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R.C.A. SPECIAL NOTICES

This issue marks another turn in the R.C.A. calendar. We hope it has been a year of usefulness to our membership. The Radio Club of America has continued to grow and prosper because it has endeavored to fill a long felt need in the Radio field, so open to experimentation and development on the part of everyone.

Each Radio Club meeting grows more interesting with open discussions on the part of the membership. Discussions are most welcome and we hope during the coming year to get more of them into print.

1923:—A wish for a big and prosperous Radio year.

Walter S. Lemmon—*Editor*, 342 Madison Ave., N.Y.C.
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Vacuum Tube Amplification

*By S. E. Anderson**

A Paper Presented Before The Radio Club of America, Columbia University, New York, December 1, 1922

EVERYONE in any way associated with radio, excepting possibly the very newest of the new radiophone listeners, is more or less familiar with the manifold applications of the vacuum tube, in all of which it contributes in generous measure to make radio what it is today.

Probably more vacuum tubes are used as amplifiers of one sort or another than in any other capacity, such as an oscillator, modulator or detector. Indeed, a vacuum tube could not be an oscillator were it not first an amplifier, which has been pointedly, though somewhat inaccurately, described as something into which one puts nothing and gets out a lot of things he didn't expect. Modulation and detection are special modifications of this amplifying characteristic. By far the largest application of vacuum tube amplifiers, from a numerical standpoint at least, has been in the telephone repeater. It is this which has made transcontinental telephony possible and it has

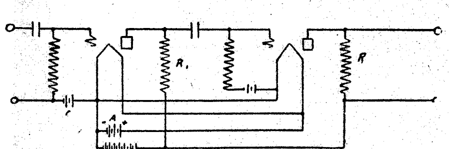

Fig 1
Resistance Coupling

also enabled us to put in compact underground cables the telephone circuits between large cities, such as New York and Chicago. The number of telephone repeaters in a single office, such as Newark, may run well into the hundreds and the vacuum tubes necessary for these repeaters would keep the amateurs stocked up for some time to come.

But we are interested in amplification as applied to radio. I am going to assume that we are all sufficiently familiar with the "bottles" to enter at once into a discussion of the circuits in which they are employed as amplifiers. Before taking up in detail the various types of amplifiers as distinguished by the frequency range in which they operate, let us first consider the three general types of amplifier circuits.

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We first have the "resistance-coupled" amplifier as shown in Figure 1. This was possibly the first type of coupling to be employed and is still used extensively for some purposes. The resistance R_1 is of the same order of magnitude as the internal impedance of the tube, or from 10,000 to 50,000 ohms. This means that the plate

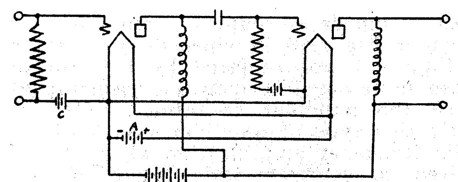


Fig 2 Impedance Coupling

potential is about half the "B" battery voltage and this excessive battery waste is the chief disadvantage of this circuit. Another disadvantage is that the fraction of the pulsating voltage developed in the plate circuit of the first tube which is impressed on the grid of the second tube is proportional to the coupling resistance and if we make this small to save "B" battery we decrease the amplification. Making this resistance equal to that of the tube simply represents a reasonable compromise and with coupling resistances of this value the voltage amplification for each stage is obviously half the amplification constant of the tube. A minor disadvantage is that a condenser and grid leak are required for each tube but this is also true of impedance-coupled amplifiers. The big advantage of the resistance-coupled amplifier is that it

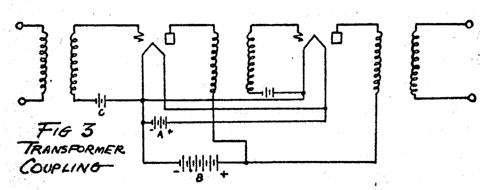
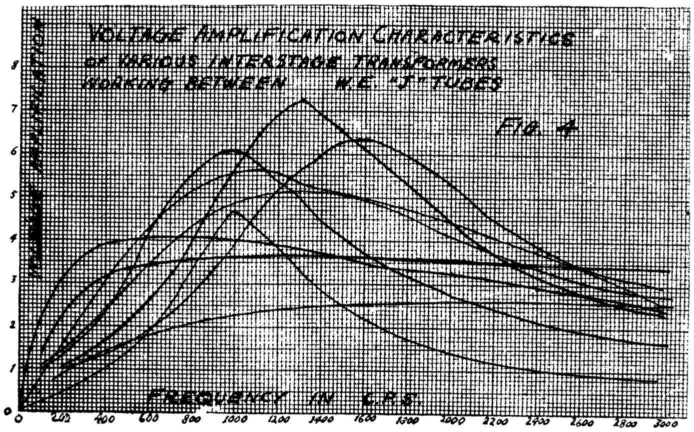


