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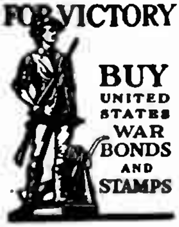

WIDE BAND AMPLIFIERS*

The design of wide-band television amplifiers, covering a frequency range from 50 cycles to 5 megacycles

For television applications and for other purposes which are today classified as military information, circuits are employed which will amplify uniformly a wide band of frequencies. The television amplifier, or video amplifier as it is often called, must fulfill two primary qualifications not considered in the ordinary audio frequency amplifier. First, it must have a favorable gain characteristic for frequencies ranging from as low as 30 cycles per second up to four or five megacycles. The second requirement for the video amplifier is that it introduce no phase distortion. In an audio amplifier phase shift is relatively unimportant because the human ear is incapable of detecting it in the amounts present.

In the video amplifier, however, phase shift must be both dealt with and restricted, since phase distortion

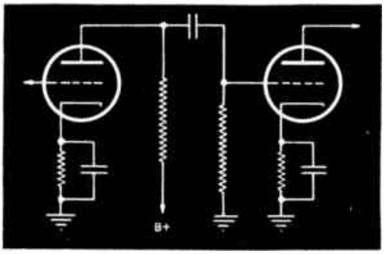

Fig. 1. Resistance-coupled amplifier.

of the signal will result in a distorted image on the television screen. The time delay of the video amplifier must, therefore, be either zero or a constant over the entire range of its amplification. To understand fully the design considerations encountered in the video amplifier, one must first acquaint himself with the operation and shortcomings of the conventional resistance-coupled amplifier shown in Fig. 1.

For purposes of simplification of calculation, the circuit of Fig. 1 may be resolved into the equivalent circuit shown in Fig. 2. The tube here has

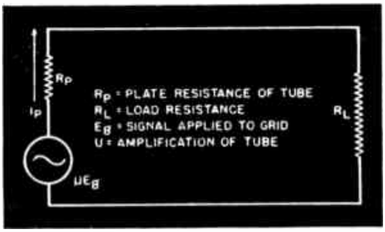

Fig. 2. Equivalent circuit.

been replaced by a generator developing a voltage of μe_g and having an internal resistance of R_p. The voltage developed by the generator causes a current, i_p, to flow through the circuit consisting of R_p and R_L in series. The value of the current, i_p, may be calculated by simple Ohm's law: $I=E/R$. The E in this case being μe_g, and R being R_p plus R_L in series.

Therefore, the current flow in the circuit of Fig. 2 is

$$i_p = \frac{\mu e_g}{R_p + R_L}$$

The voltage developed across the load resistance, R_L, is the calculation of most importance, since it is this voltage which is applied to the grid of the next stage. The voltage developed across R_L may be determined by again resorting to Ohm's law. The voltage is equal to current (i_p) times

* *By Edward J. Bukstein in "Radio News."*

the resistance (R_L). Multiplying R_L by the equation already derived for i_p:

$$\text{Voltage across load} = E_{RL} = \frac{\mu e_g R_L}{R_p + R_L}$$

It is often advisable to rearrange this equation by dividing both the numerator and denominator by R_p:

$$E_{RL} = \frac{\mu e_g}{R_p} \bullet \frac{R_p R_L}{R_p + R_L}$$

Since $\dfrac{\mu}{R_p} = G_m$ or transconductance of the tube

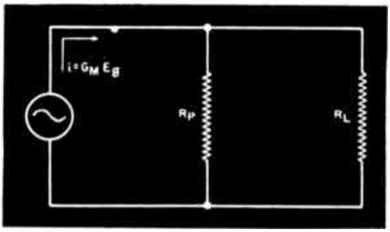

Fig. 3. Constant-current version of Fig. 1.

Then:

$$E_{RL} = G_m e_g \frac{R_p R_L}{R_p + R_L}$$

The calculations made thus far are based upon the equivalent circuit of Fig. 2. This equivalent circuit is known as the constant-voltage generator type and is most useful in making calculations where triodes are used. When pentodes are employed, however, another type of equivalent circuit is best suited to calculation. This is the constant-current generator type and is shown in Fig. 3.

