NATIONAL RADIO INSTITUTE

Complete Course in PRACTICAL RADIO

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LESSON TEXT No. 12

AUDIO-FREQUENCY AMPLIFICATION

Originators of Radio Home Study Courses
···Established 1914···
Washington, D. C.

SOME GOOD STUDY HABITS

A Personal Message from J. E. Smith

Cheerfulness. In the army there is a motto, "Do It Well; Do It Cheerfully; Do It Now." This would be a good motto for every student. It requires more energy to frown than to smile. It has been said that a frown brings into use something like sixty-four muscles, and that a smile requires the use of about fourteen. Hence, it is more efficient to smile than to frown. But how can cheerfulness become a habit? Just as anything else can—by practice. Go through the motions of being cheerful and you will soon feel that way.

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Complete Course in Practical Radio

NATIONAL RADIO INSTITUTE WASHINGTON, D. C.

AUDIO-FREQUENCY AMPLICATION

In our previous study of radio reception, we learned that a typical radio receiver consists of several important parts. These parts are as follows:

(a) *Collector* of radio energy, or antenna.

(b) *Selector*, or tuning system, by means of which waves of various lengths are selected.

(c) *Radio-frequency amplifier*, which adds to the strength of the waves, so that they can effectually operate a detector.

(d) *Detector*, which so modifies the radio-frequency waves that when put into a loud-speaker, sounds will result that the ear can perceive.

(e) *Audio-frequency amplifier*, which strengthens the output of the detector, so that the ear can hear the output of the loud-speaker with comfort.

(f) *Reproducer*, or loud-speaker, which converts the output of the audio-frequency amplifier into sound waves.

This outline is given here for the purpose of helping you to locate yourself mentally before we go into the study of the audio-frequency amplifier. As you can see in this outline above, by the time the radio waves have entered the detector circuit, and have been *rectified*, they are in such a condition that they would operate a loud-speaker as to enable the ear to hear the sound waves generated by it. In other words, we could connect a loud-speaker to the output of a detector, and, if we would hold our ears close enough to it, we could hear the signals that we are tuning the receiver to.

Nevertheless, notice that we said you must hold your ears pretty close; this is generally true excepting in the case of very strong signals, as for instance, if we should tune the set to a powerful nearby broadcasting station. Generally the output to the loud-speaker, when connected directly to the detector, is not sufficient for comfortable listening. The degree of loudness, or the *volume* of sound that we require from a loud-speaker, is about the same as the original volume of the sounds when they originate at the studio of the broadcasting station. When we listen to a man speaking, for instance, it is desirable that we hear the same volume of sound coming out of the loud-speaker that we would hear if we were listening to the man himself.

You might ask, "Can we not amplify the radio-frequency currents sufficiently so that when the loud-speaker is connected directly to the detector, the volume would then be this great?" The answer is: "Sometimes, but not generally; in fact, only rarely." The volume in that case might be great enough, as we said before, only where we were tuned to a powerful nearby station.

The reason for this is that there is a limit to the strength of signal that the detector tube will handle without overloading. When the detector overloads, the volume does not increase, but as a matter of fact, sometimes it may be decreased. Then, too, the quality of the music or speech, or whatever we may be listening to, is generally spoiled when the detector is overloaded. In our previous lesson you have learned the general principle of the electron tube as it is used in radio receivers. You learned something about the way in which it acts when it *detects* or *rectifies* the radio-frequency currents coming out of the radio-frequency amplifier. Let us first review briefly what goes on in a detector.

In Figure 1 we have drawn in very heavy lines, the wiring diagram of an electron tube used as a detector of radio-frequency oscillations. The input is on the left of the diagram, and the head-phones are connected in the output circuit, which is on the right of the diagram. These head-phones are shunted by a by-pass condenser.

We have impressed on the input of the detector circuit a high-frequency alternating voltage, which comes from the tuned circuit which is generally connected to the input of the detector. As you learned before, these high-frequency oscillations have a frequency ranging anywhere from 500,000 to 1,500,000 cycles per second, in the broadcasting range of wavelengths. These are plainly too rapid for the human ear to respond to, or even, for a loud-speaker to respond to.

Furthermore, these oscillations are not *regular* or *uniform*, for they are modified or changed in accordance with the sound entering the microphone at the broadcasting station. Glance for a moment at Figure 2. This illustration shows a radio-frequency wave as we might picture it in order to let our eyes help us in understanding it. Suppose we start out at the point o and travel to the right. We can imagine that at the instant

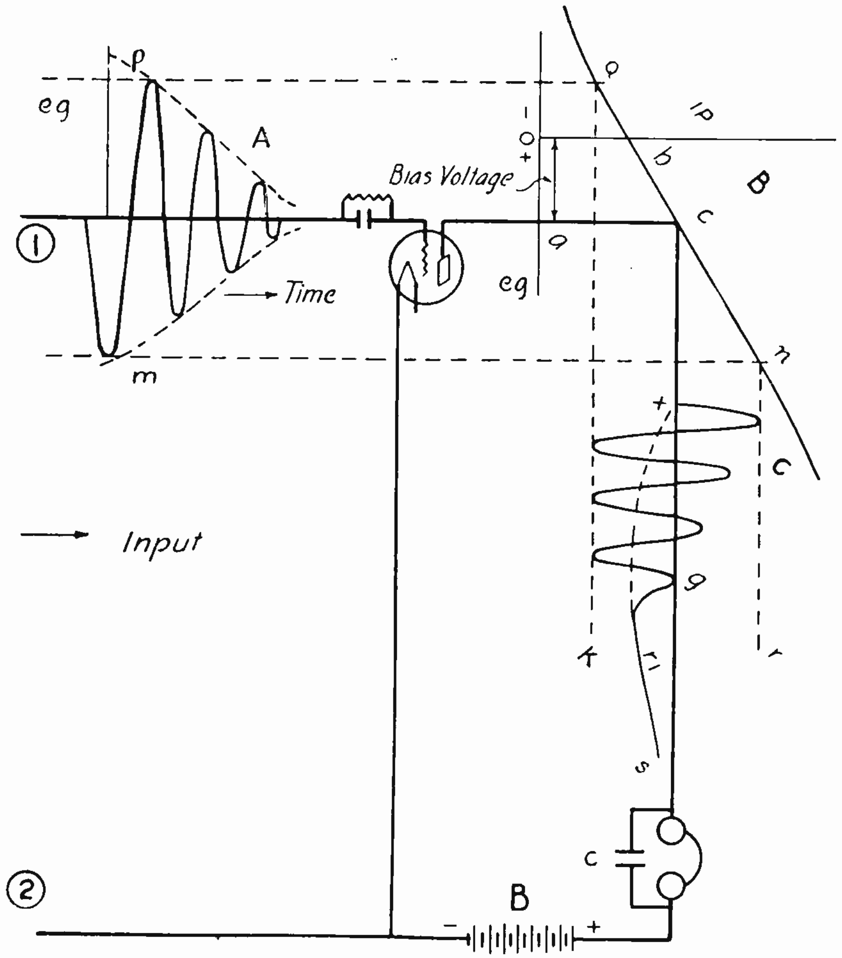

Fig. 1—This Diagram Shows in a Schematic Way How Rectification is Accomplished by Means of the Vacuum Tube.

we start out, the radio wave has no voltage, or there is no current flowing in the circuits. As time goes on, that is, as we travel to the right, the voltage increases steadily, along the line oa in the direction of the arrow. Then, as time goes on, we find that the voltage decreases, as it does at the point a.