Fig 3
Transformer Coupling

is practically independent of frequency up to the lower radio frequencies of 20 or 30 kilocycles. Here the efficiency begins to decrease rapidly and at a frequency of 1000 kilocycles, corresponding to a wave length of 300 meters, the amplification with ordinary tubes is exceedingly small.



Audio Frequency Amplification

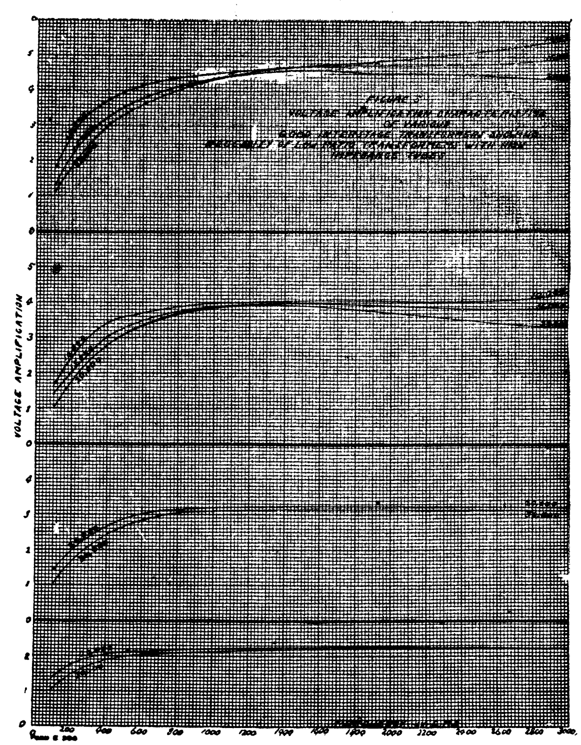
It is natural that amplification at audio frequencies should be the first to be developed, both because of the relative simplicity of the task and because there are numerous applications of the vacuum tube amplifier where only the lower frequencies are involved.

For very special purposes where it is desired to have uniform amplification over a wide range of frequencies, say from as low as 10 cycles per second to as high as 10,000, the resistance coupled amplifier is used. For this purpose, in order to overcome the inherent inefficiency of this method of coupling, a tube having as high an amplification constant as possible is usually employed. One standard tube used for this purpose has an amplification constant of 30, this being adopted after a tube with an amplification constant of 40 had been found impractical.

It may be well to point out here that a high amplification constant does not neces-

An "impedance-coupled" amplifier is shown on Figure 2, in which the resistances of Figure 1 are replaced by inductances whose value depends upon the frequency at which the amplifier operates. Until recently this type of amplifier was used for audio frequency amplification where it was desired to cover a wide range of frequencies without the battery waste of the resistance coupled amplifier, as the D.C. resistance of the choke coils is comparatively small. Recent improvements in transformer design, however, make it possible to get a very good frequency range with much greater amplification, as it is obvious that in an impedance-coupled amplifier the amplification per stage can never exceed the amplification constant of the tube unless resonance occurs, which destroys the desirable frequency characteristic. The impedance-coupled amplifier is used to some extent for radio frequency amplification, but even this use is declining as we learn more about transformers because of the extra apparatus — condensers and grid leaks—required by the impedance-coupled amplifier.