In this circuit the tube has been replaced by a generator which causes a current, $G_m e_g$, to flow through the plate resistance and the load resistance in parallel.

The action of an amplifier varies with frequency; therefore, to completely understand the operation of the amplifier, one must study its behavior in the different frequency ranges. These frequency ranges are divided into three groups: low frequency, intermediate frequency, and high frequency.

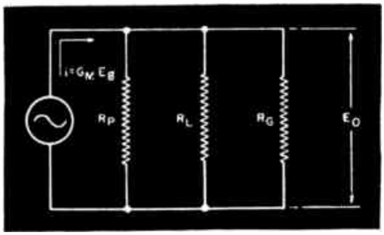

Fig. 4. Mid-band equivalent circuit.

The equivalent circuit of an amplifier operating in the intermediate frequency range is shown in Fig. 4.

The plate resistance (R_p), the load resistance (R_L), and the grid resistance of the following stage (R_g) are paralleled across the generator supplying the current ($G_m e_g$). The amplified output voltage of the stage is e_o.

At the low frequencies the reactance of the coupling condenser increases and becomes appreciable. It must,

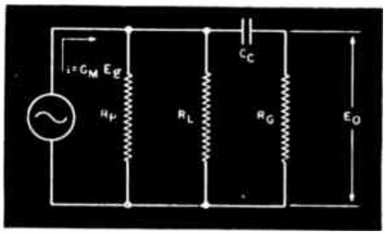

Fig. 5. Equivalent circuit for low-freq.

therefore, be considered in the circuit analysis as shown in Fig. 5.

It is the reactance of the coupling condenser, C_c, which limits the low frequency response of the amplifier.

In the high frequency range, the reactance of C_c is very small and is therefore negligible. However, at the high frequencies, the shunt capacity

(Continued on page 13)

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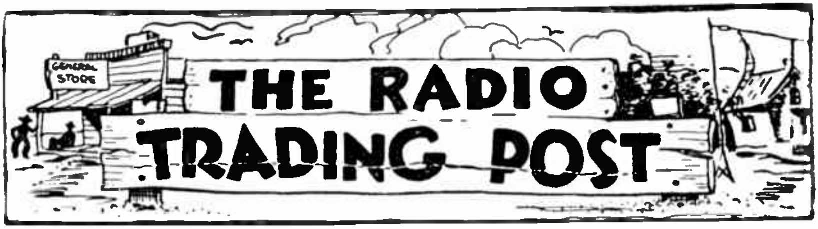

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(Continued on page 15)

Superstability at UHF *

To fully utilize the communication channels opened up in this range requires unusual attention to factors that control circuit constancy

PART II

Form-factor of the coil

In uhf coil design we must quickly recognize that we cannot design a coil per se. It must be part of a structure including the tuning condenser, the trimming and tracking means, the tube socket, etc. Connection leads (in the usual sense) must be entirely absent. The only band switch that can be tolerated is one where the coil terminals engage the socket terminals directly, and so on. The length and diameter of the coil must then be designed as part of this structure. Fortunately the form factor is not critical.

For use with a variable condenser, the coil must be long enough to reach from stator to stator. The condenser must be specially designed to go with it. Since the internal resistance in the tank circuit is only a few milliohms, no sliding contact can be used to ground the rotor.

For iron-core tuning, the length must be sufficient to insure a reasonable length of core travel, to permit the design of a reciprocating movement for a reasonably large dial. Coils of the dimensions shown are a good compromise to tune from 100 to 140 mc with a suitable low-loss core immune to temperature drift (in certain cores this may be below 2 parts in a million per deg.).