We are letting the height of the curve above the horizontal line represent how great the voltage is at any instant. For instance, as we have shown in Figure 2, after 1/1,000,000th of a second the value of the voltage is represented by the height of the point a above the point b.

Now, as time still goes on, the voltage decreases, until at the end of 2/1,000,000ths of a second, we find that the voltage has decreased to zero, as at the point c. After this, as time still goes on, we find that the voltage changes its direction. Instead of the current flowing in the same direction it flows in the opposite direction. We can represent this state of affairs by drawing our curve below the line instead of above

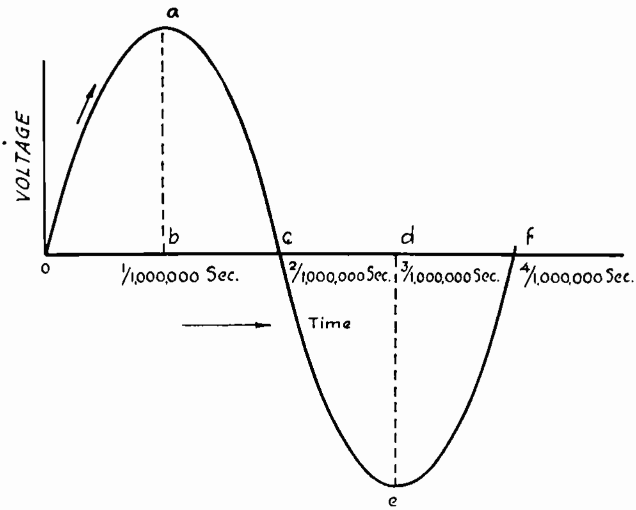

Fig. 2

it. Thus, after 3/1,000,000ths of a second the voltage is in a direction opposite to what it was after 1/1,000,000ths of a second, but its value is the same. We represent this by making the line de the same length as the line ab, but extending below the horizontal line instead of above it. Then, as time still continues to go on, the voltage again decreases, until after 4/1,000,000ths of a second it has again become zero, and after that the whole (action or cycle) is repeated as time goes on. From the point o, which represents the instant when we started to count time, to the point f, which is an instant 4/1,000,000ths of a second later, we have what is called a *cycle;* it is called a cycle because we start out at a certain value of voltage and after a certain length of time come back to the same value again; we started out at o with zero voltage, and after 4/1,000,000ths of a second come back to zero voltage again at f.

This cycle of events repeats itself continuously; if we should represent the voltage wave over quite a few millionths of a second, it would look as shown in Figure 3. In that illustration we have shown eight cycles of a radio-frequency wave; these cycles are numbered. For convenience, we have taken 4/1,000,000ths of a second for a complete cycle, but of course you know that this varies considerably. For instance, table

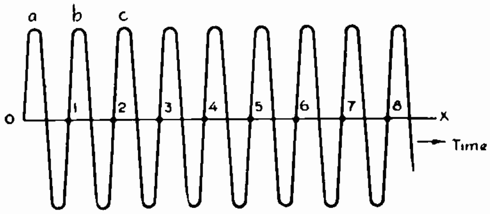

Fig. 3—A Continuous (C W) Radio Wave.

No. 1 gives you some idea of how the time for a cycle varies with the wave-length of the radio wave:

Table No. I

Wave-length (meters)	Period (sec.)	Frequency (cycles per sec.)
200	1/1,500,000	1,500,000
300	1/1,000,000	1,000,000
400	1/750,000	750,000
500	1/600,000	600,000
600	1/500,000	500,000

The time of a complete cycle is called its *period.* That is to say, a complete cycle requires a certain *period* of time. In Table No. I we have also included the frequency; it is clear enough that if the time taken by a complete cycle is one millionth of a second, there must be one million of these cycles occurring in a second.

The wave shown in Figure 3 is the wave as it comes from the radio-frequency generator at the broadcasting station. But it is not the wave you hear. There is another wave to consider, and this is the wave of sound that enters the microphone at the broadcasting station when someone talks or when music is played before it. The sound waves are very much slower; their period may be anywhere from 1/32nd to 1/20,000th of a second. In other words, the frequency of sound waves is only from about 32 to 20,000 per second. Furthermore, these waves vary in strength. The wave in Figure 3 does not change in strength; the *peak* voltage, or the maximum voltage, of the wave during each cycle is always the same, just as the points a, b, c, are shown the same height above the line ox. The peaks of the curves below this line ox are also the same distance below as the upper ones are above.

This is not so with sound waves. The waves may have any shape and any strength; Figure 4 shows a sample sound wave. The frequency of the sound wave changes from one instant to the other. When the frequency is high the person at the microphone is singing a high pitched note, or is speaking in a high pitched voice; when the frequency is low the pitch of the tones going into the microphone is low. And the strength of the sounds is changing from one instant to another, one moment the person is talking softly or singing loudly.

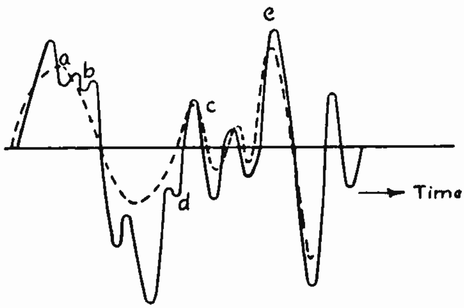

Fig. 4

There is another thing that you must notice, for this is very important. Notice that the waves of Figure 4 are not at all regular. There are kinks in them, as pointed out by the letters a, b, c, etc. These kinks tell us that there are other waves there besides the main one which we have drawn in broken lines. Any irregularity in the wave indicates that there is another wave present. These other waves are called *harmonics;* they are called *overtones* by musicians. The frequencies of these harmonics are always an exact number of times the frequency of the main wave, which is called the *fundamental frequency.* That is, a wave which has a fundamental frequency of 1,000 cycles per second, may have a second harmonic of 2,000 cycles, a third harmonic of 3,000 cycles, and so on. Not all the harmonics may be present; for instance, there may be in a certain wave only the second, third and seventh harmonic. Another wave may have the second, third and fourth, or any other combination.

The harmonics, and the strength of the harmonics, are different in sounds coming from different sources. For instance, in the sounds coming from a violin, there are many harmonics; the third and seventh harmonics are especially strong. The rest are much weaker. In the sounds coming from a flute, there are very few harmonics; the third is the principal one. All the other harmonics are very weak. A child's voice has very few harmonics, or at least they are very weak. A grown person's voice may have many harmon-

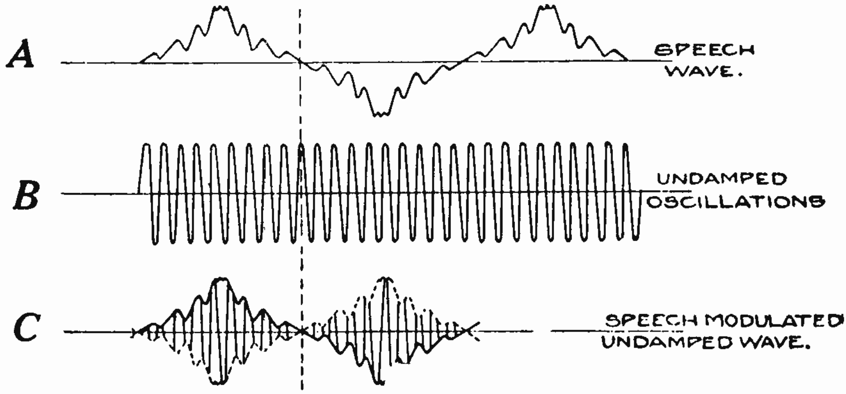

Fig. 5—Carrier Radio Wave Modulated by Sound Waves.

ics of varying strengths. It is on account of the different harmonics and the strength of these that we are enabled to distinguish different musical instruments from another by the sounds they give out, or one person's voice from another.