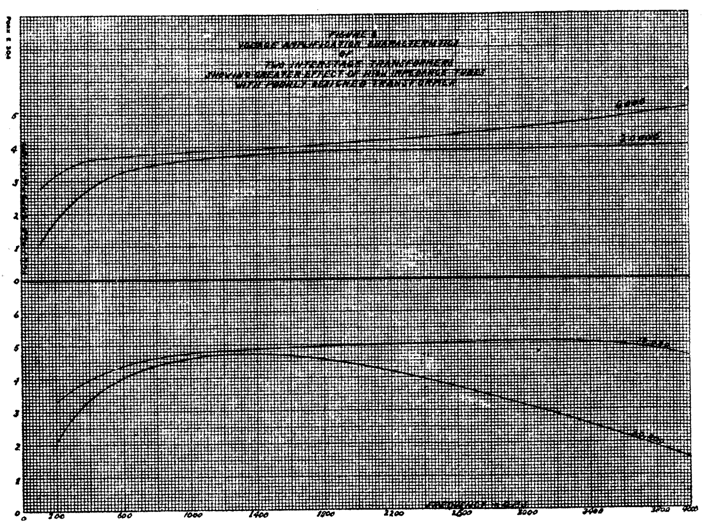
An amplifier using transformer coupling is shown in Figure 3. This type of amplifier is coming more and more into general use for several reasons. *First,* by means of a step-up transformer an amplification of several times the amplification constant of the tube may be obtained at moderate frequencies. *Second,* it is economical of plate battery. *Third* the frequency characteristics may be made as good as those of an impedance-coupled amplifier at all frequencies. *Fourth,* the grid condenser and grid leak are eliminated.



sarily mean a superior tube. For most purposes the excellence of a vacuum tube, aside from those general points of construction which tend to increase the stability, uniformity and life, is measured by a factor called its "mutual conductance," which is proportional to the change in plate current caused by a given change in grid voltage. Probably the most desirable amplifier tube from all standpoints, except use in a resistance coupled amplifier, is an oxide-coated filament tube having an amplification constant of about 5 and a plate impedance of about 6000 ohms. The tube with an amplification constant of 30 has a plate impedance of 60,000 ohms, so, although the voltage amplification is higher, the mutual conductance is only 6/10 that of the 6000 ohm tube.

former-coupled amplifiers, let us consider what is necessary in a good audio-frequency amplifier. The audio frequencies, or those frequencies which produce audible sounds, range from about 16 cycles per second to about 16,000 cycles per second. The lower limit is rather definite, as below this frequency the ear perceives the sound, not as a single low note, but as a series of sounds close together. The upper limit varies with different persons and with the same person under different conditions. Almost anyone can hear a frequency of 10,000 cycles per second and a few people can hear as high as 18,000 or 20,000.

In connection with ordinary telephone apparatus it has been found that for the transmission of good understandable speech it is necessary to use only the frequency



Impedance-coupled audio frequency amplifiers, as previously pointed out, are practically obsolete, though some splendid multi-stage amplifiers of this type have been built. The writer recalls one four-stage amplifier using tubes with an amplification constant of 30 and choke coils having an inductance of 350 henries with a minimum distributed capacity. At a frequency of only 80 cycles per second the impedance of such a choke coil is approximately 175,000 ohms, with the impedance at other frequencies in proportion. This impedance being three times the tube impedance, 75% of the plate voltage at 80 cycles is impressed on the following grid, so that the amplification per stage is nearly equal to the amplification constant of the tube over a wide frequency range. Incidentally the total voltage amplification of this amplifier was approximately 800,000 times.

Before considering in some detail trans-

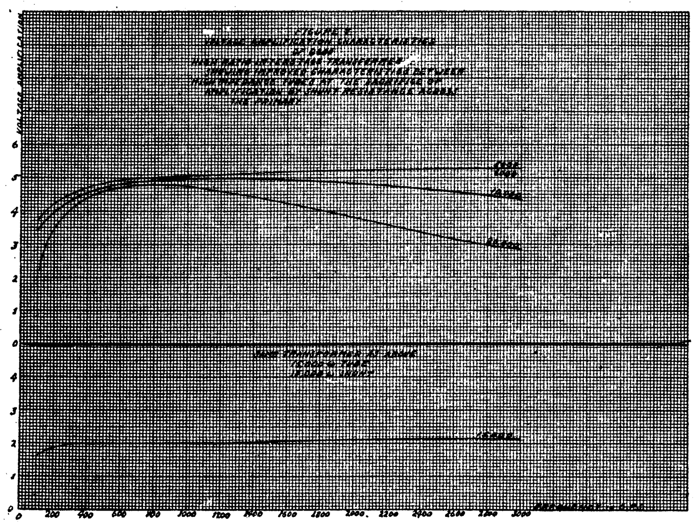
band from 200 to 2000 cycles, and the first radio transmitters were designed on the same basis. It was soon found, however, that music transmitted by means of these sets had an undesirable "tin pan" effect due to the absence of the higher and lower frequencies. It has been found that to transmit good quality music the frequency band must be extended to include all frequencies from 100 to 4000 cycles, and if it is desired to transmit perfectly such music as is produced by a large organ, the lower limit must extend down still lower to about 30 cycles. Not only must all frequencies within this band be transmitted, but they must, within limits, be transmitted uniformly so that the amplitudes of the various frequencies in the emitted wave correspond to those in the original sound wave.

