator: the " tuned grid-tuned anode " circuit is often used for very high frequency oscillators. But suppose that we desire to use the valve as an amplifier and wish to tune both its grid and its anode circuits in order to obtain selectivity. You will recall that the greater the number of tuned circuits in cascade the higher is the selectivity obtainable. Again, there is the question of very high over-all amplification by means of a series of valves with tuned circuits. In both cases instability—the liability of circuits to fall into oscillation owing to positive feed-back—presents a problem.

We shall see more of the Miller Effect and of methods of counteracting it when stability is required in our discussions of amplifying circuits in later chapters.

Meantime let us make a summary of what we have seen about positive feed-back effects.

(1) If there is a coupling between the anode and grid circuits of a valve, voltage changes are induced by the former in the latter.

(2) This induction effect is called feed-back. The feed-back is positive when the induced voltages are in phase with those occurring on the grid and serve to increase the amplitude of these.

(3) Positive feed-back reduces the damping effects of R_{hf} in the grid circuit and therefore increases the Q.

(4) This is accomplished by a transfer of energy from anode to grid circuit sufficient partly or entirely to cancel out the energy lost in overcoming R_{hf}. This energy is drawn from the source of anode current supply.

(5) Provided that the feed-back can be controlled, as it can in a well-designed reaction circuit, a very high degree of amplification is obtainable in this way.

(6) The response, however, to f_0 becomes more and

more peaked as the Q is increased, and when the reaction coupling is tightened beyond a certain point the quality begins to suffer owing to side-band cutting.

(7) In a receiving set with reaction the highest degrees of amplification and selectivity are reached at the threshold of oscillation, when energy from the anode circuit is almost sufficient to annul the R_{hf} losses in the grid circuit.

(8) A further increase in the feed-back results in the complete cancellation of resistance damping effects in the grid circuit. The valve now goes into oscillation and becomes a generator of power.

(9) Radiation of undamped, continuous waves occurs if the oscillating valve is coupled to an aerial system.

(10) Positive feed-back can take place by a capacitance path between anode and grid. Such a path exists in the triode owing to the stray capacitance C_{ag}.

(11) Though C_{ag} may be only a few $\mu\mu F$, the effective stray capacitance between anode and grid is $(1+A)\times C_{ag}$.

The "Straight" Receiving Set

ONLY two classes of radio receiving set are in general use for broadcast reception, the STRAIGHT and the SUPERHETERODYNE. The straight, with which we are concerned in this chapter, was for a long time alone in the field. When the more complicated superheterodyne system made its appearance the term straight—possibly an abbreviation of straightforward—was coined to distinguish receivers of the original comparatively simple type from the newcomers.

There must be a detector, which receives impulses at signal frequency and converts them in its output into rectified impulses at audio-frequency. The crystal set, the diode set of Fig. 51 and the single-valve set with reaction of Fig. 65 are the simplest forms of the straight set.

In the first two the only amplification is that at signal frequency due to the Q of the tuned circuit; but this amplification is much reduced by the damping introduced by the diode and the crystal respectively. The effect of the presence of either is as if an amount of resistance were added to the tuned circuit.

Fig. 68 shows how the tuned circuit is affected. At f_0 $X_L = X_C$ and the two reactances cancel out. But R remains as a source of damping, since work must be done in driving current through it.

When a triode valve with reaction is employed, as in Fig. 65, both signal frequency and audio-frequency amplification are obtained. By the skilled use of reaction the damping in the tuned circuit may be largely overcome and the effective Q increased. But, as we have seen, there is a limit to what can be done in this way without serious deterioration in the quality of reproduction.

As the rectified voltages appearing on the grid of the valve control the anode current and give rise to magnified voltages at the anode, audio-frequency amplification also takes place. Both telephones and loudspeaker are power-operated devices, and the power available in the anode circuit of a single-valve set is very small. It will provide good enough telephone reception, but unless the received station is a powerful one at very short range it cannot suffice to give reasonable volume from even the smallest kind of loudspeaker.

I remember in the very early days of wireless, when the

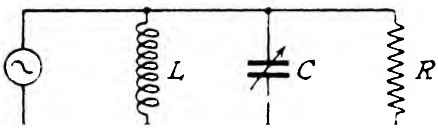


FIG. 68.—Illustrating the damping effect of the resistance R introduced when a crystal or valve is connected across the tuned circuit L, C.

Eiffel Tower was the only station in the world sending out regular broadcasts of speech and music, astonishing friends by letting them hear it faintly from a tiny loudspeaker. This was done with a single-valve set—and a single-valve set was a proud possession in the days when it could not be made for much less than £20 ! As the result of much painstaking experiment this set had been brought to such a point of perfection (!) that it could be operated on the very verge of oscillation, provided that one was prepared (as one was in those days) to spend a quarter of an hour or more in making the hair's-breadth adjustments necessary to obtain the greatest possible volume from the desired station.

To work its little loudspeaker that set must have been operating with a gigantic Q and such a hearty cutting of sidebands that speech and music must alike have sounded like nothing on earth. But wireless was a new thing then and we thought it wonderful. Our radio or gramophone reproduction to-day would probably seem equally ludicrous, could they sample it, to those who listen-in thirty years hence.

The single-valve set is easily expanded into a more sensitive and selective receiver by the addition of a signal-frequency amplifying stage or stages between the aerial and the detector. Similarly, its output may be made sufficient to operate a loudspeaker by the addition of audio-frequency amplification. Fig. 69 shows a block

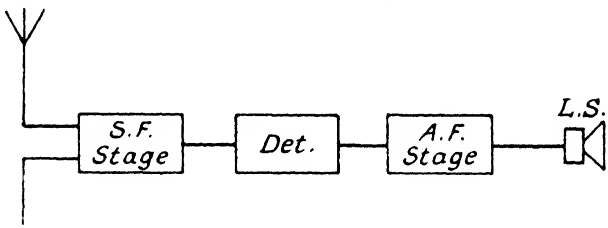


Fig. 69.—Block diagram of straight set with one S.F. and one A.F. amplifying stage.

diagram of a straight set with one S.F. and one A.F. stage. In such a set the voltages due to the currents induced in the aerial are first of all amplified at their original frequency. Until it has passed through the detector stage the signal consists of impulses corresponding to the carrier wave with its A.F. modulation envelope of sidebands. After detection the S.F. impulses corresponding to the carrier have been removed as well as one of the sidebands. What is left is an electrical copy of the original sound waves in the studio in the form of voltages at audio-frequency. These are amplified in the A.F. stage.

The only valve in the receiver which is called upon to deliver current as opposed to voltage changes in its output is that connected to the loudspeaker and supplying the power to work the instrument by moving its diaphragm or cone. The last valve in the set is therefore one of the type known as power valves, and its output is measured in watts.

Fig. 70 shows one of the many ways in which the receiver whose block diagram is shown in Fig. 69 might be realised in practical circuit form. The circuit is a rather old-fashioned one, for it is made up entirely of triode valves. In a modern circuit some of the more complicated valves, of which we shall see something in the next chapter, would be used. The general principles, however, are much the same. The circuit contains many points of interest and we will go through it in detail.

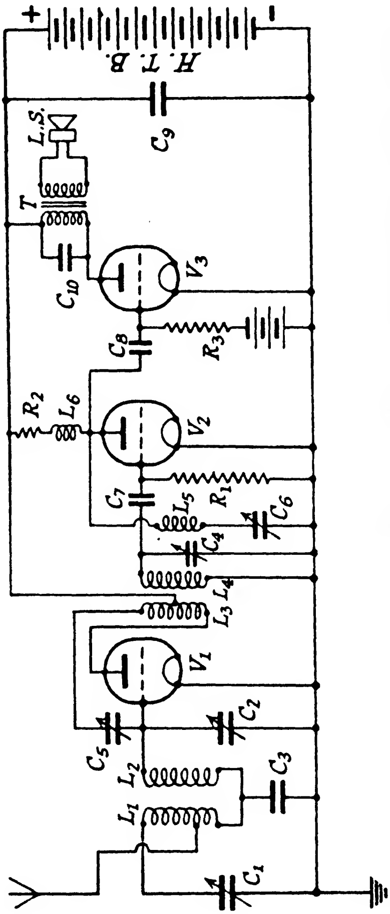


FIG. 70.—One circuit which might be used for the set whose block diagram is seen in Fig 69.

The aerial is connected not to the top of L_1 (the top of a coil is the end electrically farthest from earth) but to a point much lower down. The reason is this. The aerial has resistance and if the aerial were connected to the top of the coil a large amount of this resistance and the accompanying damping would be transferred to the tuned circuit L_1 C_1. By connecting the aerial to a tapping on the coil resistance and damping are reduced.

L_1 C_1 and L_2 C_2 are both parallel-tuned circuits, coupled by C_3, which serves to convey energy from the

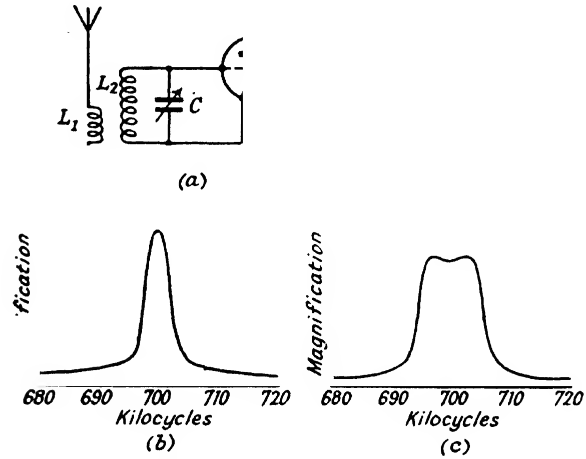


Fig. 71.—The circuit at (*a*) would have a response curve like that at (*b*). By using the band-pass circuit of Fig. 70 we obtain a response curve like that at (*c*).

aerial circuit L_1 C_1 to the grid circuit L_2 C_2. Such a combination is a form of band-pass circuit. We want selectivity in the aerial circuit and we could achieve it by using the Fig. 71*a* arrangement; but if we did we should obtain a response curve something like that seen in Fig. 71*b*. Both this curve and the next in Fig. 71*c*, by the way, are purposely rather idealised in order to make the explanation clear.

The Fig. 71*b* response curve cuts the sidebands badly.

The set would be very selective, but the reproduction would be horrible. If two tuned circuits, such as L_1 C_1 and L_2 C_2 in Fig. 70, are rather tightly coupled their combined response curve is like that in Fig. 71*c*. What really happens is that each has an individual response curve like that at *c*, but one peaks a little below f_o and the other a little above. If the design of the circuit is good the combined curve has an almost flat top, the two slight humps representing the peaks. Such a curve shows a good response to the required band of frequencies (695·5 kc/s – 704·5 kc/s if f_o is 700 kc/s) and a very poor response to other frequencies. It therefore provides good selectivity without spoiling the quality. The two variable capacitors C_1 and C_2 can be "ganged," the moving plates of both being actuated by the same knob.

V_1 in Fig. 70 is the S.F. amplifier, coupled by the transformer L_3 L_4 to the detector V_2. That part of the circuit is straightforward enough; but what is C_5 doing? It is called a NEUTRALISING condenser and its purpose is to prevent V_1 from becoming unstable owing to positive feed-back through the stray anode-grid capacitance. The grid of V_1 is tuned by L_2 C_2. Its anode circuit is also tuned, for the coupled circuit L_4 C_4 "pulls" the anode coil L_3 into resonance. Positive feed-back would therefore cause instability. Voltages due to positive feed-back are in phase with the signal voltages on the grid of V_1. C_5 enables just the right amount of out-of-phase voltage to be applied to neutralise positive feed-back effects. Neutralising is quite out of date in the receiver nowadays, but it was used in one type of war-time radar transmitter.

L_5 C_6 form the reaction circuit of V_2. L_5 is coupled to L_4, in which it induces voltages in the right phase to provide positive feed-back. L_6 is a choke whose purpose is to direct part of the oscillating anode current through L_5 C_6, and as the capacitance of C_6 is variable the amount of current flowing and therefore the feed-back are controllable.

R_2 is the anode load of V_2. The voltages developed across it by the variations of anode current are passed through C_8, the coupling condenser, to the grid of V_3. Grid bias is applied to V_3 through the grid resistor R_3. The type of coupling between V_2 and V_3 is known as resistance-capacitance, or simply resistance coupling, and it is employed in the majority of A.F. circuits to-day.

V_3, the output valve, is of the small power type. It is connected to the loudspeaker by the output transformer

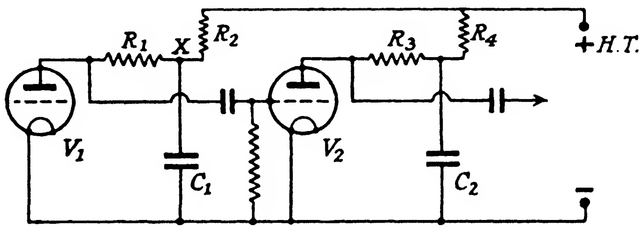


FIG. 72.—Illustrating decoupling. R_1 and R_3 are the anode load resistors of V_1 and V_2. R_2 C_1 is the decoupling circuit of V_1 and R_3C_2 that of V_2.

T, the purpose of which is to match the output impedance of the valve to that of the speech coil. Across the H.T.B. is a large condenser C_9. Its business is to provide a path to earth for oscillating currents and to keep them out of the H.T.B. The battery or other source of anode current contains resistance, and this resistance is common to all the anode circuits. Any oscillating currents, if allowed to pass through the resistance of the battery, would set up voltages across it. There would thus be couplings between the circuits likely to lead to instability were the by-pass capacitor C_9 not there.

Even such a by-pass is not sufficient to prevent undesired couplings and instability if there are several amplifying circuits. Fig. 72 shows the precautions taken to "decouple" a pair of resistance-coupled amplifiers in cascade. R_1 is the anode load resistance of V_1. Oscillating voltages which have done their work and arrive at the point X find the decoupling resistor R_2 offering them a difficult path to the H.T. supply source, whilst an easy one to earth is provided by C_1. They are thus drained away before they can get into mischief. R_4 and C_2 similarly decouple the anode circuit of V_2.

In a set such as that illustrated in Figs. 69 and 70, C_1, C_2 and C_4 would be ganged, so that there would be only one tuning knob. The reaction condenser C_6 would also need to have a control knob on the panel; but the neutralising condenser might be of the small "pre-set" type with no control knob.

The straight circuit is not very widely used for broadcast reception to-day. It is mostly found in small low-priced sets, usually of the three-valve type, and in some battery portables.

One reason is that to obtain the sensitivity and selectivity desirable for modern conditions a great deal of amplification and many tuned circuits are needed. In the straight set each additional tuned circuit means an extra section of the ganged tuning condenser, and that makes construction expensive. The reaction adjustment is apt to be rather a nuisance: really satisfactory band-passing, except in the aerial circuit, is difficult to obtain and the performance of the set is uneven over any wave band that it covers. The Q of tuned circuits is better at lower frequencies than at higher; hence on the medium-wave band such a set is more sensitive between 350 and 550 metres (longer waves, lower frequencies) than between 200 and 350 metres (shorter waves, higher frequencies).

CHAPTER XIII

The Valve: (4) More Complex Types

FOR a good many years battery-operated diodes and triodes remained the only types of valve available for radio purposes.

There are a number of limitations and drawbacks quite inevitable in any valve worked from batteries. Such valves are, of course, the only kind that can be used for portable receivers or for "fixed" receivers in homes which have no mains supply of electricity. Modern improvements have made them very good of their kind, but it was realised long ago that greater efficiency would be achieved could a means be devised of making current from the mains do the work hitherto done by batteries.

One of the biggest problems was the cost of keeping the cathode at a temperature sufficient to ensure the emission of the necessary stream of electrons. In battery triodes the cathode is nearly always a filament, directly heated by current from the filament, or low-tension battery (L.T.B.). Early valves had tungsten filaments, which must be brought to a very high temperature by the passage of a comparatively heavy current to ensure the necessary emission.

Such filaments commonly required 0·75A at 4V=3W apiece from the L.T.B. Suppose that the accumulator used as L.T.B. in a 4-valve set could supply for twenty hours the 3A needed for filament heating (such an accumulator is rated as having a "capacity" of $3 \times 20 = 60$ ampere-hours) and that to have it charged cost 1s. The E.M.F. is 4V and at 3A the battery provides $4 \times 3 \times 20 = 240$ watt-hours at one charge for 12d. The power used in heating the filaments thus costs $\frac{1}{20}$d. per watt-hour. The average cost of power from the mains is probably about 2d. per Board of Trade Unit, which is one *kilo*-watt-hour, or 1,000 watt-hours. From the battery one gets 20Wh for 1d.; from the mains 500Wh. Hence battery-supplied filament heating power costs twenty-five times as much as that from the mains—4s. 2d. per unit against 2d. That takes no account of the deterioration of the battery, whose useful life is by no means unlimited.

The first line of attack on this problem was to find means

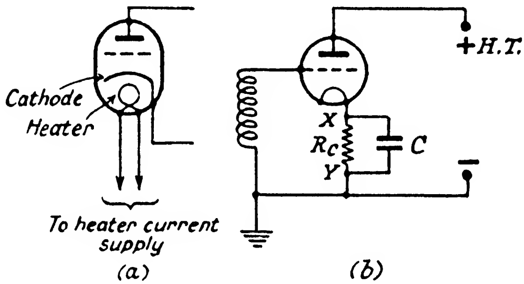


FIG. 73.—(*a*) The arrangement of the indirectly heated valve. (*b*) Showing how grid bias is obtained for such a valve.

of improving filament efficiency. It was found that enormously increased emission could be obtained by combining thoria with the tungsten of the filament. Modern battery valves require from 0·1A to 0·25A at 2V (from 0·2 to 0·5W) apiece of filament current: a 4-valve set to-day probably averages about 1 watt of filament heating power. A big improvement; but do not forget that this power costs about 4s. 2d. per unit and that accumulators have to be recharged constantly and renewed when they succumb to old age.

One of the landmarks in valve history was the introduction of the INDIRECTLY HEATED CATHODE.

It does not matter *how* the cathode is heated for the valve to be able to work; all that matters is that it should be brought to a temperature high enough to produce adequate emission. In valves of the type under discussion the heater consists of a coil of fine wire, made hot by a current passing through it. The heater keeps the cathode (which is thoria-treated) at the right temperature, but is completely insulated from it. Fig. 73*a* shows the arrangement diagrammatically. As the heaters and their circuits have nothing to do with the amplifying, detecting or oscillating functions of valves, they are often omitted altogether from diagrams, as in Fig. 73*b*.

As it is insulated from the cathode the heater can be energised by alternating current. This makes it a very simple business to obtain heater current from A.C. mains. If the heaters of a set are each rated at 4V, 1A, and the mains are 200V, all that is needed is a properly designed transformer with a 50-1 step-down winding.

One rather important point is that the whole of the emitting surface of the indirectly heated cathode is at the same potential. This is not so with a filament. Suppose that a filament has an E.M.F. of 2V applied to it. The whole two volts are dropped across the resistance provided by the filament; hence the end connected to the + terminal of the L.T.B. is 2V positive to the other end, the midpoint of the filament is 1V positive to the negative end, and other points are at different positive potentials with respect to the negative end according to their distance from it. We need not go further into this point, except to say that it does not add to the efficiency of battery valves: the larger emitting surface of the indirectly heated cathode, combined with the fact that the whole of this surface is at the same potential, makes it possible to obtain in mains valves a considerably higher mutual conductance than in battery valves of similar types.

So far we have seen how the indirectly heated valve enables the L.T.B. to be eliminated. The grid bias battery can also go and Fig. 73*b* indicates how it is dispensed with. All potentials in a valve, remember, are measured with respect to the negative end of the filament or to the cathode. In a battery valve we connect the positive pole of a grid battery to the filament and its negative pole to the grid. We then say that the grid has a negative bias, meaning that we have made it more negative than the filament. We might say alternatively that we had made the filament more positive than the grid, for this comes to exactly the same thing.

That is what is done in Fig. 73*b* by the use of the CATHODE RESISTOR, or BIAS RESISTOR R_c. The whole of the anode current flows through this resistor to the cathode. Suppose that the current is 25mA and that the resistor has a value of 300Ω. Then the voltage dropped across the resistor is $0{\cdot}025 \times 300 = 7{\cdot}5$V. The point *x* is 7·5V more positive than *y*. The cathode is connected to *x*, the grid to *y*. Hence the grid is 7·5V negative to the cathode, or has a negative bias of 7·5 volts.