Now to get back to our complicated wave of Figure 4. As we have said, in the radio-frequency generator of the broadcasting station, we have the radio-frequency waves like Figure 3. Then we have going into the microphone sound waves as pictured in Figure 4. The two are combined together; the sound wave is said to *modulate* (or change) the radio-frequency wave. Let us see how they are combined. Look at Figure 5.

In Figure 5-B, we have the radio-frequency wave. Immediately above it, we have the sound wave. When the two are combined in the transmitting station, we finally get a wave like that shown in Figure 5-C. You see, the sound wave has merely increased or decreased the strength of the continuous radio-frequency wave. The waves in Figure 5-C are the same waves as in Figure 5-B, but in some places they are made stronger and in other places weaker. To show this we have drawn a heavy line through the peaks of the waves or oscillations of Figure 5-C, which we call the *envelope*. This envelope has exactly the same shape as the sound wave. Moreover there are two parts to it, one above the line and one below the line. This is because the radio-frequency currents reverse during each cycle, and we can have the voltage increased in one direction as well as increased in the other direction, and the same as regards decreasing.

This is the kind of wave that comes to the detector tube in a radio receiver. It is called a *modulated* wave. It is the job of the detector tube to *demodulate* it, separating the radio-frequency wave from the sound wave, and then we can pass this *audible* wave on to the audio-frequency amplifier to be strengthened. The word "audible" means capable of being heard, and the word "audio" refers to frequencies that can be *heard*.

Now, let us go back to Figure 1 and see how the detector tube demodulates this complicated Radio wave. You will notice that the wiring diagram has been drawn in heavy lines, but that we have also drawn some light lines in the illustration. For instance, at A in Figure 1, we have drawn a modulated radio-frequency wave. The height of the curve at any point indicates the strength of the voltage at that instant. This is supposed to be the radio-frequency voltage impressed on the input of the tube, and comes from the tuned circuit connected to it between (1) and (2).

In the output circuit, we have drawn the characteristic curve of the electron tube used as a detector. You will have to look at this curve from the left-hand side of the page, in order to see it properly. In other words, when you look at this characteristic curve, turn the book around and look in the direction of the arrow at the input. The line marked e_g represents the voltage impressed on the grid of the tube. The line marked i_p represents the current which flows in the detector output circuit. The distance of a point on the curve from the

e_g line shows how much current is flowing in the plate circuit when there is a certain voltage placed on the grid.

For instance, suppose we have no voltage at all on the grid, in other words, suppose the grid voltage is zero. The plate current will then have a value represented by the line ob. This current is flowing from the plate of the filament, through the "B" battery and phones and back to the plate. We do not actually have a zero voltage at any time on the grid. As you remember, we connect the grid-return to the positive side of the filament, so that we always have a small positive bias on the grid. This positive bias is represented by the line oa, and is marked "bias voltage." On account of this bias, the steady current flowing in the plate circuit has a value greater than it would be if the bias were not there. Instead of having a value represented by the line ob, it has the greater value represented by the line ac. Remember this is the *steady* plate current. It is the current which flows when there is no signal, radio-frequency, or voltage on the grid.

Now, suppose we have an alternating signal voltage on the grid. What happens? Well, as you learned before in a previous lesson, the current in the plate circuit fluctuates just as the grid voltage fluctuates. When the grid voltage is positive, the plate current increases; when it is negative, the plate current decreases. This is shown by drawing a few broken lines which we may call *projection* lines. Starting at m (Figure 1), we draw a broken line which cuts the characteristic curve at n. Then going at right angles we draw the line nr. We do the same thing starting at p, going through q and ending at k. You would think from this that the wave of the plate current would be included between the two lines qk and nr, but it is not. Let us see why.

This brings us to the matter of the grid condenser. The grid condenser more or less prevents the negative charge from leaving the grid. The grid is in the path of the electrons which go from the filament to the plate, so it can't help but capture a few, and as a result, it acquires a negative charge. Now, when the signal voltage coming onto the grid is negative, the negative charge of the grid is greater. When the signal voltage is positive, it tends to reduce the negative charge of the grid, which enables the grid to take on more electrons, and in that way again increase its negative charge.

At any rate, the negative charge on the grid becomes greater and greater. As a result, as you have already learned in a previous lesson, the plate current becomes less and less. All the while it is deceasing, the oscillations are still going on. The outcome of the whole matter is that the wave of the plate current takes a form like that in the curve C of Figure 1. As the oscillations continue, they gradually drop down as the grid accumulates its charge of electrons, until finally, if the oscillations persist long enough, the peak of the last oscillation in that particular group drops down to the value of the steady plate current. This is the point g in the curve C of Figure 1.

Now you must understand that the grid cannot go on forever collecting electrons and thereby having its negative charge increase continuously. There comes a time when the voltage of this grid charge becomes great enough for the charge to *leak off the grid* through the grid leak resistance. When this happens the grid loses its high negative voltage and the plate current at the same time rises again to its normal original steady value. This action is represented by the section ri, s, of curve C, of Figure 1.

Now you know the complete action of the detector tube using the grid leak and condenser; the condenser blocks the electrons which the grid collects. As the charge due to these electrons increases, the steady plate current decreases; all the while the oscillations are continuing, but gradually drop as the plate current drops. When the grid charge becomes great enough, it leaks off the grid through the grid leak and the plate current rises again to its original value. This is briefly the story of detection.

Notice that we still have radio-frequency oscillations—not audio-frequency. On account of this, the by-pass condenser C must be provided for the radio-frequency current cannot flow through the telephone receivers, due to their high impedance. Of course, it is often possible to operate the detector without the by-pass condenser, but this is made possible only because the receivers have enough capacity in their windings, and in the cord to the telephones, to act as a by-pass condenser. If this capacity in the phones were not present in the phones, we could not operate the detector without a by-pass condenser.

How do we get the audio-frequency out of this? The answer is simply this: the impedance of the telephone receivers responds to the low (or audio) frequency part of the train of oscillations; the phones act as if a current is flowing through them, whose wave shape is represented by the curve x, ri, s, which is a sort of average curve for the wave-train C in Figure 1. This average wave corresponds to the *envelope* of the radio-frequency wave originally impressed on the grid, which envelope contains the audio-frequency (or sound) waves which we want to hear. The final wave is not exactly the same as the original wave; the detector introduces a certain amount of *distortion* in the signals, which is what we call a change of wave form. As a result, the sounds coming out of the loud-speaker will not be *exactly* the same as the sounds that went into the microphone, but this distortion is not very noticeable in well-designed receivers.

All this may sound very complicated to you, but it is not very difficult to get a fair understanding of it if you keep in mind the different steps in our description. We have gotten

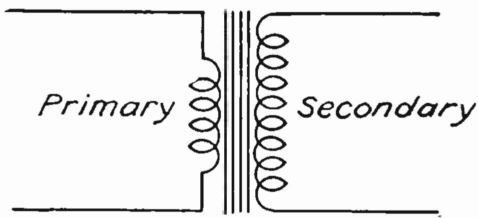

Fig. 6—A. F. Connections to Coils (P) and (S).