Obviously it does us no good to transmit nearly perfect music if the receiving apparatus amplifies some frequencies within the desired band five or ten times as well as other frequencies. This is exactly what happens with many of the amplifying transformers on the market. In Figure 4 are shown the characteristics of a number of these transformers, the amplification shown being that of the transformer alone when working between Western Electric "J" tubes, which have an output impedance of about 15,000 ohms. Of these transformers only two could be considered satisfactory and one of these falls off too much at high frequencies.

The maximum amplification of any transformer represents approximately its turn ratio. It is worthy of note that all the transformers having a ratio higher than 4 are very poor, while only one having a ratio less than 4 is bad and it is not nearly as bad as the others. It has been found by experience that a ratio of 4:1 represents the maximum which can be used and still give uniform amplification, and this is too high for most tubes.

On Figure 5 are shown a number of transformer characteristics representing the most advanced design. The upper curves are of a transformer having a ratio of 4.75:1 working out of the impedances shown on the curves. Comparing these with the curves below which are of a transformer having a 4:1 ratio, it may be noted that the difference in characteristics caused by using tubes of different impedances is much more pronounced in the higher ratio transformer. The same is true, to a lesser degree, of the two lower sets of curves showing transformers having a 3:1 and 2:1 ratio. There is one value of tube impedance—20,000 ohms—common to all the curves and it will be noted that the lower the transformer ratio the more uniform is the amplification when working out of this impedance. When the impedance is increased to 30,000 ohms, the superiority of the lower ratio coil is obvious.

Merely making the ratio low does not suffice, however, though it is much easier to make a good low-ratio transformer than



a good high-ratio one. At the bottom of Figure 6 is shown a poorly designed transformer having a 5:1 ratio working out of a 10,000 ohm tube. This transformer is very fair with this tube, but out of a 20,000 ohm tube it is most unsatisfactory, though not as bad as some of the transformers on Figure 4. The upper curves of Figure 6 show a well designed transformer with a 4:1 ratio and the excellence of the characteristic when working out of a 6000 ohm tube, the amplification being both high and uniform, emphasizes the desirability of using low impedance tubes. It is to be noted, however, that even with a 20,000 ohm tube this transformer is much better than the other, though not as good as a lower-ratio coil would be. This transformer was designed to amplify the higher frequencies more strongly and actually continues to do so up to 6000 cycles in order to compensate for the fact that the average loud speaker discriminates strongly against these high frequencies.

If one has a high-ratio transformer which is being used with high impedance tubes, and it is suspected of amplifying the frequencies around 1000 cycles more than the others, the characteristic may be greatly improved at some sacrifice in amplification by connecting a shunt resistance of 10,000 or 15,000 ohms across the primary or plate winding. The results with one transformer which was designed only for low impedance tubes are shown in Figure 7.

The writer is glad to be able to say that a number of the transformers made by reliable companies have very satisfactory characteristics. It should be remembered that a good audio frequency amplifying transformer having a turns ratio of more than 4:1 has never been produced except for very low impedance tubes. A transformer having a 3:1 ratio is a very good compromise when working with most of the amplifying tubes available. It would be a good plan for the manufacturers to furnish, either in their advertising or with the transformers, curves showing their characteristic with moderate accuracy so that the transformers could be intelligently selected to work to the best advantage with the tubes available.

In Figure 8 is shown a standard two-variometer regenerative receiver followed bv three stages of audio frequency amplification, which is the maximum number