The anode current would set up oscillating potentials across R_c, which is common to both anode and grid circuits, and coupling would take place in this way between these circuits were it not for the presence of the by-pass capacitor C, which offers a low-impedance path to earth to the oscillating component of the anode current.

The voltages set up on the grid if C were absent would be in opposition to those due to signals arriving on the grid. The feed-back would thus be negative. We shall see later how and why NEGATIVE FEED-BACK is usefully employed in certain circumstances.

The value required for R_c can be found from the load-line. Suppose that at the working point E_g is −5V and

I_a 10mA. Then the resistance needed for R_c is

$$\frac{5}{0 \cdot 01} = 500\Omega$$

The H.T.B. is also unnecessary with mains valves. In this case the mains voltage is stepped up as required by the mains transformer. It is then rectified and smoothed and fed to the anodes. We shall discuss power supplies from the mains in detail at a later stage.

One of the weak points of the triode is, as we have seen, the comparatively large anode-grid capacitance which is inevitable in a valve constructed in this way. It is mainly owing to the positive feed-back effects of C_{ag} and the resulting instability that it is exceedingly difficult to obtain large amplification of high signal frequencies with triodes. Neutralising is not a complete remedy and the adjustments it calls for are far from easy when an attempt is made to use several triodes in cascade.

When triodes were the only valves available as amplifiers it was quite usual to " hold down " the signal frequency stages of a set by running the valves with positive grid bias. Grid current then flowed. A flow of grid current means that the grid robs the anode of some of the emitted electrons which would otherwise go to it. Current swings in the anode circuit are thus damped down sufficiently to prevent oscillation. Amplifiers worked under such conditions were exceedingly inefficient. Further, partial rectification was bound to take place in the S.F. amplifying stages with the consequent introduction of heavy amplitude distortion.

The shortcomings of the triode were recognised early in its history and for years attempts were made to find a way of setting matters right by reducing C_{ag} to insignificant proportions. It is surprising, when one looks back, that so many years elapsed between the evolution of the triode and the coming of the SCREEN-GRID

VALVE. This valve, revolutionary though its effects were on the development of wireless, embodied no theoretical principle that was not already well known; nor was there in its construction any practical difficulty that might have proved insurmountable even thirty years ago. Actually the screen-grid valve did not appear until 1927—five years after the inauguration of a regular broadcasting service in this country and twenty years after the invention of the triode.

The principle is quite simply this. In the triode the

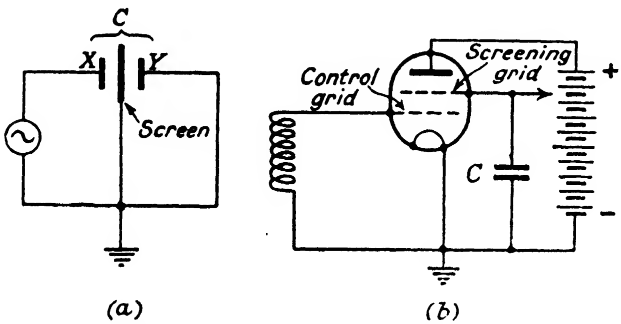


FIG. 74.—(*a*) The capacitance between the plates X and Y is reduced to zero by the presence of the earthed metal screen. (*b*) In the screen-grid valve the screening grid, interposed between control grid and anode, is earthed via the large capacitor C.

grid forms one plate of a capacitor and the anode the other. The capacitance between any pair of plates can be reduced to zero (Fig. 74*a*) by placing a screening plate connected to earth between them. We could not put a sheet of metal between the grid and the anode of the valve, for if we did no electrons could pass from cathode to anode. But the screen need not be solid: a fine mesh of wire will do just as well. The screen, though, must be physically large enough to make each plate electrically "out of sight" of the other. In the screen-grid valve the grid is surrounded by a coil of fine wire, which lies between it and the anode and is insulated from both.

This coil cannot be connected directly to earth, for it would then have a negative potential relative to the cathode and would dam back the flow of electrons from the cathode. But it can be earthed, so far as oscillating currents are concerned, in the way shown at *b* in Fig. 74, by means of the condenser C, whose large capacitance offers so little reactance to them that it forms practically a short circuit to earth for them. The screening coil can now be given a D.C. positive potential and made to help in drawing electrons across the vacuum.

Since the screening coil is made in the same way—a coil of wire—as the original grid, it is also called a grid. The two are distinguished by naming the grid to which oscillating voltages are applied for amplification the CONTROL GRID and that which forms the screen the SCREENING or SCREEN GRID. The screen-grid valve, having four electrodes—cathode, control grid, screening grid and anode—is a TETRODE.

If we plot the anode-volts anode-current characteristic of a tetrode with the control grid at -1V ($E_g = -1$V) and the screen grid at $+80$V ($E_s = 80$V), we obtain an at first sight rather astonishing curve, such as that shown by the solid line in Fig. 75. As the anode volts are raised from zero the anode current I_a starts by rising, as we should expect it to do. But when a certain point is reached an increase in the anode volts results in a falling off in the anode current. The curve makes a pronounced dip, then begins to rise again as further increases are made in the anode volts.

The somewhat surprising behaviour of the anode circuit is explained if the current in the screening-grid circuit I_s is measured whilst the anode-volts anode-current curve is being taken. The screening grid is at a fairly high fixed positive potential all the time. When the anode volts are zero all of the electrons drawn across the vacuum from the cathode are attracted to the screening grid. During the rise of the anode volts from zero to about 20 in the case illustrated more of the electrons are attracted to the anode and fewer to G_s. Hence I_a increases, but I_s decreases.

The speed of an electron through a vacuum depends

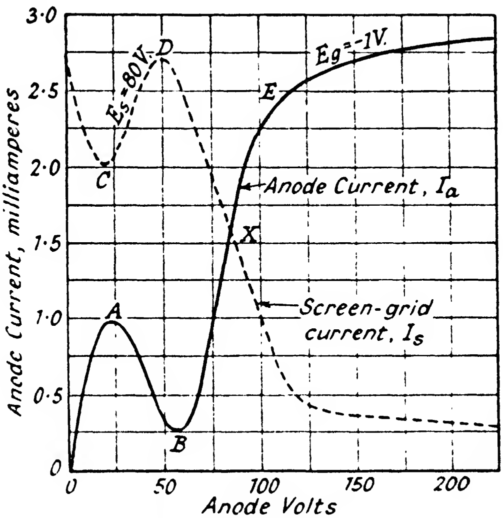


FIG. 75.—Characteristic curves of tetrode.

upon the positive E.M.F. pulling it. The higher the anode voltage the greater is the speed of electrons arriving from the cathode. An electron striking a metal surface at high speed dissipates so much energy that other electrons are driven out by its impact.

This is happening all the time in the triode, but there the SECONDARY ELECTRONS, as they are called, are pulled back to the anode after they have made a brief excursion from it. In the screen-grid valve these electrons come under the attraction of the positive voltage on the screen E_s. At the point A in the I_a curve of Fig. 75 the combined pulls of E_a and E_s are drawing a stream of electrons from the cathode at considerable velocity. Secondary emission from the anode takes place and E_a is not sufficient to ensure the return of the expelled electrons in face of the stronger pull exerted by E_s as they approach the screen.

This state of affairs becomes more and more marked for a time as electron velocity increases with rising E_a (A to B in Fig. 75). The anode current declines, since every electron reaching the anode results in a loss of two or more to the screening grid. Meantime I_s rises (C-D in Fig. 75) owing to its gains by secondary emission. Peter is indeed robbed to pay Paul !

When the point B is reached the anode voltage begins to assert itself: fewer and fewer electrons are lost as E_a is raised, and at X half of the total electrons are going to the anode and half to the screen. From that point onwards the anode takes charge; I_s falls away rapidly, and when the point E is reached its value is small and almost steady.

That kink in the curve, ABE, is a serious drawback. If only the curve could rise smoothly and continuously between A and E the tetrode would be a marvellous valve; that was realised by those (Hull in America and J. H. Round in this country) who produced the first practical types. It *is* a wonderful valve, for it makes enormous amplification at radio frequency possible without instability; but it has been so largely superseded for broadcast reception purposes by the PENTODE—which is nothing but a screen-grid valve *plus* something which straightens out that kink—that I do not propose to devote further space to a separate discussion of its characteristics or its uses. Except that the kink is no longer there, the anode-volts anode-current curves of the pentode are very similar to those of the tetrode. As a radio-frequency amplifier the tetrode serves much the same purposes as the pentode, though its efficiency is as a rule somewhat smaller.

As Fig. 76 shows, the " little something " which makes the pentode superior in performance to the tetrode is the addition of yet another grid, the SUPPRESSOR. This

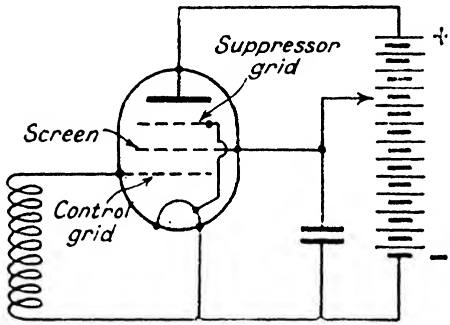


FIG. 76.—Diagram showing the arrangement of the electrodes of the pentode.

is connected for normal working purposes to the cathode and its action is as follows.

The suppressor is at cathode potential. When electrons are travelling fast from cathode to anode this potential has little effect on them and they pass on their way through the fine wires of the suppressor. Electrons of secondary emission, however, are travelling more slowly; they are repelled by the suppressor and forced back to the anode. Thus no stealing of the anode's electrons by the screen occurs and there is no kink in the anode-volts anode-current characteristic.

Another effect of the suppressor is that changes in anode voltage exercise less effect in the pentode than in the tetrode on changes in anode current. Recalling that $R_a = \frac{dE_a}{dI_a}$, you will see that this means that the anode resistance tends to be higher in the pentode.

Fig. 77 shows an anode-volts anode-current family of curves for a small pentode. They are not quite so easy to read as triode curves owing to the very small changes in

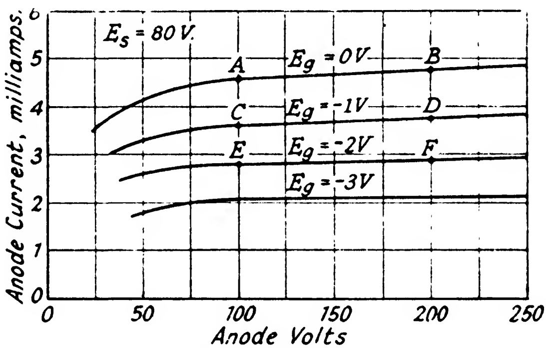


FIG. 77.—Anode-volts anode-current curves of pentode.

anode current. It is the almost horizontal parts of the curves that are used.

At grid volts zero the mutual conductance is 1mA/V, for a change of 1 volt (from A to C) on the grid changes the anode current by 1 mA. A change in E_a from 100 to 200 changes I_a by only 0·2mA. The anode resistance is $\frac{100}{0 \cdot 0002} = 500{,}000\Omega$. At $E_g = -1V$ $g_m = 0 \cdot 8$mA/V and the change in I_a for 100 volts change in E_a is 0·15mA: R_a is therefore 667,000Ω. When we come to $E_g = -2V$ g_m is 0·6mA/V and R_a $\frac{100}{0 \cdot 0001} = 1{,}000{,}000\Omega$, or 1 megohm (MΩ). From these figures we can obtain the amplification factor, for $\mu = g_m \times R_a$. For $E_g = 0$ we have 0·001 $\times$500,000=500; for $E_g = -1$, 0·008$\times$667,000=534; and for $E_g = -2$, 0·0006$\times$1,000,000=600.

Such amplification factors are far beyond anything obtainable from triodes—the μ of a pentode may actually run to 2,000 or more; but, whereas we can have with a triode a stage gain which is a considerable percentage of μ, the stage gain realisable with both tetrodes and pentodes is only a comparatively small fraction of the amplification potentially available. This results from the very high anode resistance R_a of such valves. The stage gain A, we know, is $\mu \times \frac{R_l}{R_a + R_l}$. If the anode load is a tuned circuit we may achieve a dynamic resistance R_d of 100,000Ω or so, and that is considerably greater than the R_a of any ordinary triode. When resistance-capacitance coupling is used with a triode R_l can again be made a good deal larger than R_a.

But neither in the tuned circuit nor in the resistor is R_l likely to equal the anode resistance of the pentode in value. In the tuned circuit $R_d = \frac{L}{CR_{hf}}$ and there are limits to what can be done in the way of reducing H.F. resistance. When R_l is a resistor, its value cannot be increased beyond a certain point if the standing D.C. anode voltage and the direct anode current are not to become over small.

The high μ of the pentode, however, leaves us a large margin to play with, even if we are unable to realise more than a fraction of its theoretically possible amplification. And this is coupled with stability due to the now minute anode-grid stray capacity. An average C_{ag} figure for the pentode is 0·005 $\mu\mu$F, and in some high-efficiency types the figure is as low as 0·003 $\mu\mu$F. Taking the larger figure, the effective "Miller" C_{ag} of a pentode with a stage gain of 100 is only $0{\cdot}005 \times (100+1) = 0{\cdot}505\ \mu\mu F$. Compare these figures with those which we found for a triode and you will see that unwanted positive feed-back ceases to be a bugbear, at any rate at the frequencies used for broadcasting.

Even though the load resistance must be small in comparison with the anode resistance when the pentode is employed, the stage gain is still a good deal larger than that obtainable from a triode. Take for example a pentode with $\mu = 500$, $R_a = 500{,}000\Omega$ and $R_l = 50{,}000\Omega$. $A = 500 \times \frac{50{,}000}{500{,}000+50{,}000} = 500 \times \frac{1}{11} =$ approx. 45. The pentode is actually capable of better things than that. A typical valve, for example, might have a mutual conductance of 3mA/V, an anode resistance of 600,000Ω and an amplification factor of 2,000. Were R_l here 50,000Ω, A would be $2{,}000 \times \frac{50{,}000}{600{,}000+05{,}000} =$ approx. 154.

The value of R_l is usually insignificant in comparison with R_a when the pentode is in use. Hence for round-figure working R_l may be omitted from the denominator of the formula:

$$A = \mu \times \frac{R_l}{R_a + R}$$

$$\text{Then } A = \frac{\mu}{R_a} \times R$$

$$\text{But } \frac{\mu}{R_a} = g_m$$

Therefore $A = g_m \times R_l$.

It follows that with a given R_l the determining factor for the stage gain obtainable with a pentode (and the same is true of a tetrode) is the mutual conductance. This is an important point, of which we shall see more in a moment.

The tetrode was first produced as a radio-frequency amplifying valve; the pentode as an output valve. The tetrode has remained on the radio-frequency side of the receiving set, but various types of pentode have been developed for service as both radio-frequency and audio-

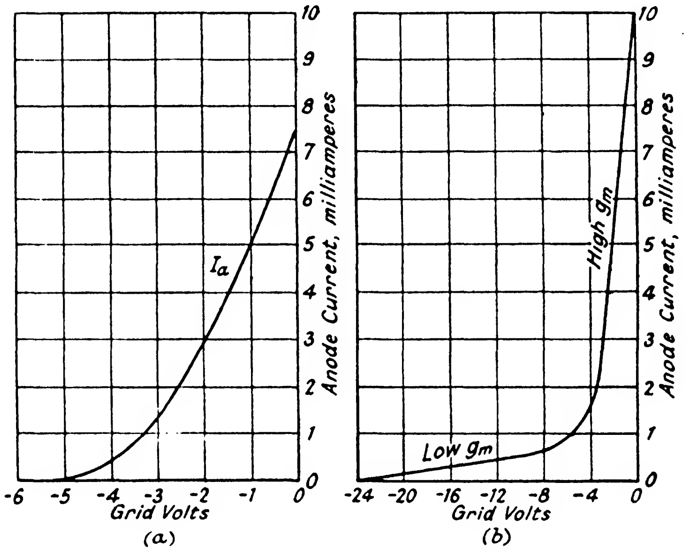


FIG. 78.—(*a*) Grid-volts anode-current curve of R-F pentodes of normal type. (*b*) Grid-volts anode-current curve of vari-mu pentode.

frequency amplifiers. Both tetrode and pentode may be used as gridleak and condenser detectors.

The grid-volts anode-current curves of both standard tetrodes and standard pentodes are of the same general shape as those of triodes. Fig. 78*a* shows that of a radio-frequency pentode. Both valves, however, are made in another form, known as the variable-mu, or vari-mu. This is sometimes wrongly written "variable-μ." Mu is actually an abbreviation (rather an unfortunate one, since μ is pronounced mu) for mutual conductance. We have already seen that the mutual conductance of pentodes can vary a great deal according to the grid voltage. In the variable-mu valve this feature is accentuated by special design.

In Fig. 78*b* is seen the grid-volts anode-current curve of a vari-mu pentode; those for vari-mu tetrodes are similar. You will see that the portion of the curve corresponding to grid volts between zero and -4V has a steep slope, or a high mutual conductance. The mutual conductance falls off rapidly between $E_g = -4V$ and $E_g = -8V$; from $E_g = -8V$ to the cut-off point at $E_g = -24V$ g_m is low.

We saw that with the tetrode or the pentode the stage gain A is approximately equal to $g_m \times R_l$. Hence when a vari-mu valve is in use the gain can be raised or lowered by increasing or decreasing the negative grid bias. This is what takes place in AUTOMATIC VOLUME CONTROL (A.V.C.), which is more correctly called AUTOMATIC GAIN CONTROL (A.G.C.). The term A.V.C. has, however, become so deeply rooted that I shall use it, partly to avoid being pedantic, but mainly to insure you against the mental headaches which might otherwise result from reading articles on wireless and the specifications of receiving sets issued by manufacturers. Do not forget, though, that if you come across the term A.G.C. in textbooks it has the same meaning as A.V.C.

To obtain A.V.C. the signal reaching the receiver is made to cause negative voltages to be developed, which can be applied as bias to the grids of the R.F. amplifiers. The amplitude of these biasing voltages is proportionate to that of the incoming signal. When a very strong signal arrives the biasing voltage developed is such that the R.F. vari-mu amplifiers are taken down on to the low-mu portion of their characteristics; the signal is thus prevented by the reduced gain of the amplifiers from overloading the receiver. For a weak signal the negative biasing voltage is correspondingly small and the valve operates on the high-mu portion of its characteristic.

Fig. 79 is a skeleton circuit explaining the working principle of the A.V.C. Here V_1 is a vari-mu pentode acting as S.F. amplifier and V_2 is a diode which serves both as detector and as supplier of A.V.C. voltage. V_3 is an A.F. amplifier. Detection of the amplified voltages passed on by V_1 takes place in the normal way in the

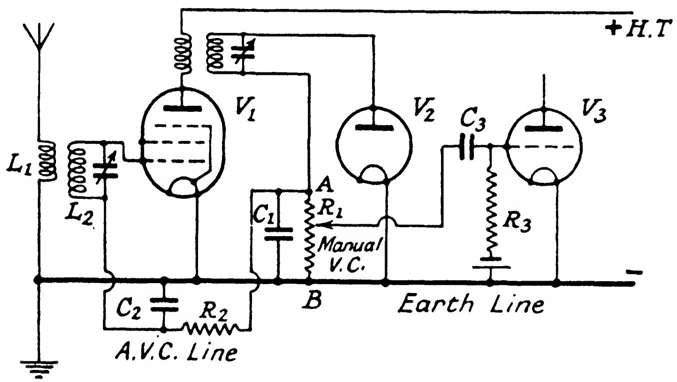


FIG. 79.—Skeleton circuit explaining the principle of A.V.C. The diode V_2 acts both as detector and as source of A.V.C. voltage.

diode, R_1 and C_1. The A.F. signal voltages developed across R_1 are "tapped off" by making this resistor take the form of a potentiometer and fed through C_3 to the grid of V_3. Any proportion of the available signal voltage across R_1 may be passed to V_3 by varying the position of the sliding contact. The arrangement thus provides a manual volume control. R_3 is the usual grid-leak which serves both as a path *to* the grid for any steady negative biasing voltage that may be required and as a path *from* the grid for accumulated charges, which would otherwise choke the valve.