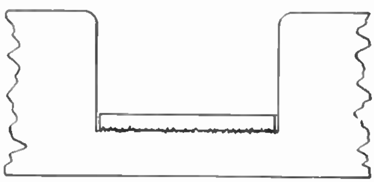

Fig. 6. Ceramic crystals lock strap in place

A little-recognized effect encountered in lengthening a coil is the enlargement of the "phantom turn" as shown in Fig. 7. The rectangle completed by the heavy dotted line is the phantom turn. It is true that the wire of the coil is in spiral form in going from A to B, but it also forms a field due to its progression from one point to another. This is usually ignored in coils of a hundred turns or so, but does co-operate with the loop formed by the tuning condenser to form an inductance as shown. This loop may easily be 10 per cent or more of the circuit inductance at 150 mc and is little affected by the iron core.

An undesirable effect results when such small coils are lengthened too much, in that the field of the coil ceases to be axial. The coil of Fig. 2 has a winding pitch of about 9 degrees. This tends to isolate the end turn from the group field to some

* *By S. Young White in Electronic Industries.*

extent, and the field may have a maximum intensity which is ten to fifteen degrees off the axis line especially when there is a tuning condenser up against one side. This must be allowed for when coupling the coil to something else, and also in designing the shield around the coil. This effect also increases the eddy current losses in the conductor. This is a clue for any engineer wishing to design SLF core tuning, as permeability tuning can be made absolutely SLF for about 1 : 1.25 tuning range.

The economics of making ceramic tubes for core tuning also dictates as short a coil form as possible. Every slight increase in length increases the probability of the tube developing camber—that is, ceasing to be straight.

Selection of coil diameter

The smaller the diameter the more compact the structure, the more concentrated the external fields, and the less chance of their coupling into surrounding metal to cause eddy current losses.

The resultant lessened inductance-per-turn allows a wider range of choice to the designer in tailoring his L/C ratio to fit the band in which operation is desired. The coil of Fig. 2, for instance, has a current sheet inductance of a little over 80 millimicrohenries. If we keep everything constant but vary the turns only, we can make up the table:

No. of turns	Inductance Mmh
1	9
2	36
3	82
4	146

Both Acorns and 9000 series tubes are quite sensitive to L/C ratios, and these inductance jumps are quite large. A coil one-quarter inch in diameter would allow much greater freedom, in choice of inductance in this range.

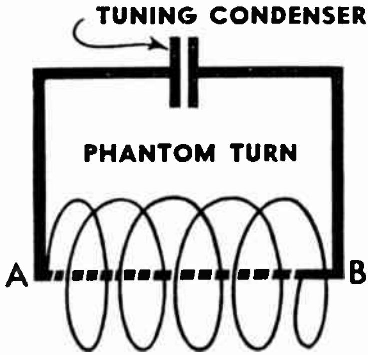

Fig. 7. Showing effect of lead connections external to the coil

If the coil is to be used with a variable condenser, the Q falls slowly as we reduce the diameter to a quarter inch, and then quite rapidly, and at about 1/8 in. is quite low. The optimum range of diameter is 200 to 425 mils.

Tuning control rod

Two other factors guide us if we are using core tuning, however. The core must be mounted somehow on an actuating push rod, and to obtain maximum tuning range, which can hardly ever reach 1:1.50, we must arrange the diameters of the core and coil so that the core fills the coil as much as possible. In superstable oscillators we must mount the core on a ceramic rod, a reasonable size being 3/16 in. so if we used a 250 mil core there wouldn't be much iron in the core.

It is difficult to produce ceramic tubes with a wall thickness below about 20 mils and still have freedom from ovality and camber so the core can freely slide through them. The smaller the diameter, the less room there is for the core, reducing the tuning range. Incidentally, the grooved form of Fig 3 is much easier to make, as the thick "lands" between the grooves reinforce the thin wall during firing.

These two considerations decided the choice of the diameter of the form shown in Fig. 3. This form works out quite well in practice and provides sufficient mechanical movement of the core to permit the design of a good dial mechanism.

Winding under tension

Most low resistance metals suitable for use as a conductor will expand about 18 parts per million per deg. C. The Invar type alloys expand only about 1 part, but because of their high nickel content cannot be used in the field of the coil. The magnetic loss in the nickel being very high, they must be well plated with silver or copper.