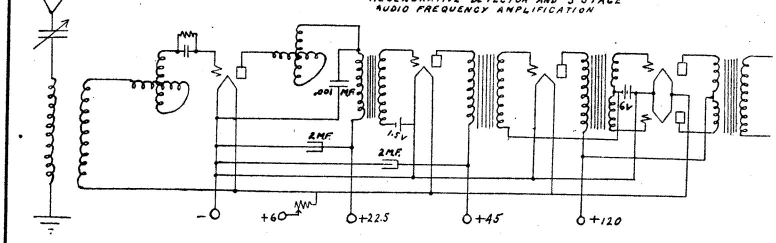


FIGURE 8
REGENERATIVE DETECTOR AND 3 STAGE AUDIO FREQUENCY AMPLIFICATION

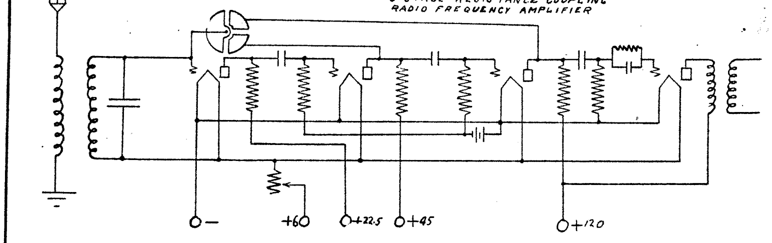


FIGURE 9
3 STAGE RESISTANCE COUPLING RADIO FREQUENCY AMPLIFIER

which should ever be used by the amateur. Indeed, the elimination of the second stage, leaving only two stages, is quite desirable when used with a regenerative receiver because it is very easy to ruin the quality by overloading the amplifier. For the large loud speakers used outdoors as many as nine stages of amplification may be employed, the last stage using four 50 watt tubes. Such an amplifier, of course, is far beyond the needs of the amateur and requires very careful shielding and balancing to prevent howling.

The circuit of Figure 8 differs from the circuits usually employed in three details. *First,* grid biasing batteries are used on the amplifier tubes. *Second,* audio frequency by-pass condensers are used across the plate batteries. *Third,* the last stage of the amplifier uses two tubes connected in a balanced or push-pull circuit. If it is desirable to obtain the best possible quality, all of these changes from the usual circuit will be found well worth while. One thing that should always be borne in mind when building cascade amplifiers intended to produce a large output and which is very seldom considered, is that the available power in each stage should be greater than in the one preceding it. Speaking in terms of the tubes available to the amateur, suppose we have a U.V.200 as a detector, it is well followed by a U.V.201 with 45 volts on the plate as an amplifier. The second stage should be a U.V.201 with 120 volts on the plate and the third stage should use two U.V.201 tubes with 120 volts on the plate. It should be remembered that the plate impedance of a tube decreases with an increase of the plate battery voltage. For ordinary purposes the use of 5 watt tubes in the last stage will be unnecessary and undesirable unless they are used with much less than normal plate voltage, say not over 150 volts, as it is very easy to overload any loud speaker with a small horn. For the first stage a grid battery of 1.5 volts will be satisfactory and for the last two stages 6 to 9 volts may be used.

It may be pointed out here that more than one stage of audio frequency amplification will not increase the sensitivity of the set. It will merely increase the output of signals which a detector and one stage will bring in. The reason for this is that the output of the detector is proportional to the square of the input and there is a limiting minimum input below which the output is negligible and no amount of audio frequency amplification will make it audible. The minimum output, however, while it can be heard in the receivers, is distinctly below comfortable volume and one stage

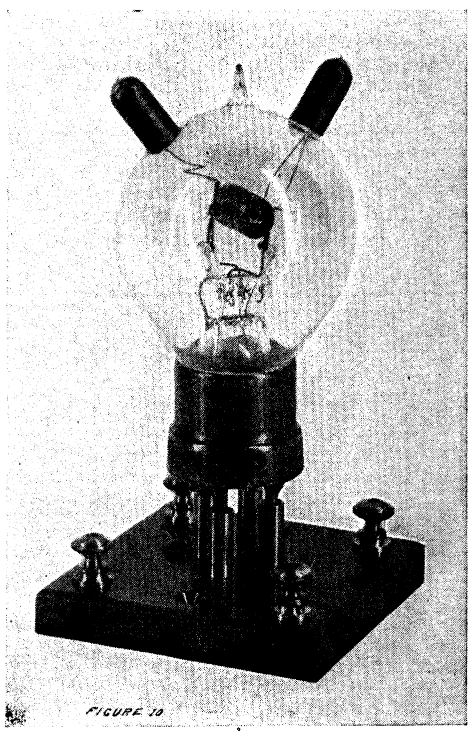


FIGURE 10

of audio frequency amplification will, therefore, materially increase the useful sensitivity of the set. It is well to bear in mind that a signal gives about the same apparent loudness in a pair of "cans" on the ears when connected to the input of a two-stage audio frequency amplifier as is produced on a loud speaker connected to the output and used in an average sized room.