Since electrons flow through R_1 from A to B, A is the negative end of the resistor. You will find it a great help in interpreting circuit diagrams to remember that the positive end of a resistor is the one towards which electrons are flowing through it. The amount by which A is negative to B depends on the current flowing through R_1, for the voltage drop is $I \times R$. The current through R_1 depends on the amplitude of the positive voltage peaks reaching the anode of V_2: the more positive its anode is made the better does the diode conduct. The amplitude of the positive voltages reaching the anode of V_2 depends on the amplitude of the signal reaching the aerial: the stronger the received signal the higher are the voltages passed on by V_1 to the anode of V_2.

In other words, the stronger the received signal the more negative is A with respect to B.

The point A is connected via the A.V.C. line and the windings of L_2 to the control grid of V_1. R_2 and C_2 form a filter whose purpose is to smooth the applied voltage by removing the alternating components due to S.F. and A.F. oscillations. Thus a very strong signal automatically biases V_1 back on to the low mutual conductance part of its characteristic, whilst a moderate signal leaves the working point on the high-mutual conductance portion. But for one snag the signal would thus automatically adjust the S.F. amplification available to suit its own strength.

The snag is that with such a type of A.V.C. (which is never used nowadays) *any* signal, no matter how feeble, increases the negative bias on V_1 and reduces the amplification obtainable. This is the last thing desirable if one is attempting to receive some weak and distant transmission. What we need is something to prevent A.V.C. from coming into action unless and until signals are of such strength that, without its controlling action, they would produce too much volume from the loudspeaker.

This is done by introducing what is called DELAY into the action of A.V.C. The term is a most unfortunate one for it suggests a deferment, though actually the

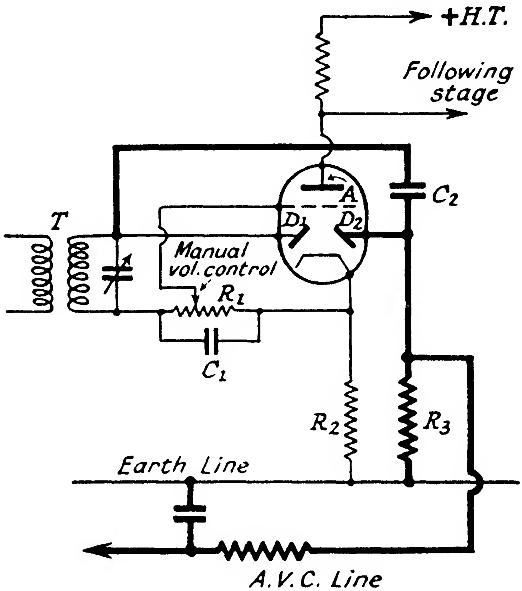


FIG. 80.—The use of a double-diode-triode valve. The circuit of the A.V.C. diode is drawn in heavy lines.

" delay " has nothing whatever to do with time. It means that A.V.C. is prevented from coming into action unless signal voltages exceed a predetermined value. Restricted A.V.C. would be a far better term.

Fig. 80 shows how delayed A.V.C. may be obtained. There are several possible methods employing different valves and circuits; but the principles of all are similar.

The method now described is perhaps that most commonly used in broadcast receivers.

The valve is a DOUBLE-DIODE-TRIODE. It is really three valves in one envelope: two diodes and one triode, with a common cathode for all.

The detecting and amplifying circuits are shown in lines of normal thickness in Fig. 80. We will take these first. The input from the preceding R.F. amplifier is by the transformer T. Incoming voltages are applied to the anode of the signal diode D_1, which detects them with the aid of R_1 and C_1. As in Fig. 79, R_1 is part of a potentiometer which enables the voltage developed across the resistor to be tapped off at any desired value; again the sliding contact of R_1 provides a manual volume control. The voltage taken from R_1 is applied to the grid and this part of the valve functions as a normal A.F. amplifier.

The anode D_1 is connected through R_1 to the cathode and is therefore at cathode potential when no signal is coming in. The arrival of any signal voltage sends the anode D_1 positive during the positive half-cycles and causes rectification to take place.

But the anode of the A.V.C. diode D_2 has a standing negative bias owing to the presence of R_2. Can you work out how this comes to be so?

With no signal coming in the current from the cathode to the anode A flows through R_2. The cathode is then positive to the earth line owing to the voltage drop across this resistor. D_2 is connected to the earth line via R_3 and, as no current flows through R_3 under no-signal conditions, there is no voltage drop across the resistor. D_2 is then at earth potential, which is negative to the cathode. Hence D_2 is negatively biased.

Part of the input voltage is applied to the A.V.C. diode D_2 through the capacitor C_2. C_2 is needed as a blocking condenser since D_1 and D_2 are at different D.C. potentials. It is, however, of such capacitance that its reactance offers negligible opposition to signal-frequency oscillations.

These S.F. voltages are thus applied to D_2. But no current can flow between the cathode and D_2 unless the amplitude of the positive half-cycles is sufficient to cancel out the standing negative bias on D_2 and to make the anode of the A.V.C. diode positive with respect to the cathode.

When the incoming voltage is sufficient to make D_2 positive the A.V.C. diode conducts. Current then flows through the load resistor R_3 and the rest of the story is the same as in the Fig. 79 circuit.

By selecting a suitable value for R_2 the delay can be made such that A.V.C. does not come into action unless the voltages produced by the incoming signal would be sufficient, if given the full available amplification, to overload the receiver and thus cause both unpleasantly great volume from the loudspeaker and distortion. Well-designed delayed A.V.C. ensures, in a word, that the working points of the R.F. amplifying valves are not carried by a strong signal beyond the limits set by their load-lines for satisfactory operation. It also ensures that the full available R.F. amplification is applied to weak signals.

A.V.C. can to a considerable extent take charge of the fluctuations in the strength of an incoming signal which are due to fading: as the signal waxes R.F. amplification is suitably reduced; as it wanes R.F. amplification is increased. But even the best A.V.C. cannot cope fully with the violently fading signal (we shall see more of the causes of fading a little later), which varies rhythmically between a roar and a whisper (or even complete silence), with considerable accompanying distortion—distortion in this case not due to any fault of the receiving set.

Ideally, A.V.C. would completely annul the effects of fading of the less violent type. In practice, it is a palliative—an exceedingly good palliative—but not a cure. A reasonably strong signal, for instance, is sufficient to override and drown background interfering noises. But when a signal fades and the amplification rises to restore the volume the background noises are also amplified, and what is called the SIGNAL-TO-NOISE RATIO is no longer sufficient to make them all but inaudible. If one listens to the output of a well-designed receiver dealing with a signal whose amplitude is making slow, regular swings between *fortissimo* and *pianissimo*, one's impression is that the strength of the signal remains steady whilst that of the background interference undergoes rhythmic variations.

A.V.C. of the delayed type is not perfect; but a receiver which includes it gives results which are definitely more pleasing than they would be were it absent.

A manual volume control is desirable firstly to make sure that the A.F. stages are not overloaded, and secondly to enable the output of the loudspeaker to be regulated as may be required.

There are many other valves of complex types. Some of these we shall meet in the next chapter during our discussion of the superheterodyne receiver.

CHAPTER XIV

The Superheterodyne

BROADCASTING conditions to-day make the need for selectivity in the receiving set a matter of great importance. The medium-wave band from 1,500 to 550 kc/s (200 to 550 metres) is packed with stations, each of which is—or at any rate should be—working on its allotted channel 9 kilocycles in width. As we have seen, a station requires a channel of this minimum width in order to be able to transmit not only its carrier wave, but also the sidebands due to the modulation corresponding to the sounds taking place in the studio.

If it is to be able to receive the wanted station without interference from those which are not wanted, the receiver must be sufficiently selective to respond very poorly to frequencies much over 4·5 kc/s above or below the frequency to which it is tuned. This would be comparatively easy were the local station always the one wanted; signals from other more distant stations are then much weaker and no great amount of selectivity is needed in order to make the response to them so small that they cause no interference. But it not infrequently happens that the user of a receiving set wishes to be able to tune in a weak transmission and to separate it cleanly from stronger transmissions on neighbouring channels.

Every efficient tuned circuit adds to the selectivity of a receiver. To obtain the minimum degree of selectivity required by listeners the number of these needed in a receiver to-day is probably five. That, remember, is for the minimum acceptable degree of selectivity; to obtain really good selectivity about double that number are needed.

Using two pentodes as signal-frequency amplifiers in a straight receiving set we might have five tuned circuits arranged like L_1 C_1, L_2 C_2, L_3 C_3, L_4 C_4, and L_5 C_5 in Fig. 81. But this would lead to considerable complications. The demand nowadays is all for single-knob tuning; a five-gang variable condenser would be needed and this is both an expensive and a bulky component.

The trouble is that each of the five tuned circuits must

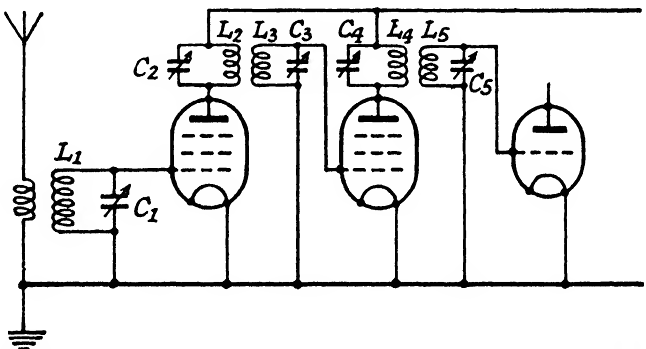


FIG. 81.—Skeleton circuit showing how five tuned circuits could be used to obtain selectivity in a straight receiving set.

be simultaneously retuned whenever we pass from one station to another. If some means could be found of making the tuning of some circuits remain fixed, so that only two, or perhaps three, of them had to be retuned on passing to a fresh station, the problem would be very largely solved.

That is exactly what happens in the superheterodyne receiver. The majority of its tuned circuits have fixed tuning. Many broadcast receivers of this type have from five to seven tuned circuits, in only two—or at the most three—of which the tuning must be varied in order to change from one station to another. Thus with a two-gang or three-gang variable condenser a small super-heterodyne can provide from five-tuned-circuit to seven-tuned-circuit selectivity. That explains why it is now the most widely used kind of set for broadcast reception.

The principle of the superhet, to give it its most generally used name, is illustrated in the block diagram of Fig. 82. It is simply this: *all* incoming signals, no matter what their frequency, are converted into signals of *one* fixed frequency. The conversion is done by the FREQUENCY CHANGER (F.C.). The input to this stage is the incoming signal at the frequency received by the

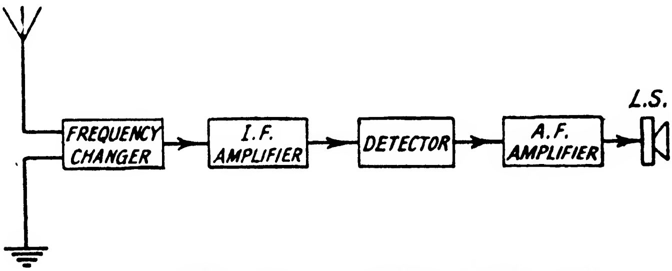


FIG. 82.—Skeleton diagram of superheterodyne receiver.

aerial; its output is the same signal altered to what is known as the INTERMEDIATE FREQUENCY (I.F.). Whatever the frequency of the incoming signal the F.C. changes it to the fixed I.F. of the receiver. How this is done we shall see in the paragraphs which follow; but you will realise at once what an advantage it is. The skeleton circuit of Fig. 83 shows how, with a fixed I.F., four tuned circuits can be controlled by small " pre-set " capacitors. The capacitance of these can be varied within limits by turning a screw. They are adjusted when the set is lined up by the makers so that the circuits L_1 C_1, L_2 C_2, L_3 C_3 and L_4 C_4 are all tuned to the I.F. They then require no further attention until the wireless serviceman checks over the alignment of the receiver.

So much for the general principles of the superhet. Now let us see how it works.

When two signals at different frequencies are fed into a circuit there are instants when they are in phase and others when they are 180° out of phase; but during a large part of the time they will never be quite " in step " or quite out of it. When they are in phase the two assist

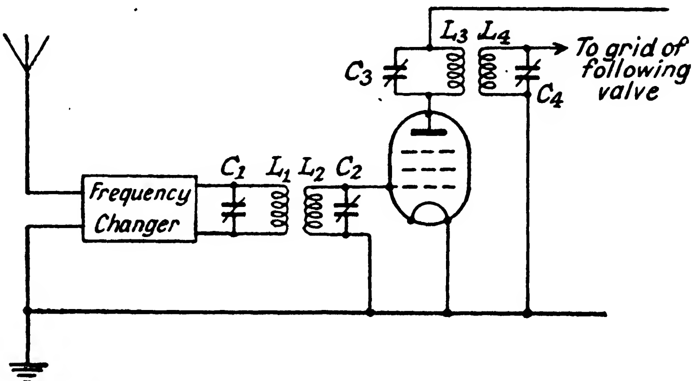


FIG. 83.—Showing how with a fixed I.F. four tuned circuits can be obtained by the use of small pre-set capacitors. The oblique lines without arrowheads transfixing the capacitors indicate that their capacity, once adjusted, is not varied when the set is tuned.

one another and what is called a beat occurs. The number of times a second that these beats occur can be found by subtracting the lower frequency from the higher; in other words, the BEAT FREQUENCY is the difference between the two combined frequencies.

On the medium-wave band devoted to broadcasting there are always a few stations which are not working on the frequencies that they ought to use. If you run over this band with a receiver of average sensitivity you are almost sure to hear a few whistling sounds which vary in loudness but not in pitch as you alter the tuning. These are due to beats between the carriers of stations which are working on frequencies too close to one another. Suppose that one station is transmitting on 472 kc/s and that another is at work on 473 kc/s; the resulting beat is a frequency of $473-472=1$ kc/s, or 1,000 c/s. This produces from the loudspeaker a steady note with a frequency of 1,000 c/s, or nearly that of the C two octaves above the middle.

Such a beat between two different frequencies is called a HETERODYNE. The name superheterodyne is a contraction (can you wonder?) of supersonic-heterodyne receiver. The intermediate frequency in such a set is produced by causing a heterodyne to occur between the incoming signal and oscillations generated in the set. This heterodyne is supersonic, or of higher frequency than audible sounds. In most broadcast receivers of to-day the I.F. is of the order of 460 kc/s.

Imagine now an unmodulated carrier wave (Fig. 84*a*) being combined in the receiver with locally generated waves of a higher (oscillator) frequency (Fig. 84*b*). The result is shown diagrammatically at *c*. The difference, or intermediate, frequency appears as a modulation of the oscillator frequency.

The waveform at *c* reminds us of one that we have already seen—those of carrier waves with their modulation envelope in Figs. 49 and 52. In discussing these we saw that the only way of making them suitable for amplification was to detect them, which means removing one half of the modulation envelope and the frequency which, so to speak, carries it. This process is again necessary with the waveform seen at *c*, and the result is that shown at *d*—the intermediate frequency.

We will run over the process again, this time with some figures. The signal frequency is, we will take it, 1,200 kc/s and the I.F. of the set 460 kc/s. The oscillator is tuned by the main tuning knob and it is so arranged that it is always 460 kc/s higher than the frequency of the wanted signal. When we turn the tuning scale pointer

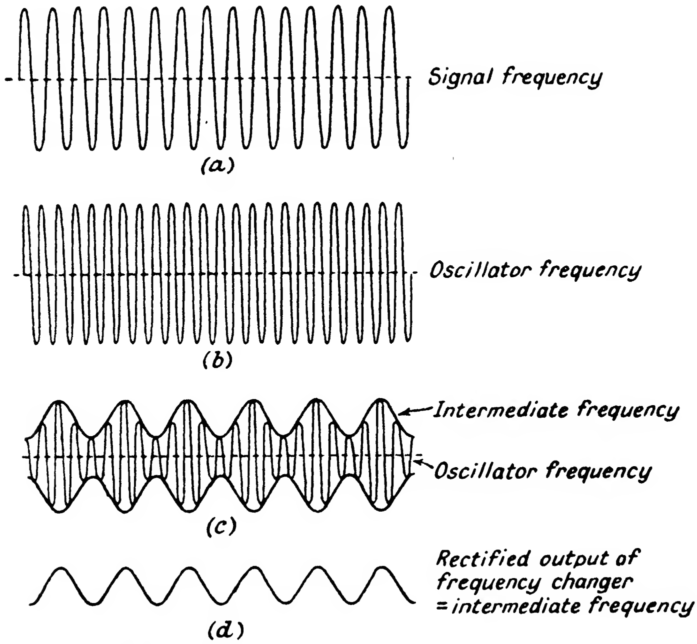


FIG. 84.—Diagrammatic representation of the method of frequency changing in the superheterodyne.

to 1,200 kc/s (250 metres) the oscillator is thus generating oscillations at 1,660 kc/s.

The combination of the 1,200 kc/s carrier and the 1,660 kc/s local oscillations in the frequency changer results in a 1,660 kc/s frequency, varying in amplitude 460 times a second (Fig. 83*c*). We cannot make use of such a waveform since each rise of the 460 kc/s envelope above the zero line is exactly counterbalanced by a simultaneous fall below it. Therefore detection follows and results in a waveform at the intermediate frequency of 460 kc/s.

If the signal frequency carrier is modulated, its modulation envelope is retained as a similar envelope for the intermediate frequency. The net effect, therefore, of frequency changing is to dismount the modulation from its original carrier and to mount it on a fresh carrier, the I.F. After amplification the I.F. itself thus requires detection in order to produce an intelligible signal at audio-frequency.

Fig. 85 shows in skeleton form an early type of superhet. It will be seen that frequency changing is done by means of two valves: the local oscillator (shown in block form) and the first detector. The oscillations generated by V_2 are combined with the incoming signal frequency in V_1, which acts as both " mixer " and detector. V_3 and V_4 are I.F. amplifiers, V_5 a gridleak-and-condenser second detector for I.F., and V_6 is the output valve. Such sets were wonders in their day.

Nowadays the work of V_1 and V_2 is done by a single valve of complex type known as the frequency changer. We no longer speak of the second detector; the valve which does the work of V_5 in Fig. 85 is known simply as the detector.

A valve much used as frequency changer to-day is the triode-hexode, so called because its bulb contains both a triode and a hexode, with a cathode common to both. Fig. 86 shows this valve in a typical circuit arrangement.

The triode portion forms the oscillator. R_8 is the anode resistor and L_4CB the anode tuned circuit. This is coupled by way of L_3 to the triode grid. C_3 is the grid condenser and R_5 the gridleak.

CA and CB are sections of a two-gang tuning condenser. As the oscillator must in the case illustrated always be at a frequency 465 kc/s higher than the signal

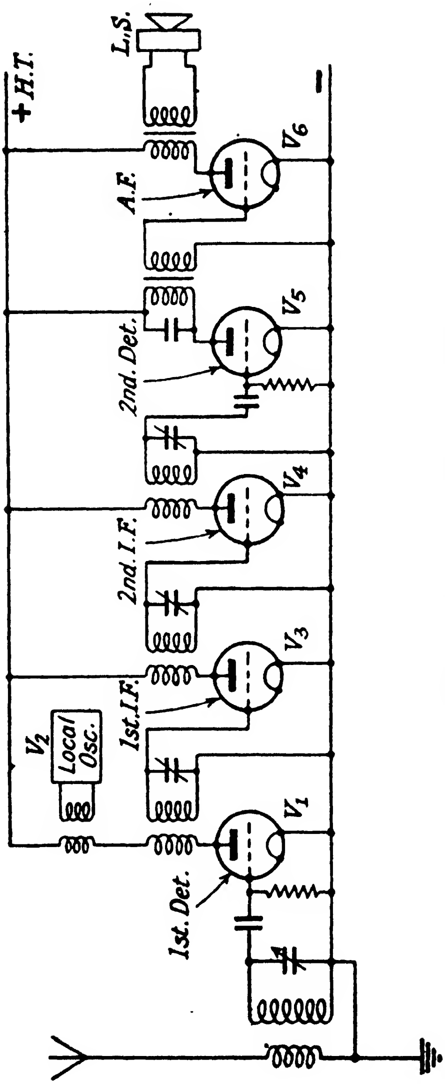


Fig. 85.—Skeleton circuit of an early type of superhet.

input circuit L_2CA, the "padder" condenser C_4 is used to make it track properly over the whole tuning range.