Only two possible coil-form materials have almost infinite secular stability—glass and ceramic. The ceramic expands 6 parts per million per deg. C. In severe mobile work, a temperature range of 100 deg. C. is encountered. Severe thermal working of the parts with such different expansion coefficients must be overcome.

The ceramic form is the most reliable member of the combination. The only way it can change dimension is by breakage, so we know its dimensions will be identical a thousand years from now. Its expansion of 6 parts per million per deg. C. is fairly low. It is much better to try to bring the expansion of the wire down from 18 to 6 than to attempt to make a coil form which would expand 18 parts. Although the latter would result in an assembly free from thermal working, it would have a much greater change in inductance.

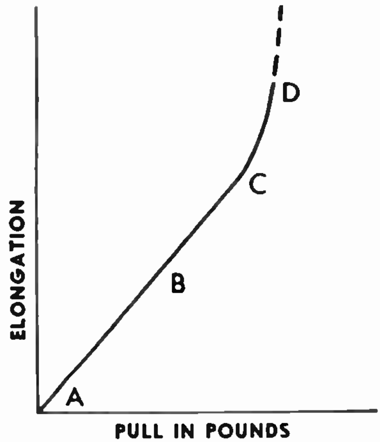

Fig. 8. Determination of winding tension

Better results are obtained by taking advantage of the elasticity of the metallic conductor. If we weigh and stretch a ten ft. length of the silver strap used on the coil of Fig. 3, for example, we can run the curve of Fig. 8. The length will increase in a linear manner at first, and if we remove the weights it will spring back to its original length. When we reach C on the curve, we have exceeded the elastic limit, and the strap will be permanently stretched. We note the midpoint of the curve, at B, and wind our coil with the wire under that tension. It will then hug the coil form like a rubber band, and while its cubic volume will continue to change at 18 parts per deg., its length will always be just sufficient to go around the form, the difference being taken up by the elasticity. It is thus truly the slave of the coil form.

If we use a conductor with a lower coefficient of expansion than the coil form, such as Invar with its 1 part per million, suppose we wind it on the form at room temperature without stretching. Then we cool the assembly to 40 below zero, and the coil form shrinks. This would leave the Invar winding unsupported, and of course its dimensions would change radically, as a spiral is the weakest possible geometric form. To avoid this, we must stretch the Invar on anyway, so its inside diameter would change 6 parts per million, the same as silver or copper stretched on. If we plate the Invar with silver, we find that we must put a dense, burnished coat at least 4 mils thick on it to prevent the flux from reaching inside to the high loss nickel.

If the conductor had no dimension and was the slave of the coil form, our formula for true inductance shows that the temperature coefficient of inductance of the coil would be 6 parts per million. Since the important term is d^2/l and since both expand 6 parts, the result is d, which is 6. The change in apparent inductance would of course be greater, as the dielectric constant of the coil form would also be increasing, at about 70 parts per million, increasing C_1 of Fig. 1 by that amount.

While winding under suitable tension will maintain the inside coil diameter at that of the form, the wire itself will still change in cross-section at the rate of 18 parts per million. In the coil of Fig. 2 the outside diameter of the winding will expand 7.8 parts per million by adding the contribution of the active copper to that of the more inert ceramic. The o.d. of the strap coil increases only 6.16 per million, as the strap is so thin it adds little to the total.

Current distribution shifts

There is probably some redistribution of the current through the wire of the coil wound with No. 14 due to the great increase in resistance of the copper, which is over 3,000 parts per million per deg. C. It does not seem to the writer, however, that the mean turn is shifted much more than that due to simple expansion of the wire. Probably the mean-turn shifts about 6.7 parts per million, since it does not follow from point 3 up to 3T (Fig. 4). The capacity between turns must increase, of course, due to increased diameter of the wire.