Just a word regarding the circuit layout and we will pass to radio frequency amplification. There is no better layout for amplifiers of all kinds than the "long and skinny," but this is not always practical. In any type of construction adopted, however, the output should be as well separated from the input as possible. There are two wires in each stage which must be as short and direct as possible—the wires to the plate and grid of the tube. This becomes increasingly important in the final stages and, in general, the grid connections are more sensitive than the plate connections. For a three-stage audio frequency amplifier shielding between stages should not be necessary if the cores of the transformers are grounded. The outside connections of the transformer windings should be connected to plate and grid for maximum amplification, but reversing some of these connections may cure a persistent howl which refuses to yield to more rational treatment.

Now, although it is desirable that the plate and grid wires be short, direct and separated from everything else, all the other wiring should be bunched closely together, including the leads to the low side of the transformers. From an alternating current standpoint, all of this wiring should be at ground potential and bunching it together helps to keep it thus by virtue of the capacity between the wires and the elimination of inductive loops, remembering that the inductance of a circuit is proportional to its area. This bunching of the low potential wiring is especially effective in high frequency amplifiers.

In view of the fact that one stage of audio frequency amplification actually does increase the useful sensitivity of a receiver and that additional amplification is useful only in connection with a loud speaker, it is recommended that one stage of audio frequency amplification be always embodied in a receiving set itself, while additional stages of amplification are mounted in a separate unit. If a regenerative detector and two or three stages of audio frequency amplification are embodied in the receiver unit itself, it is very difficult to eliminate undesirable howling and squealing.

Radio Frequency Amplification

Remembering the fact that the output of a detector is proportional to the square of the input, it is obvious that amplification of the signals before they reach the detector will produce most satisfactory results.

This is a very simple job for long wave lengths but it is a serious problem on wave lengths below 600 meters, corresponding to a frequency of 500,000 cycles. While the final solution has by no means been found, much progress has been made in the last year and very satisfactory results have been obtained. In all fairness, however, I shall have to point out that the claims of some manufacturers concerning the wave length range and amplification of their transformers are rather optimistic.

The fundamental obstacle in radio frequency amplification is the very high frequencies involved. At audio frequencies the input capacity of a vacuum tube—from 5 to 15 micro-micro-farads—may be entirely neglected, but at short wave lengths it becomes very important. At 200 meters, for example, corresponding to a frequency of 1500 kilocycles, the input reactance of the average tube in a good socket is only about 10,000 ohms, which is the same order of magnitude as the output impedance. Due to the effect of the output circuit on the input circuit, the input impedance of a tube with a high amplification constant may be reduced to as low as 2000 ohms. Unfortunately, the higher the amplification constant of the tube, the lower is the input impedance. These conditions make it necessary to employ some sort of resonance coupling, which uses the tube capacity in the resonant circuit to obtain a decent amplification, and this restricts the efficient wave length range to a relatively narrow band.

Let us consider first the resistance-coupled radio-frequency amplifier, which has been developed extensively in Europe where most of the work is at longer wave lengths. A typical circuit of a three stage amplifier used in France is shown in Figure 9. The chief point of interest is the "compensator." This consists of a three plate condenser connected as shown. As the capacity between the grid of the first tube and the plate of the third tube is increased, regeneration occurs and the circuit oscillates readily with further increase of this capacity so that the amplifier may be used for C.W. signals. Increasing the capacity between the first grid and the second plate reduces the regeneration and tends to neutralize any undesirable oscillating tendency due to the capacity of the wiring. This method of regenerative control is very satisfactory.

If one wishes to use half a dozen stages of resistance-coupled radio frequency amplification, it may be all right on 200 meters. It would certainly have the advantage of fairly uniform amplification over a wide range of wave lengths, the amplification increasing gradually with the wave length. But, in view of the fact that vacuum tubes cost more than a quarter apiece, most of us are content to use fewer vacuum tubes to get the same amplification for a smaller wave length range.

Some special types of tubes have been developed in order to minimize the interelectrode capacity. The Meyers audion is an example of this type of tube and should show materially better radio frequency amplification in a resistance-coupled circuit. Figure 10 shows a photograph of a French tube developed for this purpose. It is popularly called a "Kamerad" tube because its arms are in the air. The grid and plate leads are brought out through the two "horns" which are copper sleeves cemented firmly to corresponding projections of the glass bulb through which the connections pass.