Signal-frequency voltages are fed to the control grid of the hexode part of the valve. The electron stream flowing from the cathode to the anode A_2 and controlled by this grid passes on its way through the INJECTOR GRID, which is connected inside the bulb to the grid of the triode. Here the first electron stream meets

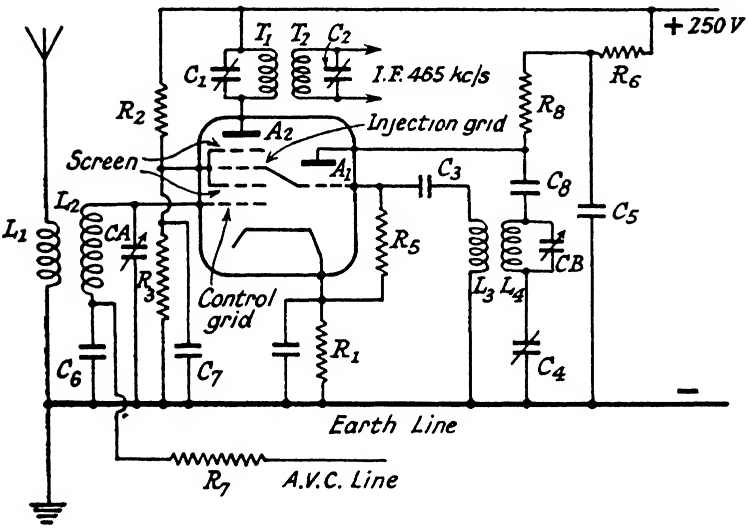


FIG. 86.—The triode-hexode as frequency changer.

and mingles with a second set of electrons forming a current oscillating at the frequency determined by the tuning of L_4CB. When this electronic method of combining signal and oscillator frequencies is used detection is not necessary in order to produce the I.F. The difference frequency appears in the anode circuit (T_1C_1) of A_2 as the I.F., carrying the original sidebands as modulation.

Fig. 87 shows another type of electronic frequency changer, the heptode, sometimes known as the pentagrid. The essential difference between this and the triode-hexode is that the triode portions of the valve (oscillator-grid and oscillator-anode) are interposed between the cathode and the control-grid. The stream of electrons belonging to the cathode/control-grid/anode portion is

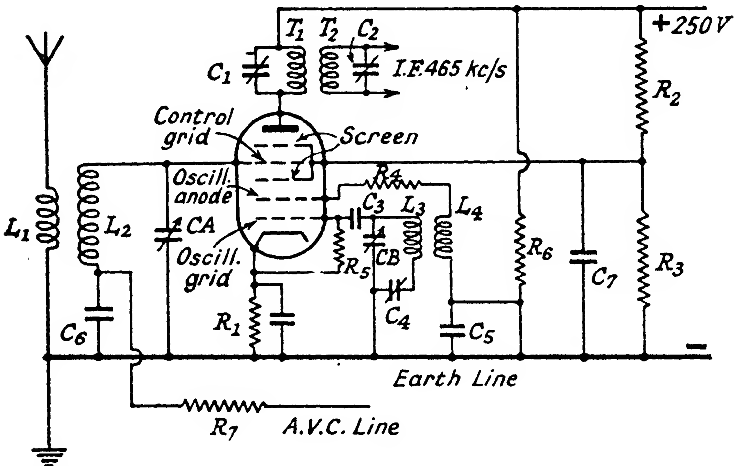


FIG. 87.—The heptode as frequency changer. Components playing the same parts in Figs. 86 and 87 are given the same numbers.

combined with that of the oscillator portion as the two streams leave the anode.

The important components in Figs. 86 and 87 which play similar parts have been given the same numbers in both drawings.

In both valves the screen takes the form of two grids internally connected. One lies between the control-grid and the oscillator portion; the other between the control-grid and the anode. The object of this double screen is to prevent couplings by capacitance between the oscillator and the tuned circuit L_2CA. Were there a strong coupling of this kind between the two, radiation at the oscillator frequency might occur from the aerial, causing interference with the reception of other listeners.

In both Figs. 86 and 87 R_2 and R_3 form a potential divider to ensure that the correct positive potential is applied to the screen. C_7 is the earthing capacitor for the screen. R_6 and C_5 decouple the anode circuit of the oscillator; the same duty is done for the control-grid by R_7 and C_6.

There are many other possible methods of frequency changing with valves of different kinds. Electronic mixing is now almost universally employed. All electronic systems are basically the same as those illustrated in Figs. 86 and 87, and if you understand these two you should have no great difficulty in following other circuits that you may come across.

Within reason we can follow the frequency changer with as many I.F. stages as we like, thus obtaining both enormous amplification and a high degree of selectivity, for each I.F. stage usually includes two tuned circuits: the input circuit to the control-grid and the output circuit from the anode of its valve. In all of these the tuning is fixed.

But no matter how many tuned circuits we have the selectivity of a receiver will not be up to the mark unless we attend to something else. It must be realised that beat frequencies equal to the intermediate frequency can and do occur on stations other than that whose transmissions are wanted. Suppose, for example, that the I.F. is 110 kc/s (as it was in most of the earlier superhets). When a station working on 700 kc/s is tuned in the oscillator frequency is 810 kc/s.

So far so good. When we turn the tuning knob until the pointer is at 480 kc/s the oscillator frequency is 590 kc/s; a station on 480 kc/s is heard because $590 - 480 = 110$ kc/s and the I.F. stages respond. But what about the station on 700 kc/s? If there is only one tuned circuit between the aerial and the frequency changer its signals are still there, even if attenuated. The difference between 700 and 590 is again 110 kc/s. The I.F. stages accept any 110 kc/s signal and have no means of discriminating between wanted and unwanted signals of this frequency. The 700 kc/s station is thus heard at two settings of the tuning dial and will interfere with another twice the I.F. away from it.

The only perfect solution, clearly, is to sharpen up the tuning or increase the selectivity between the aerial and the frequency changer. A band-pass circuit (Fig. 70) may suffice; but do not forget that each half of such a circuit needs its own variable tuning condenser. This would mean using a three-gang instead of a two-gang (one section is required for tuning the oscillator), which would be too expensive in a moderately priced broadcast receiver.

As a partial solution of the problem a higher I.F. has been standardised and most sets to-day have intermediate frequencies such as 456 or 465 kc/s. We saw that the second appearance of a signal occurs at twice the I.F. below the first; this reappearance is called the second channel. By choosing an I.F. as high as 465 kc/s the second channel is made to occur 930 kc/s below any particular station. If the station is working on 1,500 kc/s its second channel falls at 1,500 − 930=570 kc/s. As the medium-wave band extends from 1,500 to 550 kc/s (200 to 550 metres) this second channel comes just within its lower limit—the second channel of any station whose carrier frequency is below 1,480 kc/s falls outside the band. Similar consideration renders reception on the long-wave band between about 300 and 150 kc/s (1,000 and 2,000 metres) immune from direct second-channel interference.

On the short waves, however, the frequency ranges covered by the tuning are enormously greater. From 20 to 25 metres on the tuning dial is only 5 metres. But a wavelength of 20 metres corresponds to 15,000 kc/s and one of 25 metres to 12,000 kc/s; the frequency range of this little bit of the tuning dial is thus 3,000 kc/s, and with an I.F. of 456 kc/s there is plenty of room for second channels to occur. They are perhaps not so important on the short-wave range of a broadcast receiver—it has even been suggested that they may be a valuable " selling point," since the uninitiated user takes each second-channel signal for yet another distant station and is duly impressed by the " liveliness " of the set !

But second channels are by no means the only way in which lack of selectivity between aerial and frequency changer can lead to interference. The oscillator, for instance, is prone to generate harmonics of its proper frequency, and these may cause a wide variety of most disconcerting beats at the I.F.

With almost any superhet which has not an aerial band-pass circuit or one or more tuned signal-frequency stages a number of whistles can be heard which vary in pitch, running up and down the scale, as the tuning knob is moved. These are heterodynes caused by beats whose occurrence is usually due to inadequate selectivity between aerial and F.C.

To render a broadcast receiver entirely free from second-channel interference and that due to other unwanted beats at least two signal-frequency amplifying stages, or pre-selectors, are usually required. That would mean a four-gang variable condenser, two more valves with all the components of their circuits, a larger cabinet—and a much larger price. Like so many other things in wireless, the small broadcast receiver is a compromise; and not a bad compromise when all is said and done.

The average small broadcast receiver consists of a frequency changer, one or perhaps two I.F. stages, a double-diode-triode stage, acting as detector, A.V.C. voltage generator and L.F. amplifier, and a triode or pentode output valve. Sometimes a double-diode-pentode is used; the pentode portion is suitable for supplying the output power needed for working the loudspeaker, and the high stage gain makes a second A.F. amplifier unnecessary.

It is thus possible to make a superhet with moderately high over-all selectivity and gain by using only three complex valves: F.C., I.F. and detector-A.V.C.-output. To obtain anything approaching the same performance at least nine triodes and diodes would be needed. A frequency changer of the triode-hexode type does the work of three triodes (oscillator, detector-amplifier and I.F. amplifier) owing to the large amplification which its hexode portion provides. A pentode I.F. amplifier gives at least as much amplification as two triodes. To obtain the same results as those given by a double-diode-pentode we should have to use four "simple" valves: one diode as detector, a second as A.V.C. voltage generator, a triode as A.F. amplifier and another as output valve.

On the other hand, a communication receiver, such as is used for commercial purposes and by amateurs who make a hobby of long-distance reception, may contain 15 or more valves of high-efficiency types, all doing useful work.

Fig. 88 is a block diagram of such a receiver. The two S.F. stages (vari-mu pentodes) have their own source (diode) of A.V.C. voltage. They are followed by a frequency changer (pentode) which has not only a separate oscillator (triode) but also an oscillator amplifier (triode or pentode). The advantage of such an arrangement is this. With a heptode or triode-hexode oscillator there is a

(1) As the frequency (the I.F.) at which most of the amplification is done is always the same, the over-all gain of the set does not vary greatly, whatever the signal frequency.

(2) The tuning of the I.F. stages being fixed, adequate selectivity may be secured with few variably tuned circuits.

(3) Circuits with fixed tuning are much cheaper to construct and occupy less space than those with variable tuning. It follows (*a*) that, for a given cost, greater selectivity and sensitivity can be provided by the superhet system than by the straight; and (*b*) that the superhet lends itself admirably to compact design.

CHAPTER XV

Amplifier Circuits : (1) Transformers

BEFORE the coming in 1927 of the screen grid tetrode both the gain and the selectivity of radio-frequency (S.F. and I.F.) stages were low. In those days this did not matter very much in the broadcast receiver. The small amount of amplification obtainable in the S.F. stages could be made up for by the use of reaction in the detector stage, which also increased the selectivity. Selectivity was, in any event, of minor importance when stations were less numerous and far less powerful than they are to-day.

The chief reason for the lack of gain and of selectivity in R.F. stages with the triode is to be found in the large effective value of the capacitance between anode and grid owing to the Miller effect (p. 137) and the resulting positive feed-back. To stabilise a triode R.F. amplifier (that is, to keep it from going into oscillation) damping had to be introduced deliberately into the circuits of a triode such as V_1 in Fig. 90*a*. This was done as a rule by positively biasing the grid of V_1 and so causing work to be done in the grid circuit. The result was to reduce the Q by increasing R_{hf}. The tuning was thus rendered flat and the gain diminished. When two or three R.F. amplifiers were used in cascade so much deliberate damping was necessary that the actual gain was very small in comparison with that theoretically possible.

In the screened tetrode anode-grid stray capacitance is brought down to an almost negligible amount and the tuned anode circuit may be used, as in Fig. 90*b*. But the tuned anode has the same drawback as the circuit of Fig. 71*a*: it has a sharply peaked response curve like that of Fig. 71*b*. Selectivity is obtainable only at the expense of quality: the sidebands are badly cut, those correspond-

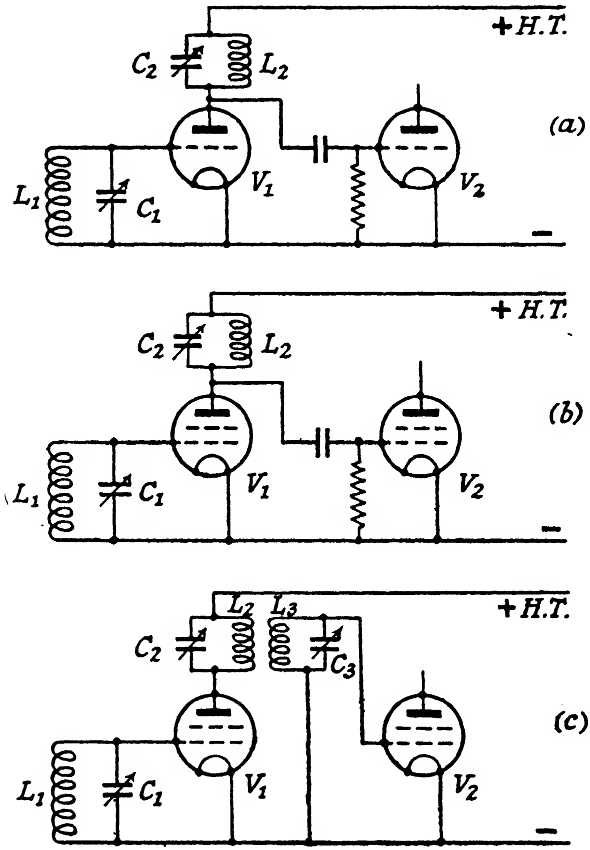


FIG. 90.—(*a*) The tuned anode circuit with triodes; (*b*) the same circuit with S.G. valves; (*c*) the R.F. transformer.

ing to the lower audio-frequencies being brought out much more strongly than those which correspond to the upper audio-frequencies.

By far the most generally used R.F. coupling to-day is the transformer (Fig. 90*c*). It gives better selectivity than the tuned anode, and that selectivity is of the right kind, for sideband cutting can be avoided. The selectivity is better because the transformer may be made up of two tuned circuits, and every additional tuned circuit means an increase in selectivity.

If the coils L_2 and L_3 in Fig. 91*c* are arranged so that only a small part of the lines of force of L_1's magnetic

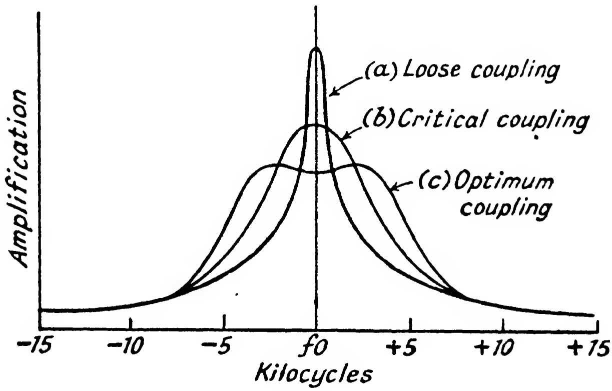


FIG. 91.—Curves showing the effects of coupling a transformer response.

field cuts the turns of L_2, the coils are said to be loosely coupled. Such loose coupling produces a steep, sharply peaked response curve (Fig. 91*a*). Gradually tighten the coupling: the response at f_0 is reduced, whilst the peak changes into a wider curve with a rounded top (Fig. 91*b*). When a certain point—that of CRITICAL COUPLING—is reached any further tightening destroys the smooth sweep of the top of the curve, which begins to develop a hollow in the middle. When the coupling between the two coils is made as close as possible the response curve is shaped like a capital M, with two sharp peaks and a deep hollow at f_o.

A degree of coupling can be found which gives the optimum response for the I.F. stages of a broadcast receiver (Fig. 91*c*). The top is nearly flat and the response is almost level from 4·5 kc/s above f_o to 4·5 kc/s below. Further, the sides of the curve are steep, so that there is a fairly sharp cut-off at f_o+4·5 kc/s and f_o − 4·5 kc/s. Such an arrangement ensures the selectivity necessary for separating stations whose carrier frequencies are 9 kc/s apart and passes a band of frequencies wide enough to include the sidebands corresponding to audio-frequencies up to 4,500 a second. A satisfactory inter-valve band-pass coupling is obtained in this way.

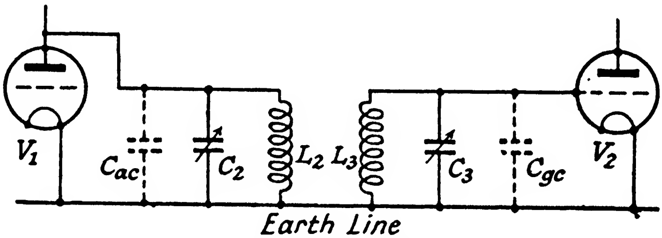


FIG. 92.—As the H.T.B. or other source of high-tension current may be regarded as a short circuit to earth from the R.F. point of view, the drawing above is the R.F. equivalent of Fig. 90*c*.

An interesting point is that the transformer circuit annuls the evil effects of two of a valve's stray capacitances. These are the anode-cathode capacitance (C_{ac}) of V_1 in Fig. 90*c* and the grid-cathode capacitance (C_{gc}) of V_2.

From the R.F. point of view the high-tension battery, or other source of H.T. current, may be regarded as a short circuit to the earth line. Fig. 92 is thus the R.F. equivalent of Fig. 90*c*. It will be seen that C_{ac} of V_1 is in parallel with C_2; the two capacitances thus add together to tune the circuit $C_{ac}C_2L_2$, and the only consequence of the presence of C_{ac} is that the capacitance of C_2 is a little less than it would otherwise be to produce resonance.

Similarly C_{gc} of V_2 is in parallel with C_3, and this stray capacitance helps to tune the grid circuit of V_2 to resonance.

With tetrodes and pentodes the other stray capacitance C_{ag} is so small that even the Miller effect makes it of little importance as a source of positive feed-back and instability so long as the frequency is reasonably low. In the broadcast superhet an I.F. of 450-470 kc/s makes it possible to obtain a combination of high gain, adequate selectivity, freedom from undue sideband cutting and complete stability when the transformer is used as I.F. coupling. The I.F. being fixed, pre-set capacitors can be used to tune all stages of the set devoted to this class of amplification (see Fig. 89).

In the audio-frequency stages, which follow the detector of either straight set or superhet, only two kinds of intervalve coupling are seen nowadays in domestic receivers: transformer coupling and resistance-capacitance coupling. Of these the resistance-capacitance method is by far the more commonly used.

Fig. 93 illustrates two ways in which the A.F. transformer may be used as an intervalve coupling. That seen at *a* is the normal SERIES-FEED method. The impedance of the primary winding forms the anode load of V_1. Since the transformer may be made to step up the voltage changes transferred from the anode of V_1 to the grid of V_2 by making the secondary turns larger in number than the primary, the A.F. intervalve transformer can considerably increase the over-all gain.

Fig. 93*b* shows the PARALLEL-FEED method of employing the A.F. transformer. Here R is the anode load resistor and the voltages developed across it are passed to the primary through the coupling capacitor C. Again a voltage step-up can be obtained by using more turns in the secondary than in the primary winding.

Leaving out of account the resistance and stray capacitance of the primary winding in Fig. 93*a*, we may take the reactance of this winding X_{L_p} as the anode load of V_1. The reactance of an inductor, we know, is $2\pi fL$,

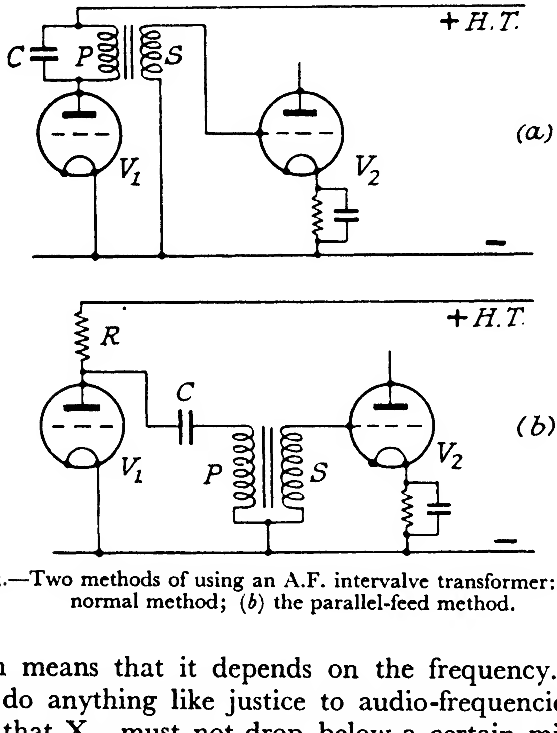


FIG. 93.—Two methods of using an A.F. intervalve transformer: (*a*) is the normal method; (*b*) the parallel-feed method.

which means that it depends on the frequency. If V_1 is to do anything like justice to audio-frequencies, it is clear that X_{L_p} must not drop below a certain minimum value when the lowest that we wish to be able to hear properly reaches it; should X_{L_p} fall below that value, the stage gain will be insufficient for adequate amplification at that frequency. The generally accepted rule is that

X_{L_p} must not be less than the anode resistance of V_1 at the lowest desired frequency.