Fig. 7—A. F. Transformer.

as far as obtaining the audio-frequency currents in the telephone receivers. It certainly must be clear to you that instead of connecting in these head-phones, we can connect in an audio-frequency amplifier in order to strengthen these audio-frequency currents, and then at the output of the amplifier we can attach our phones or loud-speaker.

We spoke of *overloading* at the beginning of this lesson. What may cause this "overloading" of the detector? Why simply this: suppose we have a *very* strong signal impressed on the input of the detector. When the detector grid "swings positive," the positive grid will attract so many electrons that its negative charge will become very great owing to the fact that the accumulated electrons on the grid do not have sufficient time to drain off before the grid swings in the other direction. As a result, the plate current will be "depressed" (or decreased) considerably. When the grid charge is sufficiently great, it will leak off through the grid leak with a "bang" instead of leaking off gradually, and a lot of extra noises will be heard in the loud-speaker. Also when the *grid swing* is too great, there will be additional distortion of the wave form due to the curvature of the characteristic curve at the top and bottom. This effect must be guarded against whenever we use an electron tube. We shall learn a great deal more about it as we proceed.

Now we have learned how the detector acts, and have seen why we must not overload it. We now come to the matter of amplifying the audio-frequency currents so that they can operate a loud-speaker satisfactorily. We shall develop the audio amplifier step by step, so that you shall learn the reason for each thing in the circuits. A few pages before this you learned that the impedance of the telephone receivers in the plate circuit of the detector is acted upon by a sort of average curve of the plate current. (See Figure 1, curve x, ri, s). So it is clear we must have some kind of apparatus which has impedance, connected in the plate circuit of the detector.

Besides this, we have to transfer the audio-frequency energy to another circuit where it can be amplified in an electron tube. A transformer which has an iron core will do both these things well. Figure 6 shows the diagram of an audio-frequency transformer, and Figure 7 shows a photograph of one. It consists of a primary winding wound upon an iron core, and a secondary winding wound over both. The iron core consists generally of a number of thin sheets, called *laminations*, which are stacked in a pile. These laminations are so shaped that they form a closed path for the magnetic field of the transformer.

The secondary winding has a great many more turns than the primary winding, generally about 3 or 3½ times as many turns. Now when audio-frequency current flows in the primary of the transformer, a varying magnetic field is established which cuts or links the secondary turns. On account of this a voltage is *induced* in the secondary winding, which is something like three times as great as the primary voltage. In some instances it may be more; at other times it may be less. We shall learn more about this later on, but at least the secondary voltage is always greater than the primary voltage. So you see the transformer can help considerably in amplifying the audio signals.

Furthermore, the primary of the transformer has the impedance we require in the plate circuit of the detector. We simply connect the audio transformer in place of the head-phones in Figure 1, and we get the circuit of Figure 9, where the primary is marked P and the secondary is marked S.

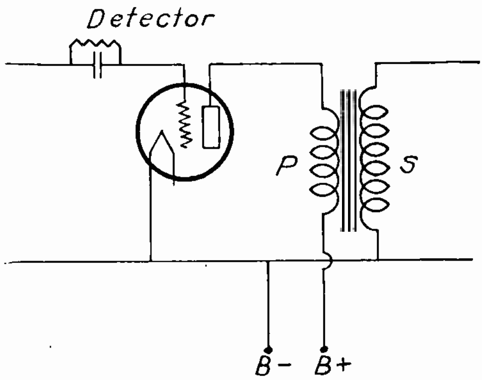

Fig. 9—Connections from Detector to First A. F. Transformer.

Now, if we wanted to, we could connect our head-phones to the secondary winding of the transformer, but this would not work very well, as we shall learn later on. Besides we would not get enough amplification. So the next thing to do is to connect another electron tube to the secondary of the

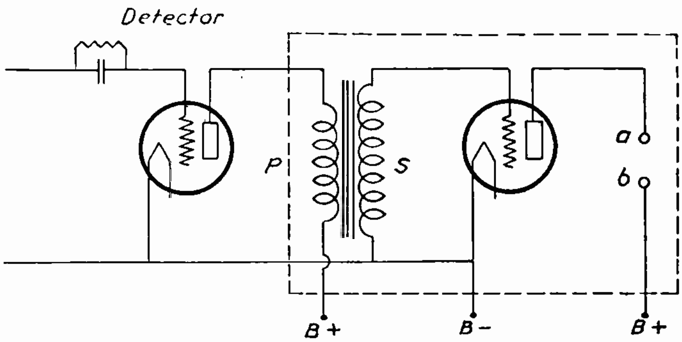

Fig. 10—Connections from Detector to First A. F. Transformer and A. F. Vacuum Tube.

transformer, and we could connect our head-phones or loud-speaker to the terminals ab in the plate circuit of this tube. The signals would then be pretty loud on the head-phones, but would not generally be loud enough on the loud-speaker. The part of Figure 10 which is included by the dotted lines is called an audio-frequency amplifier "stage." You will remember that it is very much like a radio-frequency amplifier stage except that it is not tuned, and the transformer is designed very much differently.

Well, to make a long story short, if we want still more amplification, we can add another complete "stage" to the amplifier, and get the circuit of Figure 11. This is the complete circuit of the detector and two stages of audio-frequency amplification as generally used in present day radio receivers. The loud-speaker is connected in the output of the last stage. Notice that different "B" battery voltages are connected to the plates of the different tubes. The detector tube is generally operated with 45 volts on the plate, the first audio stage with 90 volts, and the second audio stage with 135 volts. In the last stage a "C" battery of about 4 to 6 volts should be connected in the grid circuit. This is shown in the diagram, and we shall learn why in a few moments.

COUPLING SYSTEMS

Now, before we get into the detailed study of the various parts of an audio amplifier, we must first consider the various types of *coupling systems* that are employed between the tubes. Figure 11 shows transformers being used for coupling the tubes together. Other things can be used as well as transformers. You see there are two important parts to any stage of an amplifier. One of these is the tube itself, and the other is the device used for coupling two stages together. We shall continue with the different forms of coupling.

We will begin this part of our discussion in explaining why other coupling systems are used at all. This will not be very difficult if you will read carefully. In the first place, what we require of an amplifier is that it shall *amplify*. Second, it must always *amplify equally*. These are the two main requirements in an amplifier. The third requirement is that the amplifier shall not cause distortion of any kind while it is amplifying the signals; it must not introduce any frequencies (harmonics) which are not in the original sounds going into the microphone at the transmitter, nor shall it permit any of the original sounds to be lost. Of course, as you know, nothing in this life can be perfect, but we always try to have things as nearly perfect as possible. So, since there are certain recognized failings of transformers, investigators have been trying to find means of eliminating these shortcomings, or of avoiding them by using other systems of coupling.

The main shortcoming of the transformer is that it does not amplify very low frequencies well. The frequencies of sound waves are from about 30 cycles per second to above 10,000. In the average transformer used today, frequencies above about 500 or 1,000 cycles are amplified pretty nearly equally. Currents of frequencies lower than this are not amplified as well, and the lower the frequency the less is the amplification. The reason for this is that the voltage input to the transformer depends on the *impedance* of the transformer, and the higher impedance for a certain amount of current the greater will be this voltage. Finally, the higher the frequency of the current, the higher the impedance.