Even with these specially-constructed tubes resistance-coupled amplifiers have proven most unsatisfactory for wave lengths below 500 meters and practically all recent developments in this country have been in the direction of tuned interstage coupling. With this type of coupling the

FIGURE 11
REGENERATIVE RECEIVER WITH 1 STAGE OF RADIO FREQUENCY AMPLIFICATION

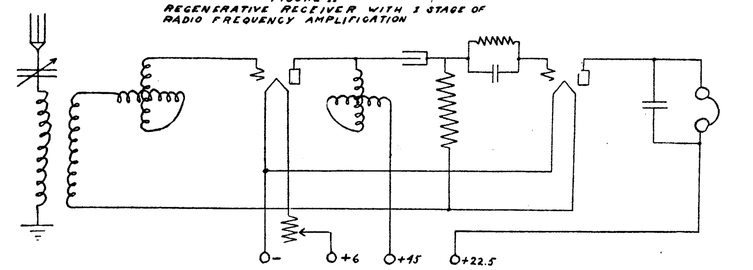
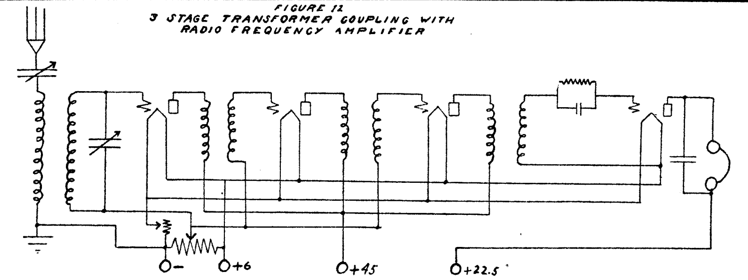


FIGURE 12
3 STAGE TRANSFORMER COUPLING WITH RADIO FREQUENCY AMPLIFIER



capacity of the tube is used to resonate the coupling coil or transformer at the wave length for which the maximum amplification is desired and thus a fairly large capacity up to about 15 m.m.f. is not a disadvantage. If this capacity is further increased, however, such as by careless wiring or poorly designed tube sockets, the interstage tuning will become very sharp and the wave length range of the amplifier will be exceedingly limited.

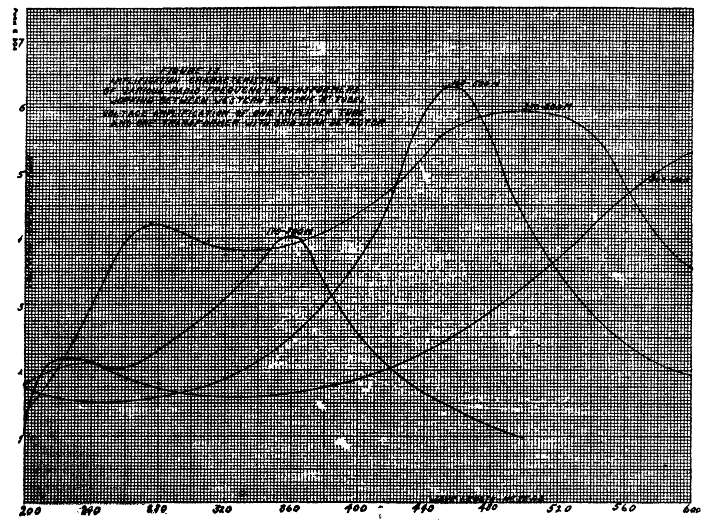
At this point the writer desires to call attention to a very satisfactory method of adding one stage of radio frequency amplification to the type of regenerative receiver using a tuned plate circuit. The tuning may be either by a variometer or a coil and variable condenser. The circuit using a variometer, which will generally give better amplification, is shown in Figure 11. This circuit has been published in a number of magazines but has not received the attention it deserves. We have here the very best type of coupling for radio frequency amplification and its use adds no adjustments to the receiver. When adjusted so regeneration occurs the impedance of the tuned plate circuit is very high and the coupling is very efficient. A multi-stage amplifier using the same type of coupling between each stage would be an excellent amplifier except for the difficulty of tuning so many interstage circuits and the impossibility of obtaining a suitable circuit that did not oscillate. The addition of one stage of radio frequency amplification to such a regenerative circuit requires only one tube, a few accessories, and minor changes in the existing circuit. It will give a voltage amplification of about five or an increase in the detector output with weak signals of about 25 times. Surely this is very much worth while.