The primary of a transformer used as in Fig. 93*a* carries the whole anode current of V_1. To obtain the high inductance values necessary for A.F. amplification a core of iron or of a special alloy is required. When the current flowing through the windings is heavy what is known as MAGNETIC SATURATION takes place and the effective inductance falls away. To avoid this either (*a*) the transformer must be large and heavy, or (*b*) it may be arranged as in Fig. 93*b* with no steady current through its primary. It is always advisable to use the parallel-feed connections for small A.F. transformers.

So far we have discussed only the transformer's response at the lower end of the audio-frequency scale. At the upper end there may be a pronounced peak in the response curve owing to certain complex resonance effects. A peaky response of this kind is sometimes deliberately arranged when it is desired to give prominence to high audio-frequencies.

The A.F. transformer, if well designed and properly used, can give very good results. It has, though, three serious drawbacks: it is much more expensive than resistance-capacitance coupling; it adds far greater weight to the receiver; it is prone when used in an A.C. mains set to pick up hum. For these reasons the A.F. intervalve transformer is not widely used in modern receivers. It is found chiefly in sets incorporating output stages of the types known as push-pull, to which we shall come a little later.

CHAPTER XVI

Amplifier Circuits: (2) Resistance-Capacitance

RESISTANCE-CAPACITANCE coupling (Fig. 93) is seldom, if ever, seen in the S.F. or I.F. stages of a receiving set. The reasons for its unsuitability in such positions are not far to seek. In the first place, since neither the anode circuit of V_1 nor the grid circuit of V_2 are tuned, it provides no worth-while selectivity—and selectivity is one of the prime requirements in S.F. or I.F. amplifiers. Secondly, the amplification obtainable from

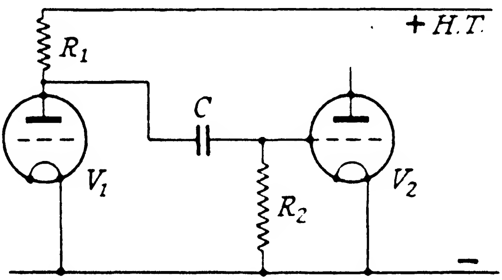


FIG. 94.—The resistance-capacitance circuit looks simple and straightforward.

R-C coupling at frequencies of the kind handled by S.F. and I.F. stages is small.

This is due to the presence of various stray capacitances in V_1 and V_2 and in their associated valveholders and wiring connections. Remembering that from the H.F. point of view the +HT line may be regarded as earth, we can redraw the Fig. 94 circuit in the equivalent form seen in Fig. 95. Here C_{ac} is the anode-cathode capacitance of V_1, which is effectively in parallel with R_1, the anode load, and provides a " shunt," or by-pass, across it.

If f=700 kc/s and C_{ac}=50 μμF, the reactance of the stray capacitance is

$$\frac{1}{2\pi \times 700 \times 10^3 \times 50 \times 10^{-12}}$$
$$=4{,}500\Omega \text{ approx.}$$

We know that when two resistors are in parallel, the total resistance is less than that of either. The same is true for alternating currents if a resistor and a reactor are in parallel. It follows that, however high we make the

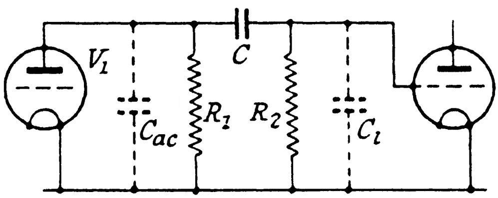


FIG. 95.—The equivalent circuit of Fig. 94.

value of R_1, the anode load must always be less than 4,500Ω at 700 kc/s.

Suppose that V_1 has a μ of 20 and that R_a=18,000Ω. Then at 700 kc/s the stage gain A must be less than

$$20 \times \frac{4{,}500}{18{,}000+4{,}500}$$
$$=20 \times \tfrac{1}{5}$$
$$=4$$

So far so bad; but that is by no means the whole story. The coupling condenser C in Figs. 94 and 95 has a capacitance relatively so large that it may be regarded merely as providing a path for H.F. R_2, the grid resistor of V_2, is thus in parallel with the anode load of V_1, still further reducing the effective resistance and the voltage amplification between the input to the grid of V_1 and the input to the grid of V_2. And in parallel with all of them is the reactance of C_i, the input capacitance of V_2. . . . But we have seen enough already to realise that we could not expect much gain from R-C coupled amplifiers in S.F. and I.F. stages.

Despite its shortcomings on the R.F. side of the receiver, R-C is a very effective form of coupling in the A.F. stages. In these we do not want selectivity: the ideal coupling stage would provide an absolutely level response to all the applied A.F.s. Stage gain is of importance, but, since the frequencies are low, stray capacitances are not likely to be such a nuisance in reducing it. Actually we can obtain with R-C couplings as much over-all amplification as we need in the A.F. stages.

The R-C A.F. circuit looks simple, and up to a point it is. If you used the Fig. 94 arrangement with values for R_1, C and R_2 chosen without any elaborate calculation, you would obtain passable results. Taking V_1 as having $g_m = 1{\cdot}5\text{mA/V}$, $R_a = 10{,}000\Omega$ and $\mu = 15$, R_1 might be $24{,}000\Omega$. Try $0{\cdot}002\mu\text{F}$ for C and $1{,}000{,}000\Omega$ (1 megohm, or $1\text{M}\Omega$) for R_2. Yes ! It works. And it will work fairly well with considerably different values of C and R_1. Then if R-C coupling is as simple as all that, why bother to say any more about it ? Actually R-C presents far more problems and far deeper ones than might at first sight seem possible for an arrangement consisting of just two resistors and a capacitor. Were those its only components all would be well; but there are others, invisible to the eye, which play very important parts. Owing to them the circuit is far from simple ! Were I to deal at all fully with R-C as an A.F. coupling we should be wallowing for pages in a quagmire of mathematics. Do not be afraid ! I am not going to attempt anything so formidable.

We can, however, see something of its interesting problems without leaving *terra firma.*

If you have the components, make up the circuit with $C=0{\cdot}002\mu F$ and $R_2=1M\Omega$ and place it between the detector and the following valve. It works, as we have said; but are you quite satisfied with its performance? Listen to music for a while: isn't it rather thin and tinny?

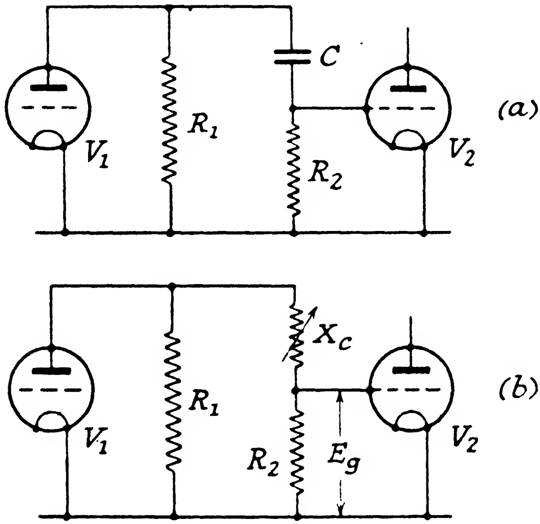


FIG. 96.—(*a*) Fig. 95 redrawn to explain the possible loss of lower audio-frequencies with R-C coupling. As shown at (*b*) the reactance of C, which varies with the frequency, is equivalent to a variable resistance in series with R_2. X_c and R_2 between them form a potential divider.

Isn't there an almost entire absence of bass? The circuit, as a matter of fact, is responding very poorly to all frequencies from about 75 c/s downwards, and when you remember that 64 c/s corresponds to the C two octaves below the middle you will realise that it cannot do much with the bass.

Fig. 96*a* is Fig. 95 redrawn so as to make it clear that

C is in series with R_2 for A.F. voltages coming from the anode of V_1. The reactance of C is thus in series with the resistance of R_2 and, since X_c depends upon the frequency, we can further redraw the equivalent circuit, showing X_c as a variable resistance, as at *b*.

X_c and R_2 between them form a potential divider. The voltage E_g reaching the grid of V_2 is that across R_2. If X_c is so low as to be negligible the whole of the available voltage appears across R_2 and on the grid of V_2; but when X is high a considerable part of the available voltage is wasted in it and only a fraction reaches the grid of R_2.

Unless we can do something about it the voltage amplification between the grid of V_1 and the grid of V_2 is going to be very different for the middle and for the lower audio-frequencies. The latter are going to receive less amplification.

That is exactly what is happening in the circuit which we have made up. Audio-frequencies are regarded as so poorly reproduced as to be "lost" when they are brought out at 70 per cent. (0·707 or $\frac{1}{\sqrt{2}}$, to be exact) or less of the general level. It may be taken as a working rule that this occurs to the lower audio-frequencies when $X_c = R_2$. Matters are of course worse when X_c is greater than R_2, for more of the available voltage is then lost in X_c.

In the present instance $R_2 = 1{,}000{,}000\Omega$ and X_c at 75 c/s=

$$\frac{1}{\frac{44}{7} \times 75 \times 0{\cdot}002 \times 10^{-6}}$$
$$= \text{approx } 1{,}060{,}000\Omega.$$

X_c is rather greater than R_2 and there will be undue attenuation of frequencies below about 75 c/s.

The more correct rule is that X_c should be less at the lowest frequency to which a good response is required than

$$\left(\frac{R_a \times R_l}{R_a + R_l}\right) + R_g$$

where R_a is the anode resistance of V_1, R_l the load resistance of that valve and R_g the grid resistance of V_2.

In the present example we have

$$\frac{10{,}000 \times 20{,}000}{10{,}000 + 20{,}000} + 1{,}000{,}000\Omega$$
$$= 1{,}006{,}666\Omega$$

With $X_c = 1{,}060{,}000\Omega$ the circuit would not deal properly with frequencies of 75 c/s.

There appear to be two possible solutions of the difficulty:

(1) increase the capacitance of C;
(2) increase the resistance of R_2.

Actually R_2 at $1\text{M}\Omega$ is already on the high side, and if we are going to increase the capacitance of C it must come down; we shall be running into other trouble if the time constant of C and R_2 becomes excessive. Let us make R_2 $0{\cdot}5\text{M}\Omega$ and C $0{\cdot}01\ \mu\text{F}$. The effective resistance is now $500{,}000 + 6{,}666 = 506{,}666\Omega$. At what frequency will the circuit reach its cut-off of 70 per cent.? The frequency is that at which $X_c = 506{,}666\Omega$.

$$\frac{1}{2\pi f \times 0{\cdot}01 \times 10^{-6}} = 506{,}666$$

$$\therefore f = \frac{10^8}{2\pi \times 506{,}666}$$
$$= \text{approx. } 32 \text{ c/s}$$

And what of the upper audio-frequencies? Here, again, capacitance has serious effects, this time the stray capacitances of the valves. In a triode there are three stray capacitances (Fig. 97*a*): (1) the anode-cathode capacitance C_{ac}; (2) the anode-grid capacitance C_{ag}; (3) the grid-cathode capacitance C_{gc}. In considering the R-C circuit these strays can be lumped, as Fig. 97*b* shows, into one capacitance C_s equivalent to the total stray capacitance. This is in parallel with the effective lumped resistance R_e, which is $\left(\frac{R_a \times R_l}{R_a + R_l}\right) + R_g$.

The higher the frequency, the smaller the reactance

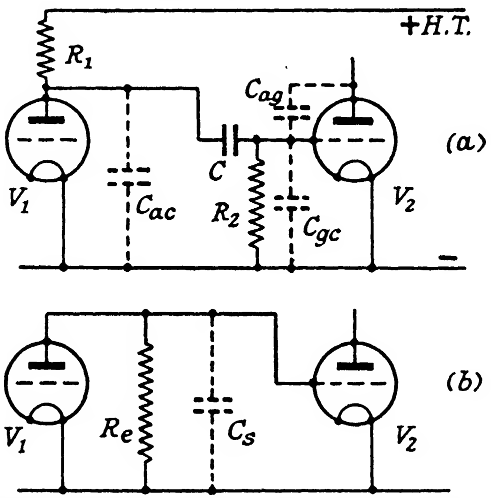


FIG. 97.—Stray capacitances have important effects on the amplification of the upper audio-frequencies.

of C_s and the impedance of R_e and C_s in parallel. Hence at the upper end of the audio scale amplification falls away. A correction may be made in the way shown in Fig. 98, where L is an iron-cored inductor and is in series with R_1. The inductance of L is made such that with C_s it forms a tuned circuit, resonating at a frequency which would otherwise be at or near the cut-off. The $\frac{L}{R}$ ratio and therefore the Q of the tuned circuit are both very low; it thus behaves after the manner of low-Q tuned circuits, showing no sharp resonance peak and responding to a widish band of frequencies.

It should be remembered that C_s consists of not only capacitances between electrodes inside the valve, but also of those in the valveholder and the wiring, which may be much larger. C_s, and its baleful effects on reproduction, can be kept reasonably low by careful design.

If V_2 is a pentode stray capacitances are not so large. The input C_s of a pentode is the sum of the capacitances

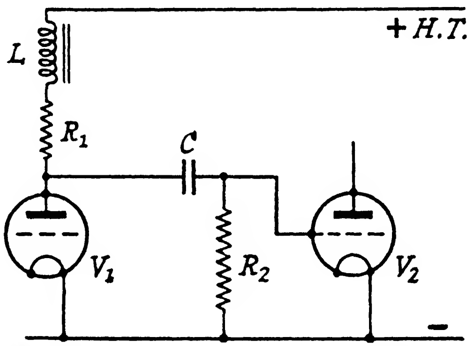


FIG. 98.—The use of an inductor to correct the falling off of the upper audio-frequencies.

control grid-screen, control grid-suppressor and control grid-cathode. Its output C_s is the sum of the capacitances anode-suppressor, anode-screen and anode-metal shield. There is not so much lowering of the stage gain in this case between the grid of V_1 and the grid of V_2 at the upper audio-frequencies. Further, the pentode has, as we shall see later, a tendency to amplify the upper A.F.s more strongly than the middle and the lower A.F.s.

Fig. 99 shows at B the response curve of a poorly designed R-C amplifying stage. The tailing off at the lower frequency end and the early cut-off are due mainly

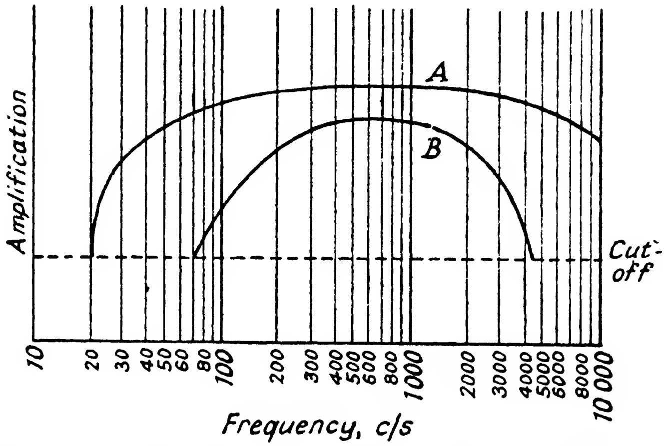


FIG. 99.—*A*, a good A.F. amplifier response curve. *B*, Response curve of a poorly designed amplifier.

to the coupling capacitor. Similar effects at the higher frequency end are due to stray capacitances. At A is a good response curve.

CHAPTER XVII

Amplifier Circuits: (3) Push-Pull

THE output stage of a receiver designed for high-quality reproduction may consist of a pair of power valves arranged as shown in Fig. 100. The output valve of any receiver required to work a loudspeaker must be of a type designed to deliver power in its anode circuit. From other valves in the receiver we want voltages, developed across the load resistance or load impedance;

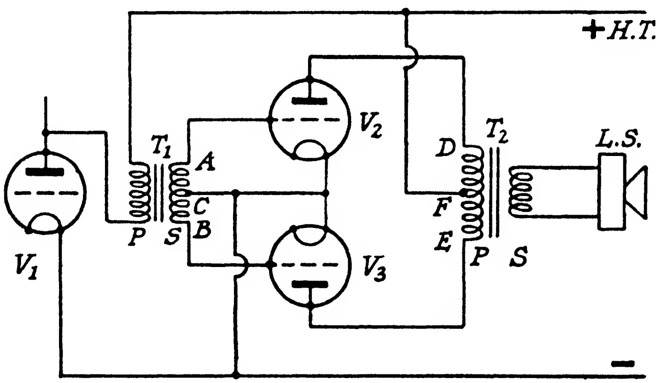


FIG. 100.—Two power valves used in push-pull.

but the output valve must deliver the watts necessary to move the cone of the loudspeaker to and fro. The Fig. 100 arrangement is known as PUSH-PULL; a very good name, for the valves operate in very much the same way as two sawyers at work on a log with a big cross-cut saw: when either is pulling the other is pushing and *vice versa.*

The effect of a positive half-cycle in the secondary of the transformer T_1 is to make the point A positive and the point B negative with respect to C, the earthed middle point of the windings. Suppose that this half-cycle peaks to +12V; then C remains at 0V, whilst A goes to +6V and B to − 6V. Similarly, the following negative half-cycle takes A to − 6V and B to +6V, C remaining always at 0V. The grids of V_2 and V_3 thus each receive half of the total voltage swing; and they receive it in

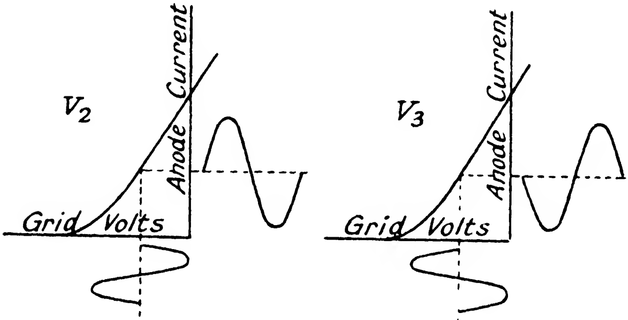


FIG. 101.—One push-pull cycle.

opposite phase. Whilst the voltage reaching V_2 is positive, that reaching V_3 is negative and *vice versa.*

Both valves are operated like normal A.F. amplifiers, the working points being in the middle of the straight portions of their characteristics. Fig. 101 shows the effect of the application by the secondary of T_1 of one voltage cycle to the grids of V_2 and V_3. In the anode circuit the H.T.+ connection is at the mid-point of the primary winding of T_2, and we have seen that so far as A.F. currents are concerned H.T.+, and therefore the point F, may be regarded as earth. Thus when the E.M.F. driving the A.F. current of V_2's output makes D positive to F, that driving V_3's A.F. output makes E negative. The two anode currents are out of phase, but they pull or push together, since they flow through different halves of the primary of T_2. In the secondary of T_2 A.F. currents are induced which are magnified copies of those in the primary of T_1.

This kind of push-pull amplification, in which both valves work on the straight portions of their characteristics and are both always active, is known as CLASS A. Its main advantages are:

(1) The pair of valves behave like a single valve with a genuinely straight "straight" portion of its characteristic. This is because the two working points move simultaneously along the load-lines in opposite directions. The total distance along the load-lines travelled by the two working points in a positive half-cycle is exactly the same as that travelled by them in the following negative half-cycle. There is thus no lopsidedness in the cycles and second harmonic distortion does not occur.

(2) The D.C. components of the anode current flow in opposite directions in the two halves of the primary of T_2. The fluxes they produce through the iron core thus cancel out and there is no risk of magnetic saturation and the accompanying distortion.

(3) As the value of the A.F. current is always zero in the H.T. lead from the centre tapping of the anode transformer primary, unwanted feed-back effects cannot take place through the H.T.+ line.

(4) There is no tendency to pick up hum from the mains.

(5) As only half of the input voltage is applied to

each valve, this arrangement can deal without distortion with twice the input voltage that either valve could handle alone.