Having given the reasons for wishing to have the coil the slave of the coil form, let us look at the coil wound with No. 14. The wire is so large and strong that it is very difficult to wind it under sufficient tension, and at the same time keep the pitch constant. In practice when we attempt this, we are never sure the pitch is uniform. The wire is only in line contact with the form, and is far from its obedient slave. When we make a severe heat run it is quite usual to find that it has shifted somewhat in pitch. It also has the bad habit of sometimes trying to "wind up"—that is, to progress away from one end and pile up at the other. Numerous heat runs still leave us in doubt as to the actual inductance versus temperature change except that in general it is somewhat more than that of the strap coil.

Use ceramics for permanence

Strap wound on any of the uhf ceramics never shifts. The microscope tells the story shown exaggerated in Fig. 6. The surface of these ceramics consists of very tiny crystals, as sharp as church steeples! When a strap of comparatively soft metal is firmly laid down on them, they puncture the surface of the metal and firmly anchor the strap at all points. Another dividend is obtained from this anchoring. Losses in the ceramics are not negligible — they are not bad, but they do exist. By impaling the strap on these "spikes" we reduce the area of the metal in intimate contact with the ceramic, and the small air-gap introduced lessens the dielectric loss.

It was at first suspected that these "spikes" would work their way deeper into the strap, but experience has shown that with very hard drawn and rolled strap this did not happen, provided a certain minimum winding tension was maintained. This could be insured by passing a controlled current through the strap while winding, thus heating it up and obtaining a shrink fit when the wire cooled. In short, the cyclic stability of the No. 14 wire coil was always in doubt, but that of the strap coil was perfect.

Since the foregoing has shown the need for a conductor at least 4 mils thick, we attempted to burn on the winding. Taking silver powder in a liquid carrier, we heated the painted-on coil to reduce it to metallic silver, and then fuse the silver particles together by melting, all in a non-oxidizing atmosphere. The coating had to be so thick that surface tension did not suffice to hold it in place, and drip points developed. The melting point of silver was so high the ceramic tended to warp. We did not succeed, and it looks like a very difficult job.

Plating difficulties

Plating-on can be done in two ways—by masking off the form so that the spiral is put on directly, or by plating the form all over and then grinding a spiral right into the ceramic, thus forming the coil.

The grinding is extremely difficult in practice. Ceramics are very difficult to grind with small wheels, being nearly as hard as the wheels. Furthermore, it is almost impossible to hold them in a chuck or on a mandril. None of their dimensions is true and they wobble quite a bit. Thin-walled forms often break. The silver is left, moreover, with a very ragged edge.

Plating after masking runs into the difficulty that a very dense high-conductivity coat at least 5 mils deep is required. The so-called jeweler's plate takes a long time, and the density decreases with the thickness. We found it necessary to plate on three mils, then buff off about one mil, then plate again, and buff down--for a total of three times to get a good 5 mil coat. The surface is quite important - - it must be buffed smooth. Apparently a coat that looks "frosty" due to surface irregularities forces the current to run up and down hill, so to speak, and the length of path and resistance are increased.

Method unsatisfactory

Both plating and burning-on would run into the difficulty that the metal would be in intimate contact with all the crystals forming the surface of the ceramic, with consequent increased dielectric losses. The writer regrets to report failure with both systems. We never obtained a really high Q coil, and we finally gave up because of the very satisfactory behavior of the coil of Fig. 3.

It has doubtless been noted that in the foregoing discussion no provision has been mentioned for a tickler winding. Except for special circumstances, an ultra-audion type of oscillator offers many advantages—the type where the tuned circuit is connected between grid and plate of a triode. This offers the advantages of grounding the heater and cathode, a necessity when ac or fluctuating dc is used on the heater. The tube capacities are also placed in series, allowing the use of a larger value of tuning capacity to swamp out the tube capacity.

Performance in oscillator

The thermal stability of an oscillator using a carefully laid out circuit based on one of these strap coils is rather astonishing. The writer has been on the air with a receiver of standard make costing nearly $150. On the ten meter band the warm up drift lasted nearly an hour. A receiver at 125,000 kc using these strap coils warmed up to within 1 kc of final frequency in 55 sec., using acorn tubes.