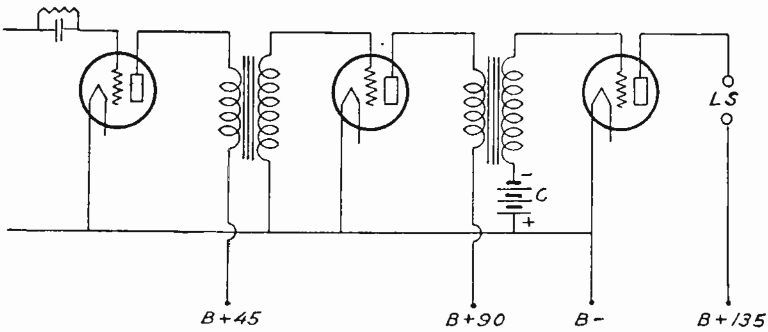

Fig. 11—Connections from Detector to Two Stages of Transformer Coupled A. F. Amplifier.

AMPLIFICATION CONSTANT

You can see from this without going much further, that the transformer is going to amplify the high frequencies better than the low ones. There is one thing that you must not forget; the voltage across the transformer cannot be greater than the voltage which drives the current through it. This voltage is the voltage that is developed at the plate of the tube connected to the primary winding. Look at diagram A Figure 12. Here we have shown a simple amplifier stage; the batteries are left out for simplicity. There is a certain voltage input to the tube, which we have marked e_g. This is the signal voltage. The tube has an *amplification constant* which we shall call μ (this is the Greek letter pronounced mu). It tells us how many times the tube will amplify. Thus a 201A tube amplifies voltages 7 times, so its amplification constant is 7.

So, with a voltage e_g impressed on the grid, and an amplification constant of μ in the tube, there is developed in the plate circuit of the tube a voltage equal μ x e_g. This is the total voltage in the plate circuit. If we have a voltage of 2 millivolts (0.002 volts) impressed on the grid, and a μ of 7, then the voltage in the plate circuit will be 0.002x7 or 0.014 volts (or 14 millivolts).

Now, you will remember from your lesson on the vacuum tube, that there is quite a large resistance in the tube between the plate and the filament. The plate current must flow over this path, and hence encounters this resistance in its path. This resistance is quite high, in ordinary practice being from about 6,000 to 15,000 ohms. It is called the *plate resistance* of the tube, and is represented by the symbol r_p. You will see it marked on the diagram A of Figure 12.

From these things, it is clear that the plate circuit of the tube may be represented according to the diagram B of Figure 12. The voltage of the plate circuit μe_g is considered as a generator G. In series with it is the plate resistance r_p, and also in series is the primary of the transformer. The load in the generator circuit is a resistance in series with a reactance. As we have seen, the reactance varies as the frequency varies, but the frequency has no effect on the resistance; it always remains the same. The total voltage μe_g is divided between the resistance and the reactance.

Read over these few lines carefully. When the frequency is low, the reactance is low. Naturally there is little voltage drop in the reactance as most of it is wasted in the plate resistance. As the frequency becomes higher, the reactance becomes greater; consequently the voltage across the transformer increases, and at the same time the current decreases, on account of this increased reactance. Since the voltage drop in the resistance is r_p times the current, and the current is less, the drop in the resistance must be less.

So you see that as the frequency becomes higher, and the input voltage e_g always remains the same, the voltage across the transformer will gradually increase and the voltage drop in the resistance will gradually decrease. The voltage that is in the resistance is useless to us—it is lost energy. The useful voltage is that at the terminals of the transformer. It is clear that at low frequencies the useful voltage at the transformer will be small and a great part of the voltage will be lost in the resistance. At higher frequencies, the useful voltage at the transformer is greater, and the loss in the resistance is smaller. (In order to simplify this discussion we have assumed the signal strength to be always the same, no matter what the frequency may be.)

Now you have learned how the voltage at the primary depends on the frequency. What happens *in* the transformer? We shall not study this very much in detail here, as it is unnecessary in this practical course. But, we may say that the voltage in the secondary is *very roughly* the voltage input to the primary multiplied by the ratio of the turns in the windings. For example, let us suppose that there are 1,000 turns

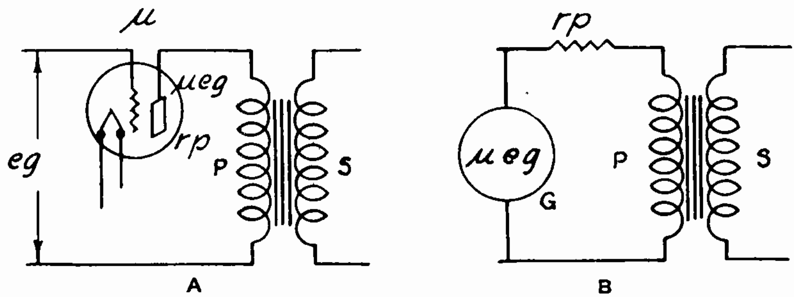

Fig. 12

of wire on the primary of the transformer, and that there are 3,000 turns of wire in the secondary winding. The turn ratio of the transformer is then 3:1 (spoken of as "3 to 1"), which is the same as saying that the voltage is multiplied approximately three times by the transformer. If we have a voltage of 1 millivolt at the primary terminals of the transformer, the voltage at the secondary terminals will be approximately 3 millivolts.

So you see that we have three important effects in an audio amplifier stage. First, amplification in the tube; second, the variation of voltage with frequency, at the primary of the transformer; third, the voltage "step-up" (as it called) in the transformer.

Now let us see what is the greatest amplification it is possible to obtain in an amplifier stage. At *very high* audio-frequencies, the reactance of the transformer is very great; therefore, nearly all the voltage in the plate circuit is available at the primary terminals as *useful* energy. This voltage is, very nearly equal to μe_g. Now, if we suppose that there are no losses in the transformer, and its turn-ratio is n_2/n_1, where n_2 is the number of turns in the secondary winding and n_1 the number in the primary, then the total voltage at the secondary terminals is

$$V_2 = \mu \times e_g \times \frac{n_2}{n_1}$$

The amplification is $\mu \times n_2/n_1$. For example, if the amplification in the tube is 7 and the turn-ratio of the transformer is 3, then the greatest amount of amplification that it is *theoretically* possible to obtain is 7x3 or 21. In other words, at very high frequencies, we can expect out of this stage an amplification of nearly 21 times. At low frequencies, as you have learned, the amplification is very much less.

In Figure 13 we have shown what is called an amplifier *characteristic curve*. It is a curve which represents how the amplification changes as the frequency changes. Take, for instance, a frequency of 500 cycles. The amplification at this frequency is about 8. At 1,000 cycles it is about 13; at 2,000 cycles it is about 17, at 5,000 cycles it is about 18. You see as the frequency gets higher and higher, the curve becomes more nearly horizontal, gradually approaching a certain *maximum* amplification at very great frequencies. This is about how the usual transformer curve looks, although it is not usually as smooth as the curve in Figure 13.

Now what does all this mean, as far as the reproduction is concerned? The answer is simple. Suppose the transformer causes the low notes to be weak. If we are listening to an artist playing the piano, for instance, it would seem as if the artist had a weak left hand and a strong right one, for he plays the high notes with the right hand and the low notes with the left hand. As another example, suppose we are listening to an orchestra. The bass-horn would not be heard very well from the loud-speaker, while the violin with its high tones would come in very strongly. In other words, the music would not sound just as it should sound.