Q.P.P., or QUIESCENT PUSH-PULL, was designed to economise H.T. current in battery sets and so cut down the cost of running them. The circuit is basically the same as that of Fig. 100. The valves, either triodes or pentodes, are given so much negative bias that the working point is taken down to the lower bend of the characteristic. Hence when no signal is coming in the amount of H.T. current passing is minute: the valves are quiescent. The anode current, when reception is taking place, corresponds to the grid voltage in its amplitude; during soft passages it is quite small and only in loud passages does it rise to a heavy drain on the H.T. battery. The output stage, in fact, adjusts its demands on the battery to suit the amplitude of the signal at any moment.

A third type of push-bell also devised for battery sets is CLASS B. The circuit is again basically the same as that of Fig. 100. The object is to obtain considerably more power than is possible for the same amount of H.T. current by other methods. With Class B output a battery set can deliver to the loudspeaker a very respectable amount of power though making surprisingly small demands on the high-tension battery. Any well-matched pair of output triodes or pentodes can be used in Class B by adjusting the bias so that the working point is taken almost to the cut-off. Valves specially designed for the purpose are, however, generally employed. The two sets of electrodes are as a rule contained in one bulb. In these special Class B valves the cut-off occurs with a very small negative grid voltage; the greater part of the characteristic lies to the right of the zero grid volts line.

The essence of Class B is that the grids of the valves are allowed to go positive when positive half-cycles reach them. This means that grid current flows and power is expended in the secondary of T_1. This power must be made good, if the output is not to be robbed of it, by power delivered by V_1. V_1 must therefore be a valve capable of delivering a certain amount of power and of *driving* V_2 and V_3. It is known for this reason as the DRIVER VALVE. In the case of Class B, T_1 is specially designed so as to be able to handle this power.

There is yet another kind of push-pull: CLASS C. This is not suitable for amplifying purposes in a receiver. It is, however, largely used in transmitters. In Class C the valves are biased back far beyond cut-off. Enormous grid voltage swings can be handled, for the working point is taken by large positive peaks of grid voltage right up to the upper bend of the characteristic. The whole of the characteristic from cut-off to saturation point can thus be utilised. Class C cannot be used in a receiver because horrible distortion would result, since the two valves between them are in operation for only about two-thirds of each cycle—some 240 out of its 360 degrees. But this does not matter in the oscillator of a transmitter, where the fullest advantage can be taken of the efficiency of the Class C system.

CHAPTER XVIII

Tone Correctors and Controls

STRICTLY speaking, the term " tone " is a misfit when applied to a wireless receiver. Tone is a characteristic quality of a particular musical instrument; the receiver should have no tone, for its business is to reproduce the sounds occurring in the broadcasting studio without adding anything of its own to them. To say of a wireless set that it has a beautiful tone is really to condemn it, for the expression can mean only that it reproduces unfaithfully, lending the transmission a colouring which should not be there.

The expressions " tone," " tone correction " and " tone control " have, however, become so deeply rooted that they must be used when discussing the audio-frequency balance of the reproduction. What " a good tone " means, I believe, is that the hearer finds the range of audio-frequencies reproduced adequate; that he notices no undue suppression of frequencies; and that none are over-strongly brought out. TONE CORRECTION refers to methods of obtaining such balance by the use of non-adjustable circuit components. TONE CONTROL denotes the means whereby the user of a set can vary the audio-frequency balance to suit his own particular requirements.

We have already seen in discussing R-C amplifiers how badly the balance of audio-frequencies can be upset by an ill-designed circuit and what steps can be taken to avoid this; the levelling up of the bass and treble response of such a circuit is one form of tone correction. Another is the use of proper band-passing in the S.F. and I.F. stages, which ensures that the sidebands carrying the upper audio-frequencies are not cut at too low a level.

But there are other points which require attention by the designer if reproduction is to be at all faithful. I am not going to discuss the more abstruse of these, for they involve physics and mathematics beyond the scope of this book; but we can deal with several of great interest.

Despite all its other good points, the pentode can be a fruitful source of lack of balance in the audio stages. One of its peculiarities is that it is prone to emphasise the upper audio-frequencies much too strongly when it is employed in the output stage. This is because the anode load is inductive: the primary of the output transformer, as in Fig. 89. A transformer is required because the high output impedance of the valve must be matched to the low impedance of the loudspeaker speech coil, and the step-down ratio of its primary and secondary windings enables this to be done.

We have seen that with a resistance as anode load the stage gain of a pentode is $g_m \times R_l$; if the load is an impedance, such as an inductor, the stage gain is $g_m \times Z_l$. Now, the reactance of an inductor is high at high frequencies and low at low frequencies, and the result is that an A.F. pentode with a transformer primary gives much too much prominence to the upper audio-frequencies—pentode shrillness is an expression that is often used.

Fig. 102 shows a simple corrector circuit, consisting of a capacitor and resistor in series placed across the primary winding of the transformer. Since the reactance of C goes down as the frequency goes up, the arrangement acts as a counterbalance to the transformer primary and the total anode load impedance adjusts itself according to the frequency. It need hardly be said that the values of C and R and the inductance of the transformer primary require to be worked out very carefully for good results to be obtained.

The pentode has another bad habit, which can lead to very unpleasant reproduction. Triodes, as we have seen, are prone to introduce second harmonic distortion, which may be eliminated by using them in push-pull. The pentode's speciality in this way is third harmonic distortion, upon which push-pull has no effect. Distortion due to prominence of even-numbered harmonics, such

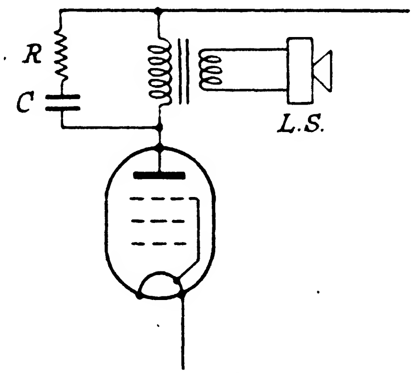


Fig. 102.—A simple tone-corrector circuit for the pentode.

as the second, is unpleasant; that caused by the odd-numbered harmonics is vastly more so.

By careful adjustment of its anode load the percentage of third harmonic in a pentode's output may be kept down; but that method becomes difficult, to say the least of it, when the anode load is an impedance varying with the frequency. Fortunately there is another way of curbing the pentode's evil propensities. This consists in using negative feed-back, of which mention has already been made. Positive feed-back, you will remember, consists in supplying to the grid circuit of a valve voltages from the anode circuit in phase with those of the incoming signal. The result is to reduce the effects of resistance, to increase amplification and to produce a sharply peaked response at resonance.

Negative feed-back supplies out-of-phase voltages from the anode to the grid circuit and, as might be expected, its effects are exactly the reverse. The most important from the point of view of quality of reproduction is that it flattens the response curve, ironing out any peaks in it.

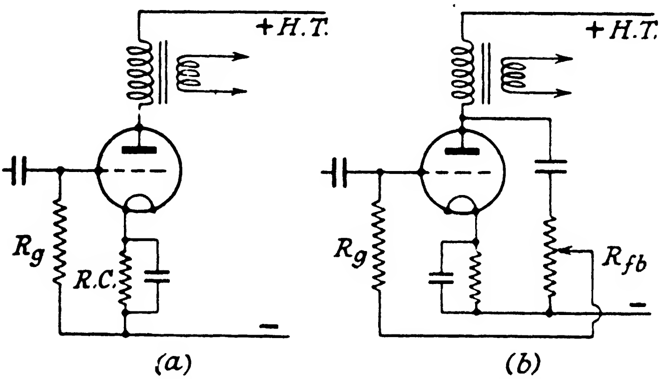


FIG. 103.—Two methods of obtaining negative feed-back.

It can also reduce enormously the pentode's unwelcome third harmonic distortion.

As usual, gains of this kind have to be paid for; negative feed-back applied in the degree necessary to produce these desirable results has devastating effects on the stage gain, which may be brought down to a quarter, or less, of its value with no such feed-back. The loss can be made good, if need be, by the use of an additional A.F. amplifier.

Fig. 103 shows two ways of obtaining negative feed-back. At *a* the grid biasing resistor R_c is common to both anode-cathode and grid-cathode circuits. Current variations in the anode circuit give rise to varying potential differences across R_c and feed-back to the grid occurs. This method is seldom used. Negative feed-back through R_c is prevented from occurring as an unwanted effect by connecting in parallel with the resistor a capacitor whose reactance is negligible at the lowest frequencies to be handled.

A commonly used method is seen in Fig. 103*b*. The feed-back resistor R_{fb} has a value very high in comparison with the impedance of the primary of the output transformer, which forms the anode load, in order to prevent wastage of output power. R_{fb} usually takes the form of a potential divider, allowing the correct feed-back voltage to be tapped off and fed to the grid via R_g.

Undue prominence to certain frequencies may be given by resonances in the loudspeaker. Negative feed-back improves matters since it reduces the effective output impedance of the valve, and a low impedance across the loudspeaker tends to damp out the effects of resonances in it. It is also possible to tap the feed-back voltage from the secondary of the output transformer, thus reducing transformer as well as valve distortion.

The tone control in many low-priced receivers would be more aptly named were it called the frequency distorter ! Its function in such sets is simply and solely to cut the upper audio-frequencies: the further the knob is turned anti-clockwise, the lower down the musical scale is the point at which the cut-off takes place. Few of such receivers respond to frequencies much above 4,500 c/s, even when the tone control knob is turned fully clockwise; with the knob turned as far as it will go in the opposite direction the highest frequency reproduced may not be above 2,500 c/s. Yet how often do listeners keep the knob permanently in this latter position and speak admiringly of the " mellow tone " of the set !

Were it possible to make a receiving set reproduce with complete fidelity, no tone control would be necessary. We may make a close approach to fidelity, but with such methods as we now have it cannot be achieved entirely. To begin with we want the reproduction of an Albert Hall orchestra in our own rooms to be a miniature of the original, the acoustic equivalent of viewing a scene through the wrong end of a telescope. That complicates matters immensely. Then there are the problems of the loudspeaker. A concert orchestra occupies several hundred square feet of space and the sounds that it makes come to us from all parts of this large area. Those from the loudspeaker all originate in the cone, whose area is unlikely to be even one square foot. Sound waves from the loudspeaker, too, take different paths in their outward travel. The very short ones, corresponding to high audio-frequencies, are projected forward from the cone almost in the form of a beam, whilst the long waves of the low A.F.s take much more divergent paths. There is also the question of the acoustics of individual rooms, which show considerable differences from one another in this respect.

Even if the receiving set had a perfectly even response to a wide range of A.F.s, we should probably not find its reproduction completely satisfactory to the ear unless some adjustment of the balance of treble, middle and bass could be made. It is possible to design tone controls allowing genuine " lifts " of either treble or bass at will —we have already discussed some of the important factors concerned. These demand elaborately designed circuits and they are therefore seldom seen except in high-priced receiving sets. From what has been said about amplification and reproduction problems you will, I feel, have gathered that fine quality in the loudspeaker's output cannot be achieved cheaply.

Sensitivity—the ability to receive weak and distant transmissions—costs comparatively little. It can be obtained (too often at the expense of quality) by using a small number of valves of high mutual conductance in high-Q S.F. and I.F. stages. Yet sensitivity rather than quality of reproduction is apt to be the criterion by which the virtues of a wireless receiver are assessed. It is a curious fact that, though he well knows that he will use it for more than ninety-five per cent. of the time that it is in operation for receiving the home, the light or the third programme from his local transmitter, the first question that the average prospective purchaser of a wireless set puts to the salesman is: How many foreign stations will it get?

In the circuit seen in Fig. 89 the combination of the capacitor C_{24} and the resistors R_{17} R_{18} and R_{19} forms an ingenious tone control. R_{17} and R_{18} between them make up the anode load of V_3. Negative feed-back from V_4 is led by way of C_{24} and R_{19} to a tapping on this load and thus passes through C_{25} and R_{22} to the control grid of V_4. R_{19}, being variable, enables both the amplitude and the frequency characteristic of the feed-back to be adjusted and the gain of V_4 at the upper audio-frequencies to be regulated at will. R_{24} is a grid stopper resistor, its purpose being to prevent any intermediate frequencies remaining in the anode circuit of V_3 from reaching that of V_4.

CHAPTER XIX

Power Packs

IT seems strange when one looks back now that the development of the mains-operated wireless receiver was so slow a business. The triode was invented in 1907 and the first broadcasts by the British Broadcasting Company, as it was then called, were made in 1922. The triode was then a purely battery valve, and such it remained for several years. The first step forward was the invention of an apparatus called the high-tension battery eliminator, which enabled the previously very expensive high-tension current to be obtained at small expense from the mains. It was not until the invention of the indirectly heated cathode that the " all-mains " receiver became possible. Early mains valves were apt to be very kittle-cattle, for it was some time before a satisfactory and reliable method of insulating the heater from the other parts of the valve could be found. Once, however, this had been worked out, progress was rapid and the mains set rapidly ousted its battery counterpart in homes with A.C. lighting supplies. The D.C. receiver followed, and hard on its heels came the A.C./D.C. receiver, sometimes misnamed the " universal " set.

To make use of mains-supplied A.C. for running the wireless receiver two things are essential. The first is a heater effectively insulated from a cathode providing a sufficient supply of ejected electrons; the second is a means of rectifying A.C., or converting it into D.C., so efficient that the D.C. is completely " pure," with no residue of an alternating component.

Requirement No. 1 has been met by modern methods of A.C. mains valve design and manufacture; insulation breakdowns between heater and cathode are now rare. The sole business of the heater is to heat and it is not connected electrically to any of the amplifying or detecting circuits of the receiver; it can therefore be supplied with

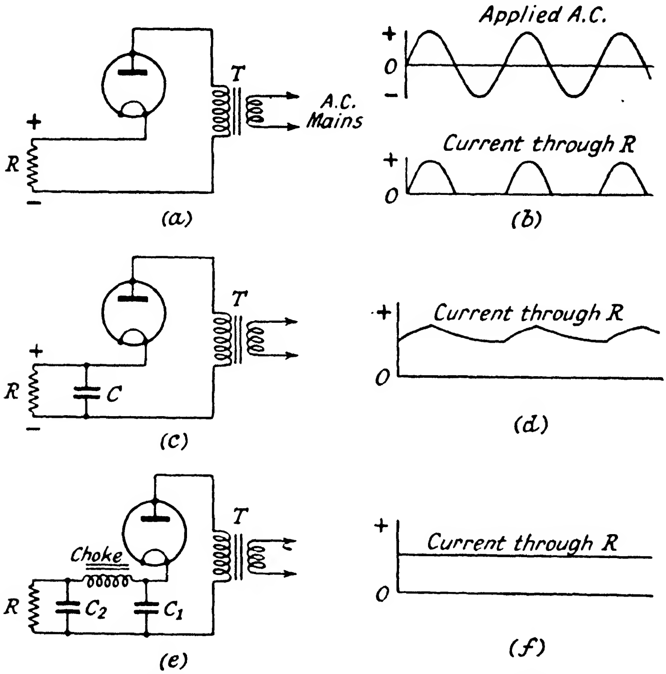


FIG. 104.—Illustrating the way in which smooth D.C. is obtained with a diode and a smoothing circuit.

A.C. by means of a transformer. For the H.T. supply the provision of D.C. by the rectification of A.C. presents no very difficult problems. We have already seen how grid biasing voltages are obtained. That part of the set which draws current from the mains and passes it in suitable form to the L.T. and H.T. circuits is called the power pack.

Fig. 104 illustrates the way in which smooth D.C. may be obtained from the mains by means of a diode. At *a* the valve is seen with nothing but a load resistance R in its output circuit. The diode conducts, or passes current, during the positive half-cycles only. The result, as seen at *b*, is a series of disjointed spurts of direct current through R. If now a capacitor C is connected across the circuit as at *c*, current no longer flows through R in discontinuous spurts. In the positive half-cycles, whilst the valve conducts, C charges, storing current. Discharge of stored current through R takes place when the valve is non-conducting in the negative half-cycles. The current through R is of the kind seen at *d*; it is continuous D.C. with a ripple on it. Note that the frequency of the ripple is the same as that of the applied A.C., one little peak occurring at each positive half-cycle of A.C.

Current of that kind would not be of much use for H.T. supply purposes, for it would produce all the time a loud note of 50 c/s, or whatever was the mains frequency. The ripple must be removed, and Fig. 104*e* shows how this is done. C_1, the choke and C_2 form a filter for the ripple, known as a SMOOTHING CIRCUIT. Instead of a separate choke the field windings of the loudspeaker pot magnet are often made use of (as in the Fig. 89 circuit), the whole H.T. current being passed through them and serving as a magnetising current.

The ripple may be regarded as A.C. superimposed on the D.C. The inductance of the choke is large and it therefore offers high reactance to the ripple but small resistance to the D.C. component. The ripple thus drops most of its voltage in overcoming the reactance of the choke, whilst the D.C. component drops very little voltage in overcoming its resistance. What is left of the ripple passes out of harm's way through the low reactance of the large capacitor C_2. The current through R, if the smoothing circuit is properly designed, is pure D.C. as at *f*. The place of R is, of course, taken by the H.T. circuits of the receiving set.

The single diode, or half-wave rectifier, is seldom used in receiving sets nowadays. Its disadvantages are (1) that it uses only half of each cycle of A.C. and (2) that the lowness of its ripple frequency makes efficient smoothing somewhat expensive to obtain owing to the large capacitances and inductance needed.

Fig. 105 gives the complete circuit of a full-wave rectifier, using a double diode. The mains transformer here

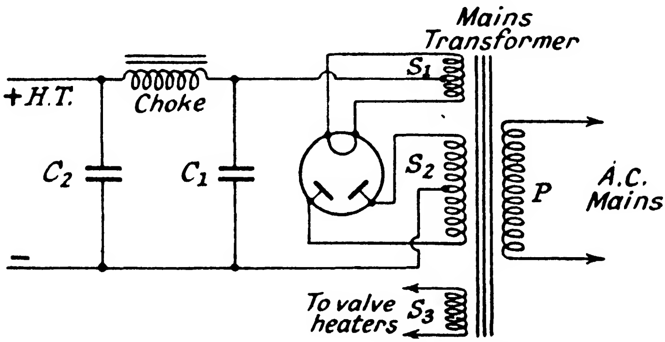


FIG. 105.—Power pack using a double diode.

has three separate secondary windings. S_1 supplies current for the filament (or heater) of the diode. The anodes are fed from the opposite ends of S_2, and current flowing always in the same direction is delivered from the centre tapping of the winding. S_3 furnishes low-voltage current for the valve heaters.

This circuit hardly requires further explanation. It will be realised that the two diodes in the valve conduct alternately, one during each half-cycle of applied A.C. The frequency of the ripple is thus double that of the mains current and smoothing is made easier.

One of the advantages of deriving power from A.C. mains is that a transformer can be used to deliver a stepped-up voltage for the H.T. circuits and a stepped-down voltage for the heater circuits.

This advantage is lost in the A.C./D.C. set, which is designed to work off supplies of either kind; a transformer cannot be used for D.C., and so either this or A.C., whichever is being used to operate the set, is applied straight to the rectifier. On A.C. the rectifier performs its proper task; on D.C. it conducts all the time, its presence merely adding a little resistance to the circuit. D.C. as delivered by the mains is seldom free from ripple; the smoothing circuit therefore has a useful part to play. The valves of an A.C./D.C. set are of a special type; their heaters are designed for a higher voltage (13-40V) and a smaller current (usually 0·2A) than those of A.C. valves. In the receiving set the heaters of the valves are arranged in series and a ballast resistor is placed in series with them, its value being such that the current in the heater circuit is 0·2A.

The performance of an A.C./D.C. set can never quite equal that of one designed for A.C. mains only. The reason is that in the absence of a transformer the available voltage is less; and not nearly the whole of the mains voltage can be applied to the anodes of the valves. Some is wasted in the rectifier and in the smoothing circuit; some again must be dropped across the cathode resistors in order to provide grid bias.