We will consider briefly impedance-coupled radio frequency amplifiers. They have one big advantage which is of considerable importance. Choke coils having moderately sharp characteristics may be used and the number of turns and consequently the wave length range may be changed by means of a simple switch. The switches of several stages may be mechanically interconnected, thus requiring only one adjustment. By tuning each stage rather sharply excellent selectivity is obtained, but, although the amplification in each stage may be fairly high, it is necessary to throw most of it away in some sort of "stabilizer," which has more properly been termed a "losser" by one of my associates, in order to prevent oscillation. This is because with the sharp tuning we have grid and plate circuits tuned to nearly the same wave length with the capacity of the tube for feedback, and at a million or more cycles there is no better oscillator than this combination. A minor disadvantage is the necessity for grid leaks and condensers, the capacity of which to ground is serious at radio frequencies. In general, the impedance-coupled radio frequency amplifier will give somewhat less amplification but greater selectivity than an amplifier using flat resonance transformers and to cover the same wave length range will require an additional adjustment.

A three stage transformer-coupled radio frequency amplifier using a stabilizer is shown in Figure 12. The stabilizer could probably be replaced with profit by the "compensator" of Figure 9. Certainly the latter is much to be preferred from a mechanical standpoint, though there is some difference of opinion as to which arrangement gives the best regenerative control. The stabilizer functions by making the grids of the tubes more or less positive with respect to the filament, as when the grid becomes positive over a portion of the cycle current flows and power is consumed, thus placing a sufficient loss in the circuit to prevent singing. The compensator, operating as it does by merely changing the phase of the feedback potential, seems to the writer a much more rational solution of the problem.

The best solution of all is to design the circuit so stabilizers, compensators or other "lossers" are not necessary. It is possible to do this with a two-stage radio-frequency amplifier and we are not convinced that it is impossible for three stages, though it has not been done yet. It simply means the painstaking elimination of parasitic feedback capacities and inductive loops. Make the grid and plate wires short, straight and clear. Make all the other wiring as direct as possible, but bunch it together. After an amplifier is obtained which is free from singing or oscillation, a regenerative control, such as the compensator, may legitimately be added, but we cannot consider that any amplifier represents a real solution of the problem if we have to decrease the amplification in some way to prevent our amplifier from becoming an oscillator.

Now a word as to the amplifying transformers themselves. To the best of our knowledge and belief, no radio frequency transformer has yet appeared giving even approximately a uniform amplification over a much greater than 2:1 wave length range and the best transformer covers the wave lengths from 250 to 600 meters. Figure 13 shows the characteristics of a number of transformers with the rated wave length range marked on the curves. At the time the curves were taken measurements could not be made below 200 meters, but from the shape of most of the curves it was apparently unnecessary. Despite the fact that such a rated wave length range is obviously rather optimistic, the best of these characteristics represent fairly good transformers and, far from accusing the manufacturers of misrepresentation, the transformers actually do amplify over their entire rated wave length range, though rather feebly at some portions of it. We honestly think, as with audio frequency transformers, that the characteristics should be made public by the manufacturers. The designing of transformers which are good at 200 meters merely awaits the lessening of the demand for transformers good at 360 and 400 meters. While plification the signals may be detected just as if they were long wave signals. With a set of this type the weakest winter static sounds like a thunder-storm in the middle of July, so it would be foolish to build a more sensitive receiver. This type of receiver will probably remain the last word in sensitivity for some time to come. At



the best results at 200 meters will prabably not be as good as the best results at 400 meters, the 200 meter results will soon be far ahead of the present 400 meter results. Improvements in design are constantly giving us an increase in wave length range without sacrifice of amplification.

It was previously noted that radio frequency amplification at long wave lengths was a very simple job. In fact, it is in some ways easier to handle the frequencies between 20 and 50 kilocycles than audio frequencies because the amplifier is tuned to the superaudible frequencies and tube noises are greatly reduced.

It has proven most satisfactory by means of a local oscillator and a modulating tube to change the frequency of the incoming signal to a much lower frequency. This may then be amplified to almost any desired degree without difficulty, the maximum practicable voltage amplification being about 10,000 times, which increases the final output 100,000,000 times. After amleast six vacuum tubes are required, but the sensitivity per tube is far ahead of that obtainable by any other method—if one has six tubes.

Summary

We will summarize very briefly. For sensitivity, direct radio-frequency amplification should be used by all but millionaires. One stage of radio frequency amplification in a non-regenerative circuit gives about the same sensitivity as a first class regenerative receiver. Two stages with good transformers will be about five times as sensitive as a simple regenerative circuit, and the regeneration in the amplifier will multiply this by about three. One additional stage of audio frequency amplification will bring the weaker signals up to a more comfortable volume. Additional stages of audio frequency amplification—never more than two—should be used only for operating a loud speaker, as they add nothing to the sensitivity of the receiver.