In the same way, the harmonics of the sounds, which are of high frequency, would come in strong and the low fundamental frequencies would come in weak. The voice of a bass would then sound much higher than it really is, for the overtones (or harmonics) are amplified considerably while the low frequency fundamental is not amplified as much.

There is one other important defect in transformers. You are aware of the fact that whenever we have two surfaces of metal separated by air or any other insulator, we have a condenser. Now, in a transformer we have a lot of metal—it is the copper of which the wire is made. So the primary winding can act as one plate of a condenser and the secondary winding can act as the other. Furthermore, different parts of the same winding can act like condensers of small capacity. On the whole then, the transformer may at times have considerable capacity.

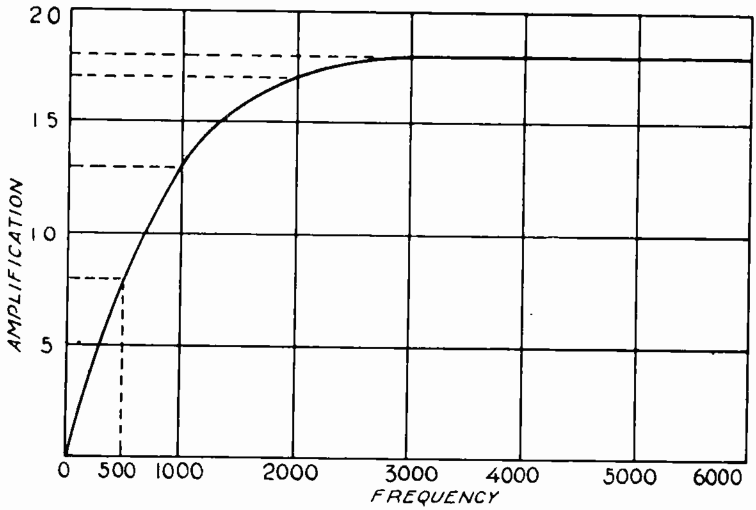

Fig. 13—An Amplifier Characteristic Curve.

Having the capacity between the windings, and the inductance of the windings, we have a *tuned circuit,* just as the capacity of the variable condenser and the inductance of the coil form a tuned circuit in a *radio*-frequency amplifier. So the transformer itself, having both inductance and capacity, is tuned to certain particular frequencies. These frequencies are generally rather high, mostly occurring at 5,000 cycles or higher. When such frequencies are being amplified, the transformer is *tuned* to them, or is *resonant* to them, and the current through the transformer becomes very great. The amplification at these particular *resonant frequencies* is very much greater than the amplification at other frequencies, and as a result we have *resonance peaks* or humps in the transformer curve.

Figure 14 shows such a curve. The particular transformer to which this curve applies is resonant to a frequency of about 5,000 cycles. The amplification at this frequency is very much greater than at say 4,000 or 6,000 cycles. The effect is, for example, that when we are listening to an orchestra, and an instrument happens to play a note having a frequency of 5,000 cycles, this particular note just "blares" out of the loudspeaker. It is much stronger than all the other notes played by the orchestra, and this effect spoils the reproduction. It is another cause of *distortion*.

Due to all these defects of audio transformers, experimenters have introduced other systems of coupling, in which

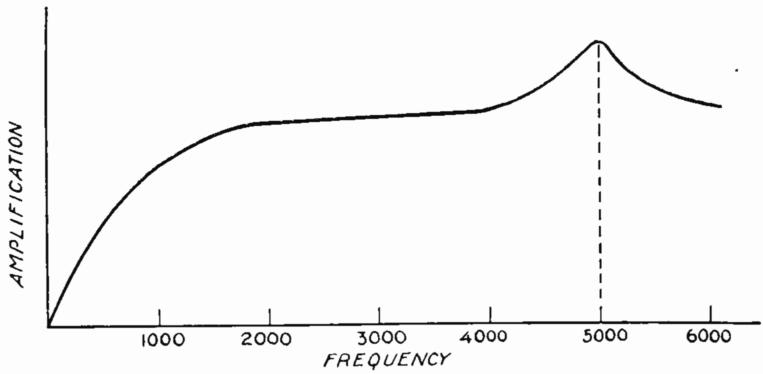

Fig. 14—Typical A. F. Transformer Curve.

they tried to avoid these defects, or at least reduce them. Although in some cases they have been successful in avoiding some of these defects, unfortunately, they have introduced other defects. The most prominent defect of the other systems is that the amplification is always less than that obtained with transformers.

The first system tried is known as "the resistance-capacity coupled amplifier." Let us study this system next.

In order to obtain energy from the plate circuit of an electron tube, we must have a "load" which can receive this energy. Now this load may just as well be an ordinary resistance. A resistance has an advantage over an inductance, in that it does not vary with the frequency. Figure 15-(A) shows what we mean. We have again left out the filament battery for simplicity. The audio voltage in the plate circuit (equal to μe_g) causes a current to flow in that circuit. This current flowing establishes a voltage across the terminals of the resistance. This voltage is equal to the value of the resistance "r" multiplied by the alternating current flowing through it "i", or

$$V = r \times i$$

If we wanted to add another tube to the amplifier, we might just as well connect it to the points a and b, as we have done in Figure 15-(B). But right here enters a difficulty.

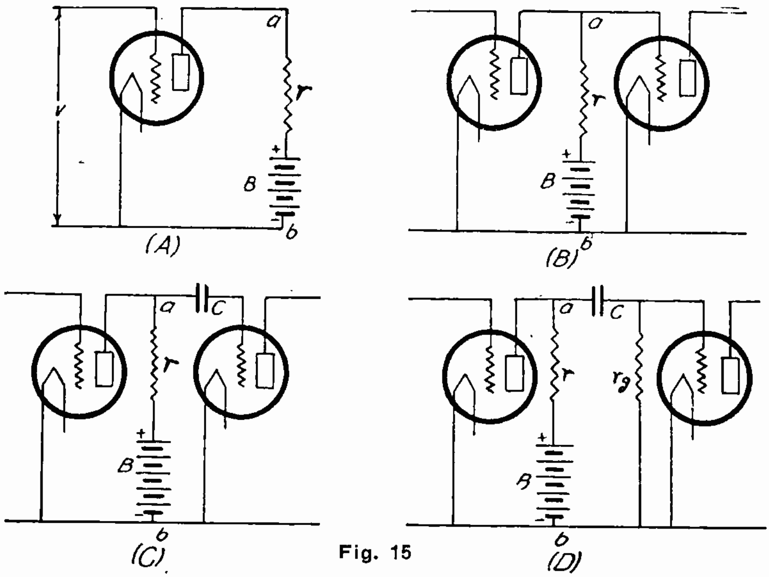

Fig. 15

Note:—These theoretical diagrams do not show all connections to the batteries.

You will notice that the positive terminal of the "B" battery is connected to the grid of the second tube through the resistance. If you remember your lesson on the electron tube, you will know that when the grid has a large positive bias, as it would have here, a large grid current will flow in the tube. A large grid current means a large power loss, and among other things, an additional cause of distortion.

In order to avoid this large positive bias we place a blocking condenser in series with the grid of the second tube, as shown in Figure 15-(C). This is marked C. Now we have introduced *two* more complications. In the first place the reactance of the condenser varies with the frequency. Its reactance at low frequencies is very high, and at high frequencies is much lower. It is clear, that we are getting right back to the trouble we tried to avoid. The condenser C will pass the high frequencies easily enough, but will offer considerable obstruction to the lower frequencies. We can make this effect (that is, unequal amplification) small by making the condenser C quite large. In practice, this condenser is never smaller than about 0.006 microfarad, and it is much better to use perhaps a capacity as large as 0.01 or 0.02 microfarad.