CHAPTER XX

How Waves Travel

RADIO waves may be divided into eight great classes:

	Class.	*Wavelength.*	*Corresponding Frequency.*
I	Very long	Over 10,000 metres	Below 30 kc/s
II	Long	1,000-10,000 ,,	300-30 kc/s
III	Medium	100-1,000 ,,	3 Mc/s-300 kc/s
IV	Short	10-100 ,,	30-3 Mc/s
V	Very short	1-10 ,,	300-30 Mc/s
VI	Metric	0·1-1 metre	3,000-300 Mc/s
VII	Centimetric	0·01-0·1 ,,	30,000-3,000 Mc/s
VIII	Millimetric	Below 0·01 ,,	Above 30,000 Mc/s

There is actually no standard or generally accepted classification of wavelengths or frequencies. It has been said with some truth that were you to ask ten eminent wireless men what they understood by, say, medium, short, or very short waves, you would probably receive at least six different answers ! But the classification given above is a good one, for the waves in each of its eight categories form a group distinguished from each of the other groups by the manner in which they travel. It cannot be claimed that the divisions between the groups are as sharply defined as the list might suggest; there would be no sudden change in the behaviour of the carrier wave of a transmitter were the wavelength altered from 999 metres to 1,001 metres. The groups, in reality, shade off into one another; but, speaking generally, each of the classes shown in the table consists of waves which behave in a particular way.

Radiation from the aerial of a transmitting station takes two different paths as it moves outwards. One set of crests and troughs, known as the ground wave, follows the contours of the earth's surface. The other, the sky wave, travels upwards as well as outwards.

In the atmosphere which surrounds the earth there are two layers of air which act on wireless waves much as a mirror acts on light. The lower of these is the Heaviside layer, whose average height is some 65 miles. Far above this, at a height in the neighbourhood of 200 miles, comes the Appleton layer. Both layers are named after the men (Oliver Heaviside and Sir Edward Appleton) who discovered them. The lower is also known as the E-layer and the upper as the F-layer.

The transmissions of long- and very-long-wave stations are conveyed from place to place mainly by the ground wave. The ground wave induces currents in the land or water over which it is passing and these abstract energy and cause attenuation, the extent of which depends largely upon the resistance of the soil. Minimum attenuation and maximum range are obtained over salt water; maximum attenuation and minimum range occur over parched desert sand. The lower the frequency of the wave (that is, the greater its length) the smaller is the attenuation over a given surface. That is why very great wavelengths, such as Rugby's 18,750 metres—nearly eleven miles—are used for high-powered transmitters designed to maintain uninterrupted communication with all parts of the world.

The long waves, being of higher frequency than the very long, suffer more from attenuation and the range of transmitters using them is shorter, though still considerable. Droitwich on 1,500 metres provides a reliable service over the whole of this country.

On the medium waves the sky wave becomes of importance. The E-layer is a poor reflector by day, but a good one after dark to such waves, bending them back to earth (Fig. 106). To provide a reliable service at all times in the area which it is designed to cover a medium-wave broadcasting station must radiate a ground wave sufficient to give good signals in every part of it, for the sky wave is in evidence only at night. It is by means of the sky wave that we hear distant medium-wave stations after dark.

The aerials of modern medium-wave broadcasting stations are designed to give maximum ground-wave and minimum sky-wave radiation, for within the service area, and particularly near its outer fringes, the sky wave

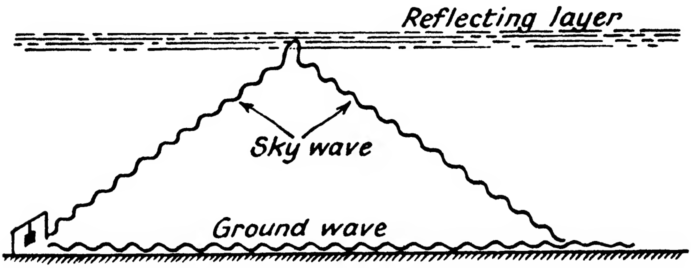


Fig. 106.—The sky wave bent back to earth by the reflecting layer.

is a nuisance. It is the sky wave which causes fading on medium-wave transmissions at dusk and afterwards.

Here is what takes place. The sky wave travels (Fig. 106) by a longer path than the ground wave from the transmitting to the receiving aerial. The length of the sky wave's path is constantly varying, for slight changes are always taking place at the under surface of the E-layer, causing reflection to take place at different angles. At the fringes of a service area, where the ground wave has suffered considerable attenuation, the amplitude of the sky wave may be as great, or even greater.

If the two waves reach the receiving aerial in phase their energies are added together and the resulting signal is strong. Should they be of equal amplitude and exactly out of phase, they cancel out and there is no signal. Between these two extremes there is an infinite number of possible combinations of the two waves. As the phase is continually changing, owing to the varying length of the sky wave's path, fading occurs. A.V.C. can take charge of fading that is not too marked, but it cannot cope with a signal which disappears altogether at intervals.

Since they produce no effective sky wave, long-wave transmissions do not suffer from fading. They are, however, more prone than medium waves to interference

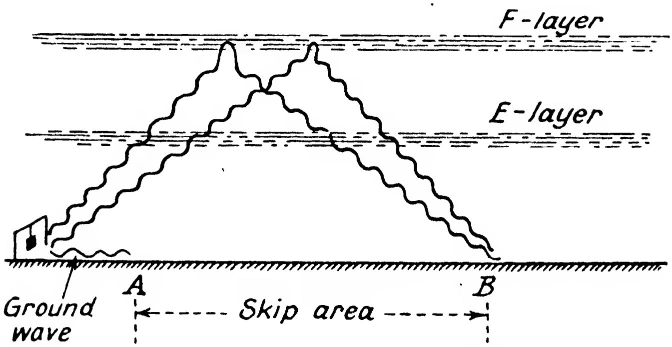


FIG. 107.—With short waves the ground wave peters out very quickly. The sky wave penetrates the E-layer and is reflected back to earth by the F-layer. No reception is possible in the skip area from A to B.

from atmospherics and that generated by certain kinds of electrical appliances. Good medium-wave transmitters rated at 100 kilowatts or so can provide reliable ground-wave reception by day and night at ranges of 50-75 miles according to the nature of the soil.

Attenuation of the ground wave is so severe on short-wave transmissions that it is useless for covering distances greater than a mile or two; the sky wave is all-important. Waves below 100 metres in length are not normally reflected by the E-layer; they penetrate this and are returned to earth by the F-layer (Fig. 107) provided that the angle at which they impinge on this layer is sufficiently oblique. Places between A and B in Fig. 107 are said to be in the skip area. No reception is possible there, for the ground wave has petered out and the range is too short for the sky wave to have returned to earth. The extent of the skip area depends upon the angle at which the waves are returned to earth, and that in its turn depends upon their frequency, the time of day or night, the season of the year and what stage has been reached in the sunspot cycle.

Notice that the sky wave can travel from A to B by different paths, which may vary in length. Fading can therefore occur on the short waves, and frequently does so, owing to the interaction of waves arriving by paths of different length.

Short-wave transmissions can span enormous distances with comparatively small transmitter power behind them. Great distances may be covered in several "hops," the waves being reflected a number of times from F-layer to earth and from earth to F-layer. They may in fact travel several times round the world, reaching the receiving aerial more than once and causing "echoes" of the original signal to arrive. The condition of the lower surface of the F-layer undergoes great changes by day and night as well as at different seasons of the year and at different periods of the sunspot cycle. On this account its qualities as a reflector of short waves of various lengths are continually varying; any station intended to maintain communications at great distances on the short waves must have a considerable number of different wavelengths at its disposal and be able to change from one to another.

The very short waves are not normally reflected back to earth by either E- or F-layers and their ground wave has a very small range indeed. Neither ground wave nor sky wave is of any value. But the very short waves can be radiated in such a way that they travel in a straight line through the ether like those of light. The range of this direct wave, as it is called, is quasi-optical: that is to say, it cannot in theory reach a receiving aerial which is much below the horizon as seen from the top of the transmitting aerial. Actually the direct wave may be slightly bent by the atmosphere and can thus reach a receiving aerial which is some distance beyond visual range. Abnormal conditions occasionally cause very short waves to be reflected and reception may then take place at great distances: the London television transmissions have been received in New York and in South Africa.

The very short waves are used for television as well as for radio links in telephone systems and for communication over short distances by the police and the fighting services. They were also used by the earlier radar appliances. As we shall see in the next chapter, they are likely one day to prove of great value for ordinary broadcasting.

The centimetric waves are also quasi-optical in their behaviour. They are occasionally reflected from regions of disturbance in the atmosphere such as storm centres. Their chief use hitherto has been in radar systems of great precision. Of the millimetric waves little use is yet made, though experimental work is going forward both in this country and in America. It is more than likely that they will enable enormous advances to be made in certain kinds of radar. The " pictures " at present obtained on the screen of a cathode-ray tube by centimetric radar devices which enable the navigators of ships and aeroplanes to see their way in fog or falling snow are somewhat vague and " blotchy." Millimetric radar appliances may one day give pictures so clear that they amount to radar television.

Apart from other causes the intensity of radiation on all wavelengths falls off with increasing distance through spreading. Exactly the same thing occurs with light. Just as light waves can be focused into a beam by a lens or a parabolic reflector, so wireless waves below 100 metres in length can be " beamed " and made to carry signals over far greater distances for the same transmitter power. Waves from 10 centimetres to 100 metres in length are usually beamed by the use of specially designed aerial arrays. Parabolic reflectors are used for centimetric waves and actual lenses are now being developed for those of shorter lengths.

CHAPTER XXI

Things to Come

THE only method that I have dealt with so far of impressing an audio-frequency signal on a carrier wave is amplitude modulation (Fig. 108*b*). This is the only system in general use for broadcasting purposes; but there are several others and a good deal of use may be made of some of them in the future.

Fig. 108*c* illustrates the FREQUENCY MODULATION of a carrier. In this system the amplitude of the carrier remains constant and modulation is applied by causing its frequency to vary. As the drawing shows, the maximum frequency occurs at the peaks of positive half-cycles and the minimum at the troughs of negative half-cycles. In amplitude modulation (A.M.) a loud sound gives rise to large changes in the amplitude of the carrier and a soft sound to small changes. As one might expect, loud sounds cause the greatest frequency change, or DEVIATION, in frequency modulation (F.M.) and soft sounds the smallest.

Owing to the very wide band of frequencies needed for each channel F.M. cannot be used on the medium or even the short waves. On the very short waves, though, there is plenty of room. The frequency range corresponding to 1-10 metres is 300-30 Mc/s, or 27,000 kc/s; compare this with the solitary thousand kilocycles included in the medium-wave broadcasting band (1,500-500 kc/s). Further, since the range of very-short-wave stations is so limited the same carrier frequency might be shared by several, provided that they were properly spaced out, without there being any mutual interference.

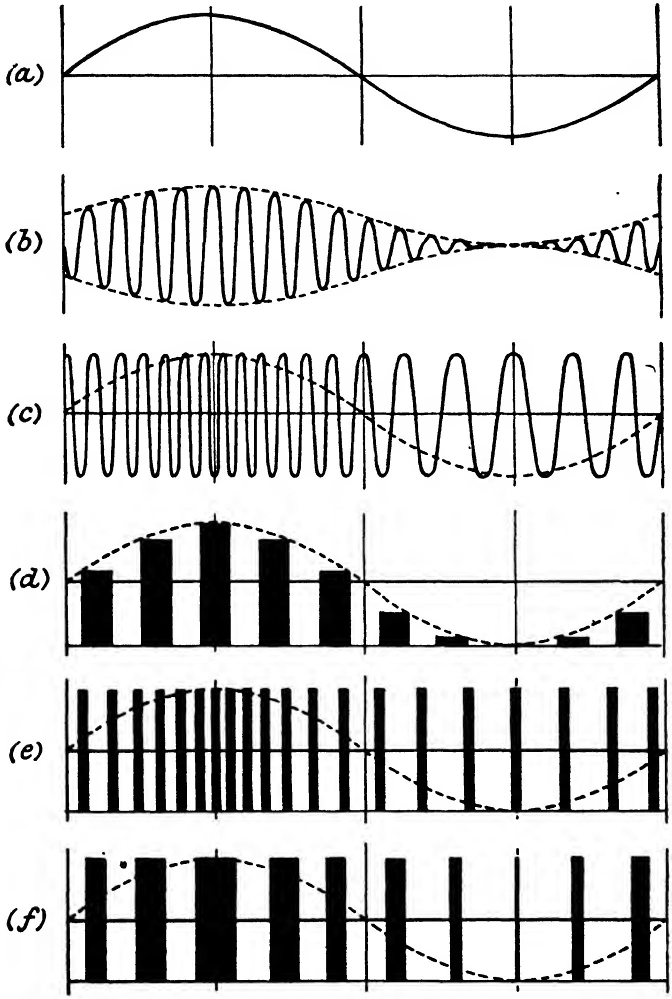


FIG. 108.—(*a*) Cycle of modulating frequency; (*b*) amplitude modulation; (*c*) frequency modulation; (*d*) pulse amplitude modulation; (*e*) pulse frequency modulation; (*f*) pulse width modulation.

For many years I have believed that the future of broadcasting would be on the very short waves and to-day I hold this belief more strongly than ever. There is not and there never can be room on the long-wave and medium-wave bands for all the stations necessary to provide the whole of Europe with a full service of broadcast programmes. Nor is this band the exclusive property of European stations; it is used by stations in all parts of the world, and after dark mutual interference can take place between stations separated by almost incredible distances. On several occasions I have been able to prove that heterodyne whistles spoiling the transmissions of certain European stations after about 9 o'clock on winter nights were due to interference by medium-wave broadcasting stations at work in the United States! As the broadcasting stations increase their power and extend their range mutual interference is likely to grow worse.

In the best of circumstances no European medium-wave station can have a channel more than 9 kc/s in width. This means that audio-frequencies above 4,500 cannot be transmitted and that music loses much of its brilliance. Such limited broadcasting is accepted by most people because they have never heard anything better and have come to adapt themselves to its imperfections, believing that "wireless must sound like that." Wireless reproduction can closely approach perfection (provided that the receiver and loudspeaker are up to the mark) if the transmitter is allotted a wide channel and makes full use of it. Those who have heard the reproduction by a first-rate receiver of the sounds accompanying the television programmes can bear this out. Both the vision and the sound transmitters of the B.B.C.'s Alexandra Palace station operate on the very short waves. The sound channel is a wide one and real high-fidelity reproduction is possible.

Amplitude modulation is used for this sound transmission at present; could a further improvement be made if F.M. were used instead? The answer is that it could. One of the outstanding features of F.M. is that it is a good deal less liable to be affected by interference than is A.M. On the very short waves almost the only kind of interference of any importance is that produced by motor-car ignition systems. As owners of television receivers know, the effects of this may be dire: a " snowstorm " on the screen and a volley of raucous noises from the loud-speaker as each motor vehicle passes. F.M. is far less affected by this kind of interference, which becomes almost negligible if the transmitted waves are horizontally instead of vertically polarised. We have, unfortunately, adopted vertical polarisation for the television radiations; but there is no reason why we should not change to horizontal when the very-short-wave broadcasting relay comes into its own.

Though the long-wave and medium-wave transmissions will undoubtedly be continued for some years, the B.B.C. is now about to develop side by side with them a country-wide system of high-fidelity horizontally polarised relay stations using F.M. The area served by each transmitter will be limited, since its radiations will have but a quasi-visual range; but the power output of each can be small and the cost comparatively low.

There is another very interesting possibility about high-fidelity transmissions relayed by an extensive network of such stations. You have probably noticed when listening to a broadcast of an orchestral concert that there was considerably less difference in volume between *pianissimo* and *fortissimo* passages than you would have heard had you been present in the hall. This is due to a process known as contrast compression, which takes place in the control room of the broadcasting station.

One of the aims of broadcasting engineers is to maintain "100 per cent. modulation." This means that with A.M. the troughs of the loudest passages broadcast just reduce the carrier amplitude to zero. In order that the service area of the station may be wide it is advisable that hundred-per-cent. modulation should occur on studio sound waves of large, but not the largest possible, amplitude. Any sound waves of very great amplitude would give rise to over-modulation and to the distortion which occurs if the modulation is allowed to exceed 100 per cent. Impulses corresponding to very loud sounds have thus to be toned down on their way to the modulator. This is done by a programme monitor, who sits with his fingers on the knob of an attenuator and his eyes fixed on the dial of an instrument showing the modulation depth at any instant. Passages which are *fff* as played by the orchestra thus differ little in volume as the loud-speaker's reproduction from those which are merely *f*.

Pianissimo passages are controlled, or compressed, in just the opposite way. To allow them their full value would mean letting the modulation level fall so low that little or nothing might be heard by listeners near the fringe of the service area. Passages which are played by the orchestra as *ppp* are therefore brought up to the equivalent of *pp* or even *p* by the controller.

With F.M. there need be no such drastic control, and the volume contrasts can be far more realistically brought out.

F.M. has been in use for some time now in America for high-fidelity broadcasts. The B.B.C.'s new system now under development is the result of extensive tests in this country with highly successful results. The long-wave and medium-wave broadcasts will continue for many years; possibly Droitwich and a certain number of medium-wave stations will be kept in action indefinitely.

But side by side with the " low-fidelity " system another consisting of small F.M. relays, each providing high-

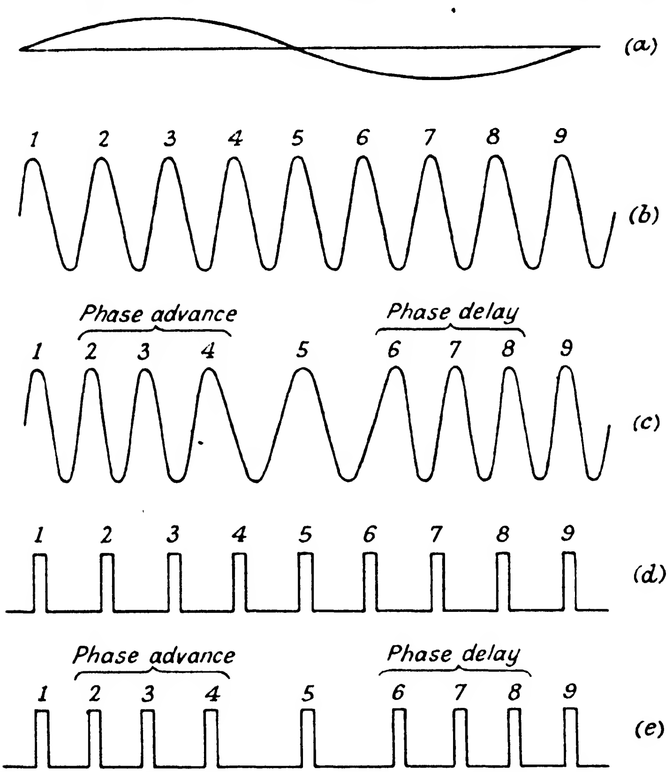


FIG. 109.—Illustrating phase modulation: (*a*) modulating frequency; (*b*) unmodulated carrier; (*c*) phase-modulated carrier; (*d*) unmodulated pulse-train; (*e*) phase modulated pulse-train. The cycles and the pulses are numbered in order to show the phase-advance and phase delay produced by the modulation.

fidelity transmissions for a small area, is coming into being.

Another possible method of impressing a signal on a carrier is PHASE MODULATION. I have tried to illustrate this in Fig. 109*c*, but it is not at all easy to make it plain by means of a diagram. In phase modulation the A.F. impulses are made to bring about changes in the phase of the carrier. In a modulation positive half-cycle the carrier-wave cycles are made to start earlier than they normally would, the maximum advance being reached at the peak. During a negative half-cycle of modulation the start of the carrier-wave cycles is retarded, the greatest delay occurring at the trough. So far as I know, no use has so far been made of phase modulation for broadcasting purposes.

Before and during the war remarkable advances were made in the technique of transmitting radio PULSES. A pulse is a short, sharp burst of waves, rising almost instantly from zero to maximum amplitude as it begins and falling as rapidly from maximum to zero as it ends. The sound-wave equivalent is a sudden loud cry such as "Hi"! The development took place because pulses and the echoes from targets to which they give rise are the basis of radar.

Suppose that a transmitter is radiating every second 10,000 pulses, each lasting one microsecond and all of equal amplitude. When no pulse is going out the oscillator is quiescent and there is no carrier wave; then it suddenly comes, so to speak, to life, works its hardest for one microsecond, and then closes down until the next pulse is due to be sent. In each second it is actually at work for $\frac{10,000}{1,000,000} = \frac{1}{100}$ sec, or 36 seconds in each hour. During ninety-nine-hundredths of each second, or 59 minutes and 24 seconds in each hour, it is resting and cooling down. The heat generated by the oscillator is one of the big problems in transmitters. When it is at work all the time, as in the transmission of a continuous-wave carrier, this heat has to be dissipated by elaborate water-cooling devices. The heat, in fact, limits the power which a given oscillator can generate. Clearly the pulsing oscillator, which in the example under discussion can devote 99 per cent. of its time to cooling down, can generate much more power during its brief working periods than a valve of similar size engaged in producing continuous oscillations.