To come to the other difficutly which we mentioned. If you look carefully at Figure 15-(C), you will notice that the grid of the second tube is "free." That is to say, the condenser prevents the electrons, which the grid may collect, from leaking off the grid and passing on back to the filament from which they originally came. We will not repeat here the ill-effects of the "free" grid as we have taken this up earlier in this lesson.

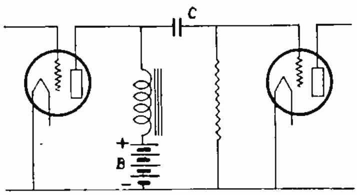

Fig. 16—Choke Coil or Impedance Coupling.

It will be sufficient to say that a leakage path must be furnished, and so we connect in the circuit the grid leak r_g, in Figure 15-(D). In this figure we have the complete circuit diagram of the resistance-capacity coupled amplifier, minus the "A" battery.

We have mentioned some of the troubles of this type of amplifier. There are several others that we must not pass over. The first of these is that quite a large voltage is required in the "B" battery in order to satisfactorily operate the system. We could use 90 volts very well when we use a transformer in the plate circuit of the tube, because there is not much resistance in the transformer, and therefore little loss of the "B" voltage in it. In the resistance coupled amplifier, the resistance r, in the plate circuit, is often about 100,000 ohms. On account of this, there is quite a loss of "B" voltage in the resistance, and in order to have enough voltage left over to operate the tube satisfactorily, it is necessary to use a "B" voltage of 135 volts or higher. This trouble is not serious because it is easy to simply add another 45-volt block to the "B" battery. As a matter of fact, nowadays with all electric A. C. sets higher voltages are being used in transformer coupled amplifiers.

The other difficulty which we mentioned is in connection with the grid leak. The greater the resistance of the grid leak, the greater the amplification will be. On the other hand, the greater the resistance, the more easily is the tube overloaded and the grid "blocked." When we say the word "blocked," we mean that the leakage path for the grid charge is of too high resistance, and the charge cannot leak off the grid easily or rapidly enough. This introduces distortion.

What is the greatest amount of amplification that can be obtained in each stage? If we make the condenser C *very*

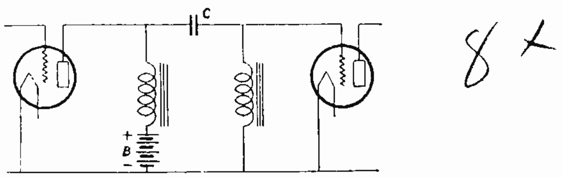

Fig. 17—Choke Coil or Impedance Coupling.

large, and make the grid leak resistance also *very* large, and if the tube were not overloaded or blocked, and we had a very large "B" voltage and a very large plate resistance r, then the greatest amplification we could obtain would be equal to the amplification constant of the tube. If the tube is the 201A, this would be 7.

We can never actually obtain an amplification equal to the μ of the tube, because if we would do all the things mentioned in the preceding paragraph the amplifier would not work anyhow. But this points out a serious limitation to the resistance-capacity coupled amplifier. Two stages of transformer coupling are generally used, but it is always necessary to use three stages of resistance coupling, in order to obtain satisfactory volume from the loud-speaker. It is claimed by many that the quality of reproduction is better with resistance coupling than with transformer coupling, and that the additional stage required is worth the trouble and expense. There are arguments for both sides, and the system you prefer is up to you.

Again, in order to avoid the difficulties of resistance coupled amplifiers, Radio Engineers have tried other methods. We will simply point them out in what follows, without going into a detailed description, for what you have already studied so far will enable you to understand them very easily. In order to avoid using a large "B" battery and also in order to obtain a much larger impedance in the plate circuit than the resistance offers, sometimes a *choke coil* is used. A choke coil is simply an impedance coil using a great number of turns of fine wire wound on an iron core. This is shown in the diagram of Figure 16. As in the previous case, a blocking condenser and a grid leak are required.

This system has the same disadvantage that the transformer system has; the reactance of the choke coil is low at low frequencies. There is the difference in that a choke coil of greater inductance can be wound in the same space as the transformer, reducing the drop at the low frequencies with

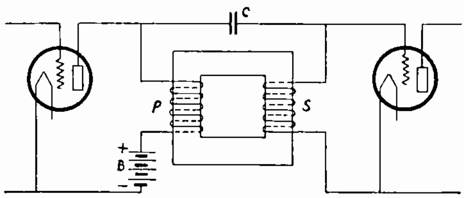

Fig. 18—Combination Transformer and Impedance Coupling System.

the transformer. As with the resistance coupled amplifier, the amplification can never be greater than the μ of the tube.

Next we have a method using another choke coil for the grid-resistance which is sometimes called dual impedance coupling. This choke coil has very large reactance to the audio-frequency currents, but has low resistance, so the grid charge can easily leak away, and the tube will not overload easily.

We have another circuit, as shown in Figure 18, in which the two choke coils of Figure 17 have been brought together onto an iron core. We have then a *combination of transformer and impedance coupling*, which is another name for choke coil coupling. In this system, the two windings are made exactly the same, having a turn ratio of 1:1. The claim is made that this system has all the advantages of the systems of Figures 16 and 17, and in addition has greater amplification.

We have now studied the most important types of audio-frequency amplifiers, as far as the coupling system is concerned.

CHARACTERISTICS CURVES

We must now study the electron tube itself—how it acts, and how it should be operated, in order to get the best results

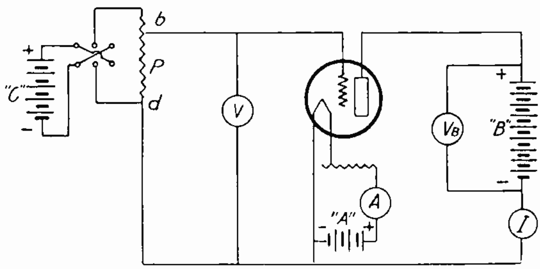

Fig. 19—Circuit Arrangement for Determining the Characteristic Curves of Vacuum Tubes.

out of such amplifiers. In order to study the tube itself, we shall make use of the circuit shown in Figure 19.

This is the circuit that is used to determine what are called the characteristic curves of the electron tubes. It consists of a vacuum tube, "A," and "B" batteries connected in

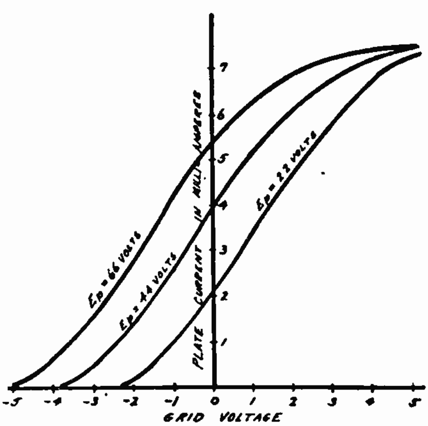

Fig. 20—Grid Voltage. Plate Current Characteristic Curve of a Vacuum Tube.

the usual way, a "C" battery with a reversing switch and a potentiometer connected in the grid circuit. There is a Voltmeter (V) in the grid circuit and an ammeter (A) in the filament circuit, also a voltmeter (VB) and a milli-ammeter (I) in the plate circuit. By throwing the switch to the right or left and moving the slider on the potentiometer, we can obtain any value of positive or negative bias we want. Now if we move the slider of the potentiometer b and take a reading of the various values of voltage and current applied to these circuits, we will have a number of values as in the table below:

Grid volts	Plate milliamperes
0	4.0
—1	2.8
—2	1.6
—3	0.7
—4	0.2
+1	5.0
+2	5.8
+3	6.5
+4	7.0

By plotting them on cross-section paper, we will obtain a curve like the curved marked Ep = 44 volts in Figure 20.

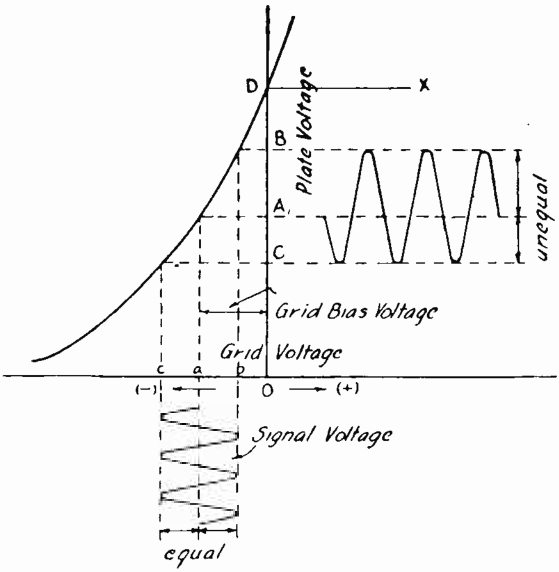

Fig. 21

Now remember while doing all of this, we keep the voltage of the "B" battery the same as 44 volts. Suppose we repeat the procedure and make our measurements with a plate voltage of 66, or 22 volts, then we will get similar curves but when plotted, they will be higher and lower than the curve for a plate voltage of 44 volts.

Now as we have learned what this is all about, why do we go to all this trouble and what do the curves tell us?

These curves furnish us with some very important information on how to operate tubes. They are called "characteristic curves."

Look at Figure 21; here we have a characteristic curve like those in Figure 20. Now suppose we have an audio-amplifying circuit and there is a "C" battery in the circuit which gives us a certain grid bias. Suppose we did not have any bias on the grid, in other words, the bias were zero. A large

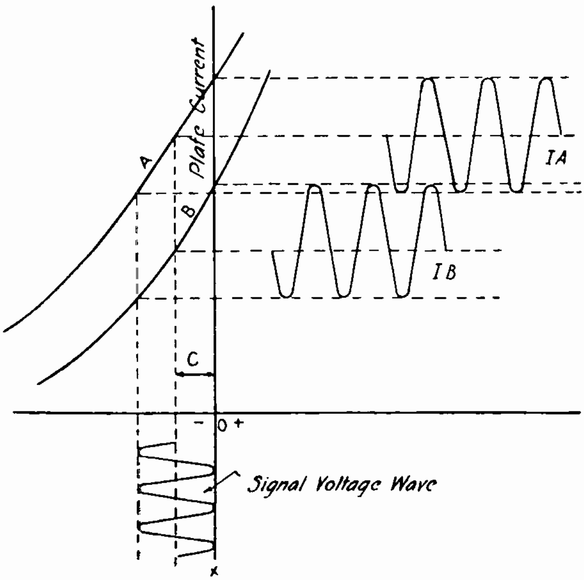

Fig. 22

plate current will then flow whose value is represented by the height of the line O-D in Figure 21.

When the "C" battery is connected in the circuit, giving us a certain negative grid bias, we can represent this negative voltage by the line O-a in Figure 21. This is called the operating voltage of the grid. When the signal voltage comes along and is impressed on the grid together with the C bias voltage, this signal voltage oscillates about the grid bias. Sometimes, making the grid voltage higher and at other times, lower.

Below the horizontal line of Figure 21, the signal voltage is shown. For simplicity, we have chosen a very simple wave form. When the signal voltage is at its maximum positive value, the voltage of the grid is O-b. When the signal voltage is at its maximum negative value, the grid voltage is O-c. When the signal voltage is zero, the grid voltage is O-a, which is the same as the bias voltage.

When there is no signal voltage on the grid, the plate current has a certain steady value O-A. This is the normal plate current. When there is an alternating signal voltage on the grid, the plate current oscillates higher and lower than this steady or normal value.

Now you will notice that although we have drawn the signal voltage wave so as to have both halves of it equal, the two halves of the plate current wave are not equal. This is because there is always a certain amount of curvature to the characteristic curve. The nearer we get to the bottom of the curve, the greater is its curvature. In other words, the plate current is not the same in wave form as the incoming signal voltage. This means that there is distortion introduced as the signal is amplified.

What must we do to reduce this distortion? Simply operate the tube at that portion where the curvature is least. In other words, we must get away from the low end of the curve.

In Figure 22, we have shown two characteristic curves for the same tube. Curve B is obtained for a certain plate voltage and curve A is for a higher plate voltage than curve B. At the bottom, we have a certain signal voltage wave. We have made the grid bias sufficiently negative that when the signal voltage comes along, the grid will never be positive. Then there can never be a grid current. You can readily understand that if the grid bias were less than negative C, the signal voltage wave would pass over the line O-X, and during part of the cycle, the grid voltage would be positive. It is necessary to make the "C" battery voltage or grid bias voltage not less, but preferably greater, than the strongest signal we expect to amplify.

Suppose with this value of grid bias, we operate the tube with a voltage on the plate corresponding to curve B of Figure 22. The plate current will then be as shown at I-B which has, as you can see, a great amount of distortion in it. As we learned before, we should not make the grid less negative, or we will have a grid current flowing. So the only other thing to do is to raise the plate voltage. When we do this, we no longer operate the tube on the curve B, but now operate it on curve A. This curve is higher than the curve B, so we are now operating our tube higher up on the characteristic curve. As a result, the distortion is much less as is shown by the appearance of the plate current wave I-A.

So you see what it means to use the proper voltages on the tube. You must use enough "C" battery voltage or grid bias as to prevent the grid from becoming positive. When you do this, you must have a sufficiently high plate voltage and see that the tube is operated far enough away from the lower bend of the characteristic curve.

We have learned in this lesson all the main things in connection with wiring and operation of audio-frequency amplifiers; also, the various coupling systems used between the tubes. We have by no means learned all about audio-frequency amplifiers. We have merely learned the most important facts—the facts that you will need all of the time in your practical Radio work. Therefore, if there are some things which you do not understand at the first reading, do not fail to go back and read the lesson again.

TEST QUESTIONS

Number Your Answers 12—1 and add Your Student Number

1. What is the purpose of an audio-frequency amplifier?
2. What is the frequency of sound waves?
3. What are the two main requirements of an amplifier?
4. Draw a diagram of a two-stage transformer coupled amplifier.
5. What is the main shortcoming of the transformer type of amplification?
6. What is the greatest amount of amplification that it is theoretically possible to obtain, using a 4 to 1 ratio transformer and a tube which has an amplification constant of 7?
7. Draw a diagram of a resistance capacity coupled amplifier.
8. Draw a diagram showing the choke coil type of amplifier.
9. Draw a diagram showing a combination of the transformer and impedance coupling systems.
10. What is the plate current for the Ep 44-volt plate curve when the grid voltage is zero (0) in Figure 20?

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