By using the modulating frequency to cause the amplitude of the pulses to vary, as in Fig. 108*d*, an A.F. signal may be conveyed by trains of pulses whose tips trace out the waveform. This is known as PULSE-AMPLITUDE MODULATION, or P.A.M.

PULSE-FREQUENCY MODULATION (Fig. 108*e*) is also possible. In this the amplitude of the pulses is constant, but their spacing is varied by the modulating frequency. At the crest of a positive half-cycle they are most crowded, and most widely spaced at the trough of a negative half-cycle of modulation. This method is known for short as P.F.M.

Fig. 108*f* illustrates a third method, PULSE-WIDTH MODULATION (P.W.M.), sometimes called pulse-duration modulation (P.D.M.). Here the modulating frequency causes the length of the transmitted pulses to vary. The longest go out at positive half-cycle crests, the shortest at the troughs of negative half-cycles.

There is yet a fourth possible system of pulse-modulation: PULSE-PHASE MODULATION or pulse-position modulation (P.P.M.). This I have tried to illustrate diagrammatically in Fig. 109*e*, though, as in the case of carrier phase modulation, it is not easy to find a satisfactory means of doing so. It consists in applying the modulating frequency to pulses recurring normally at equally spaced intervals of time and making it upset this spacing. During a positive half-cycle of the modulating frequency each pulse occurs sooner than it would if left undisturbed; a negative half-cycle delays the occurrence of the pulses.

Controversy is still raging over the respective merits of F.M. and P.M. of some kind for very-short-wave broadcast relays. I believe that F.M. will win the day, unless, of course, something better than either is invented —though P.M. certainly has its strong points.

One of these is illustrated in Fig. 110: on one and the same carrier frequency a single P.M. transmitter can radiate six or more different programmes simultaneously, the user of a suitable receiving set being able to select whichever he pleases without having to retune. All that

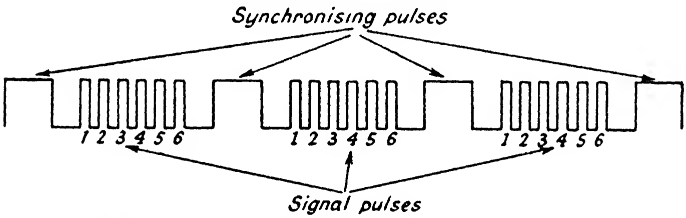


FIG. 110.—As explained in the text, six or more different broadcast programmes may be radiated by one transmitter on the same carrier frequency.

he has to do is to move a rotary switch to any position from, say, No. 1 to No. 6. The system is not merely hypothetical. It came through successfully the most exacting of tests during the war in the famous Army Wireless Set No. 10, which actually deals with eight separate telephony channels simultaneously, using only one carrier frequency.

In Fig. 110 the pulses numbered 1 always occur at the same interval of time after the finish of a synchronising pulse. Call this interval 20 microseconds. The receiver is so designed that with the switch in position No. 1 it responds to a pulse occurring 20μsec. after the synchronising pulse and to no other. With the switch in position

No. 2 it responds only to pulses occurring, say, 30μsec. after the synchronising pulse—that is, to those marked 2 in the drawing. Other positions of the switch cause it to respond only to the 3's, the 4's, the 5's or the 6's, whichever group may be selected.

Each series of pulses carries the modulation of a particular transmission. Any one of those available can thus be selected by merely turning the switch to the appropriate position. There are two important drawbacks to any such system as a means of relaying broadcasts. The first is that should the transmitter break down all programmes fail simultaneously. The second is that the waves carrying the signals are liable to reflection by hills, buildings and so on, and may reach the receiving aerial by paths of different lengths. A reflected pulse of channel No. 2 might thus arrive at the same time as the direct pulse of channel No. 4. Were the set switched to position No. 4 the two transmissions would interfere with one another.

Unless a last-minute change of plan is made, F.M. will provide our high-fidelity broadcasting, and this at no very distant date. Provided that we use good sets for its reception and reproduction, the broadcasting of the future should come very near to perfection.

APPENDIX A

Power Factor

SUPPOSE that you had in your home an electrical appliance containing 40 ohms of inductive reactance in series with 30 ohms of pure resistance, as illustrated diagrammatically in Fig. 111. The mains supply we will

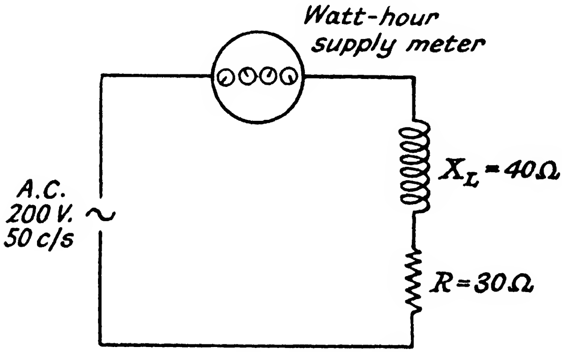


FIG. 111.

assume to be 200V, 50 c/s, A.C. What consumption of power would the supply watt-hour meter record when the apparatus was working?

The impedance of the circuit is $\sqrt{X^2+R^2}$.

$$Z=\sqrt{40^2+30^2}$$
$$=50\Omega$$

The current through L and R is thus $\frac{200}{50}=4A$. A watt-hour meter, such as that between the mains and the circuits of your home, records only the power dissipated, and that, as we know, is I^2R. In this instance, then, it would register power expenditure at the rate of $4^2 \times 30 = 480$W.

That seems quite satisfactory from the consumer's point of view: the rate at which work is done in his circuit is 480W, and that is what he pays for. But what about the supply authority? To keep an expenditure of 480 *real* watts going in the consumer's circuit it has to bring 4A at 200V, or 800 *apparent* watts, into his home.

The electrical conditions of Fig. 111 are unlikely to occur in a private house, for the load there is due mainly to lighting and heating appliances and is almost entirely resistive. In a factory, however, it may be largely reactive; unless something were done about it, the Fig. 111 conditions multiplied a thousandfold—*real* power 480 kilowatts, *apparent* power 800 kilowatts—might be obtained in the circuits of big works. The supply authority would have to generate more power than it was paid for and to provide heavier (and therefore much more expensive) cables to carry it.

The ratio between real watts and apparent watts is called the power factor (P.F.) of a circuit. In the example under discussion the power factor is $\frac{480}{800} = \frac{3}{5} = 0{\cdot}6$. Another formula, which gives exactly the same answer, is: $P.F. = \frac{R}{Z}$. In this instance $P.F. = \frac{30}{50} = 0{\cdot}6$. The ideal power factor for domestic or industrial loads is unity, for the whole of the energy delivered by the mains is then doing useful work; there is no difference between the real and the apparent watts. This can be achieved by making $X = 0$, in which case $Z = R$ and $\frac{R}{Z} = 1$.

The way to make X approach zero in the Fig. 111 circuit is clearly to add up to 40 ohms of capacitative reactance, for $X = X_L - X_C$. What is known as power factor correction is done on these lines. If the load is inductive, a balancing capacitance, the power factor condenser, is used to cancel out X_L to a large extent.

A case in point is that of the A.C. fluorescent lamp, which is now becoming so widely used. There is no stable resistance in the mercury vapour within such a tube and an iron-cored choke coil is used to limit the current passed. Uncorrected, this would make the load predominantly inductive. The corrector employed is a power factor condenser. Conditions for a 40-watt tube then become: real watts expended in producing light=40; apparent watts 10 in the reactive portion of circuit *plus* 40 in the resistive portion=50; P.F.$=\frac{40}{50}=0{\cdot}8$.

At the risk of becoming unduly mathematical I must mention that the power factor is the cosine of the angle by which the current leads or lags on the voltage in an A.C. circuit. In the Fig. 111 example the power factor is 0·6, which is the cosine of an angle of about 53·1°; as the circuit is inductive the current lags by 53·1° on the voltage. The circuit of the fluorescent lamp is again inductive, and here the angle corresponding to a cosine of 0·8 is approximately 36·9°: the current lags on the voltage by that amount.

APPENDIX B

A Mathematical Shorthand

SURPRISING as it may seem, one of the greatest mathematical inventions ever made was the sign 0. Prior to its invention by Hindu mathematicians calculations involving very large numbers were almost impossible. You may see why if you try to multiply MCMXLVI by MDCCLIX, using Roman numbers only! The Romans and other ancient peoples made their calculations with the aid of the abacus, or counting board, which, in its ordinary form, could deal with only moderately large numbers: and in any event it could not go beyond the first four rules of arithmetic.

The introduction of the sign 0 gave numbers a value by virtue of their position. Thus 2 signifies a total of 2 units; but if we move the figure one place to the left by adding a nought to it we have 20. The two, by virtue of its position, now signifies not two units, but two tens. And so every time we move that 2 one place to the left we indicate a multiplication of its value by ten. Thus $200=2\times 10\times 10$; $2{,}000=2\times 10\times 10\times 10$; $2{,}000{,}000=2\times 10\times 10\times 10\times 10\times 10\times 10$, and so on.

Now, $200=2\times 100$; $2{,}000=2\times 1{,}000$, and so on. And 100 is ten squared, or 10^2; 1,000=ten cubed, or 10^3; 1,000,000=10 to the sixth power, or 10^6. The small figure, or index, here simply shows the number of times that the ten has been multiplied by itself. Even more conveniently, it indicates the number of noughts resulting from its application to 10. Thus $10^{12}=1$ followed by 12 noughts—a billion.

You see now one of the advantages of this shorthand: it saves the bother of writing down strings of noughts. One gets tired of writing them, and it is so easy in a long calculation to put in one too many or too few.

But that is far from being all that there is to it. Suppose that you want to multiply 100,000 by 1,000,000. Well, $100{,}000=10^5$ and $1{,}000{,}000=10^6$. All that you have to do is to *add* the indices and the result is 10^{11}.

Similarly 2,600,000 is written as $2{\cdot}6\times10^6$, or as 26×10^5; $2{,}600{,}000\times4{,}200$ becomes in our shorthand $2{\cdot}6\times10^6\times4{\cdot}2\times10^3=2{\cdot}6\times4{\cdot}2\times10^9=10{\cdot}92\times10^9$, or $1{\cdot}092\times10^{10}$.

Division is just as quick and easy. Here the index of the divisor is *subtracted* from that of the dividend. The shorthand division of 2,400,000 by 3,000 is $24\times10^5\div3\times10^3$ $=\frac{24}{3}\times10^2=8\times10^2$.

Remember that the numbers preceding the indexed tens have to be multiplied or divided as the case may be. It is only with the indices that addition or subtraction is done.

Fractions are represented by negative indices: $\frac{1}{10}=10^{-1}$; $\frac{1}{1{,}000{,}000}=10^{-6}$, and so on.

We shall often come across such quantities as $0{\cdot}003\ \mu F$ or $200\ \mu\mu F$. A microfarad $(\mu F)=\frac{1}{1{,}000{,}000}F=10^{-6}F$;

$0{\cdot}003\ \mu F=\frac{3}{1{,}000}=3\times10^{-3}$ of a microfarad $=3\times10^{-9}F$.

One $\mu\mu F=\frac{1}{1{,}000{,}000{,}000{,}000}F=10^{-12}F$. Two hundred $\mu\mu F=200\times10^{-12}F$, or $2\times10^{-10}F$.

If we want to find the reactance of a capacitor of

200 $\mu\mu$F at a frequency of 420 kc/s the calculation is:

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

$$=\frac{1}{2\times\frac{22}{7}\times420\times10^{3}\times200\times10^{-12}}$$

We can rewrite this (though nothing of the kind will be necessary after a little practice) so as to show all the tens with positive or negative indices:

$$X_c=\frac{1}{2\times\frac{22}{7}\times42\times10^{4}\times2\times10^{2}\times10^{-12}}$$

Adding up the indices we have 10^6 positive and 10^{-12} negative. This comes to 10^{-6}. We now have

$$X_c=\frac{1}{2\times\frac{22}{7}\times42\times2\times10^{-6}}$$

$$=\frac{1}{2\times22\times6\times2\times10^{-6}}$$

Now $10^{-6}=\frac{1}{10^6}$, and $\frac{1}{\frac{1}{100}}=10^6$.

Therefore we have $X_c=\frac{10^6}{2\times22\times6\times2}$

$$=\frac{1,000,000}{528}$$

$$=1,894\Omega$$

None of these small steps would be needed in making an actual calculation. The steps are inserted so as to explain every detail of the shorthand method. In practice the calculation would be:

$$X_c=\frac{1}{2\times22\times6\times2\times10^{-6}}$$

$$=\frac{10^6}{528}=1,894\Omega$$

Squaring large numbers and the extraction of square roots are both simplified by the shorthand method. To square the "tens" part of a number, double the index $(10^3)^2 = 10^6$. The square of $3{\cdot}5 \times 10^4$ is $(3{\cdot}5)^2 \times 10^8 = 12{\cdot}25 \times 10^8$. To find the square root of the tens part, divide the index by 2. The square root of $4 \times 10^6 = \sqrt{4} \times 10^3 = 2 \times 10^3$.

If square roots are likely to be required, always arrange your figures so that the indices are even numbers and so divisible by 2. For example, $6{\cdot}6 \times 10^9$ and 66×10^8 both represent the same number, but $\sqrt{66 \times 10^8}$ is the more readily extracted. Here we have $\sqrt{66} \times 10^4 = 8{\cdot}124 \times 10^4$.

You will, by the way, find it an advantage to have by you a set of tables such as "Five-Figure Logarithmic and Other Tables," by Frank Castle, published by Macmillan. Such tables cost very little and they are splendid time-savers since they eliminate so many tedious calculations. You can, for instance, read off instantly from them the square or the square root of any number containing up to five figures.

You will, I believe, now find the shorthand method plain sailing, especially if you devise and work out a few examples for yourself.

APPENDIX C

Power Factor and Tuned Circuits

IN designing components for the tuned circuits of a wireless receiving set one of the chief aims must be to ensure that the smallest possible amount of work is done in them. The power factor, in a word, must be as near zero as can be contrived. It can reach zero only in those imaginary components which are completely free from resistance. If there is, as there is bound to be, some resistance in a component, the application of an E.M.F. necessarily results in a current$=\frac{E}{R}$. This current must bring in its train a dissipation of power of I^2R.

As Appendix A shows, the power factor$=\frac{R}{Z}$. It can be kept low if R is reduced to something negligibly small in comparison with Z: could R be made 0, $\frac{R}{Z}$ would be 0. The two parts of a tuned circuit most likely to introduce resistance are the coil and the capacitor. Each of these has a power factor $\frac{R}{X}$, and its efficiency is in proportion to the smallness of that ratio. It will be noted that the Q of a coil is $\frac{X_L}{R}=\frac{1}{P.F.}$

In the tuned circuit which serves as an example in Chapter VII the coil of 200 μH has an inductance at 700 kc/s of 880Ω. It was taken that the circuit resistance of 10Ω was to be found virtually entirely in the coil. The power factor of the coil is thus $\frac{10}{880}=0{\cdot}0114$.

The power factor of a good variable capacitor is of very much smaller order, being normally between 0·001 and 0·0001.

Strictly, the power factor of a coil is $\frac{R}{\sqrt{X_L^2+R^2}}$ and that of a capacitor $\frac{R}{\sqrt{X_C^2+R^2}}$; but R in such cases is so small in comparison with X that for working purposes P.F. $=\frac{R}{X}$ gives a sufficiently accurate power factor for coils and condensers.

APPENDIX D

The New Letter Symbols for Valves

AFTER this book had been set up in type by the printers details of a new system of letter symbols for valves and valve circuits were published (B.S. 1409: 1947) by the British Standards Institution. The new symbols will become more and more generally used in articles and textbooks by British authors dealing with wireless, television and other applications of the thermionic valve. I want, therefore, to make them known to my readers. On the other hand, readers who wish (as I hope many will) to go more deeply into wireless than has been possible in this small book will have to refer largely to textbooks published before the introduction of the new standard letter symbols.

You will see, then, that I had two possible choices: either to substitute the new symbols for the old throughout the book, or to leave the text as it stood and to write an appendix dealing with them. After careful thought I decided on the latter alternative. Not the least important reason for this decision is that you cannot appreciate the full beauty—or the strictly logical basis—of the new system until you know a little about wireless and wireless valves. To a beginner, lacking that knowledge, the adoption of the new standard symbols might make the drawings and their accompanying explanations rather more difficult to follow—and that is the very last thing that I want.

The basic principle of the new standard is that everything *inside* the bulb of the valve, whether it is something concrete, such as one of the electrodes, or something abstract, such as resistance or capacitance, is denoted by a small letter. Everything, abstract or concrete, *outside* the bulb is denoted by a capital letter.

For the electrodes we have:

a = anode
k = cathode (kathode, c is needed for capacitance)
g = grid
h = heater
f = filament
s = screening electrode (*e.g.*, screening grid)
m = metallised coating inside bulb

Resistance inside the bulb is r; outside the bulb, R. Similarly, capacitance is c inside the bulb and C outside it. It is to avoid any confusion with c or C that k has been chosen for the cathode. Notice that outside the bulb R and C can represent not only resis*tance*, capaci*tance*, but also resis*tor*, capaci*tor*. Reactance inside the bulb is x and outside it X; impedance is, in the same way, z or Z.

Any of the electrode symbols can be used as subscripts. Thus, the anode resistance of a valve (purely internal) is r_a, and the anode load resistance (purely external), R_a. The anode-grid capacitance, which may lead to unwanted positive feed-back effects, is termed c_{ag}. Actually, these effects may be due more to capacitance between pins, sockets and wires outside the bulb itself than to capacitance between the grid and anode of a valve. The net effective capacitance may therefore be denoted by $C_{ag}+c_{ag}$.

In multi-electrode valves the grids are numbered outwards from the cathode. The electrodes of a battery pentode become: f, g_1, g_2, g_3, a; and those of a mains pentode: h, k, g_1, g_2, g_3, a.

Some valves, the double-diode-triode, for instance, are really several separate valves, with a common cathode, contained in the same bulb. The various sections of such valves have the following symbols:

Diode = d
Triode = t
Tetrode = q (Latin quadri-: t has been used for triode)
Pentode = p
Hexode, heptode, octode, etc. = p (poly-)
Rectifier = r

All of these are used as subscripts: thus a_t would be used to indicate the anode of the triode portion of a triode-heptode and a_h the anode of the heptode portion of the same valve.

When there are two similar electrode assemblies inside the same bulb an equally logical method of distinguishing them is employed. In the double-diode-triode there are two diodes and one triode, all with a common cathode. The anode of the first diode is a'_d; that of the second, a''_d, and that of the triode portion a_t—or simply a.

Direct, or continuous, voltage is V. When we come to A.C. we have:

V_{av} = mean, or average, A.C. voltage
V_{pk} = peak A.C. voltage
V_{rms} = R.M.S. A.C. voltage

Similarly, we have:

I = Direct current
I_{av} = mean alternating current
I_{pk} = peak alternating current
I_{rms} = R.M.S. alternating current

The peak alternating, or oscillating, voltage on the second diode anode of a double-diode-triode is written, using the new symbols:

$$V_{a''d(pk)}$$

Brackets are used, as shown in the foregoing example, to avoid any possible confusion when there are two or more subscripts. Or a comma may be employed for the same purpose, as in:

$r_{g1,k}$ = resistance between first grid and cathode

Power inside the valve is p and outside it P. Symbols commonly employed are:

P_a = power dissipated by the anode, or anode dissipation

P_{out} = output power

If capacitance is measured under working conditions (*i.e.*, with the valve hot and the cathode emitting), this may be indicated by using:

c = capacitance (cold)

c_w = capacitance (working)

Thus the working grid-cathode capacitance is:

$$c_{g,k(w)}$$

Input capacitance of the grid to all electrodes except the anode is:

$$c_{in}$$

Output capacitance between the anode and all electrodes except the grid is:

$$c_{out}$$

At first blush the new system may seem a little involved; but you will soon realise that it is actually nothing of the kind. It is completely logical and its use in the articles and the textbooks of the future should ensure, firstly, that all writers use the same symbols to indicate the same things, and secondly, that each symbol has always exactly the same signification.

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