A favorite heat run on our oscillators is from 70 deg. F. to 217 deg. F. The frequency shift at the end of two hours was three kc. This is considerably better than an amateur crystal.

The voltage stability was a change of 7 kc at 125,000 for a line voltage change of from 95 to 135 volts, with an unstabilized power supply.

Since the winding must be maintained in high tension, some unyielding support must be given the termination of the winding. This can well be done by arranging some additional structure to be integral with the coil form to take the strain and provide a mounting for the tuning condenser, the band switch contacts, the trimmer, etc. If it is found necessary to fasten the coil form to another ceramic piece, cement should not be used because it will "give" slightly with time. Also avoid lead glaze, as the losses are high. Use dust glaze that melts about 1700 deg., and as little as possible.

Summary

While much of the data here given is incomplete, and some is merely guesswork based on long experience, it is thought this original attack on the various problems of low-loss stable inductances should be helpful. The facts ascertained allow us to develop a very good coil which can be produced in quantity, is almost infinitely stable both in a cyclic and secular sense, has as high a Q as can well be obtained, and inductance vs. temperature change of only 6 parts per million per deg. C. With such a coil, tunable or fixed tune gear with crystal stability can be designed.

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Wide Band Amplifiers

(Continued from page 3)

of the circuit must be considered (Fig. 6). This shunt capacity, C_s, is the sum of three individual capacities: the output capacity of the tube, the circuit wiring capacity, and the input capacity of the following tube. The reactance of C_s becomes very small at the high frequencies, and since it is shunted across the circuit that is in parallel with R_p, R_L, and R_g, it tends to decrease the response at high frequencies, in the amplifier stage.

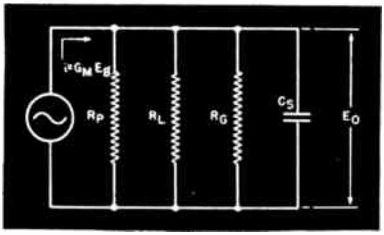

Fig. 6. Equivalent circuit for high-freq.

Having analyzed the action of the conventional resistance-coupled amplifier, we can now proceed to design the video amplifier. By making compensations to overcome the faults of the amplifier, we can extend the range to include frequencies from 30 cycles per second to several megacycles.

To compensate for the dropping off at high frequencies, an inductance is inserted in series with the plate lead. The action of this inductance is to increase the load into which the tube works, as the frequency is increased. In this manner it counteracts the ill effects of the shunt capacity. This type of compensation is known as shunt peaking and is illustrated in Fig. 7.

The value of the plate load resistor used is usually quite small (less than 2,500 ohms). By using this small value of load resistance, the gain at the intermediate frequencies is brought down to the level of the high frequency gain. Thus amplification is sacrificed to obtain a uniform frequency characteristic.

It can be proved mathematically that the amplifier's response, towards the higher frequency end, will be essentially flat (within 3 db.) up to frequencies of four or five megacycles if the following conditions exist. The value of the load resistor, R_L, should be equal to the reactance of the total shunt capacity at the highest frequency desired. The second requirement is that the inductive reactance, X_{cs}, and that X_L should be equal to load resistance, R_L.

Let us then proceed to design an amplifier to have a flat response up to

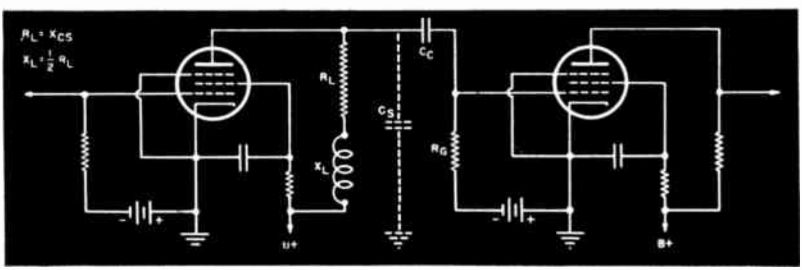

Fig. 7. Amplifier circuit diagram compensated for high frequencies.

five megacycles. Keep in mind that to obtain these results, R_L, must equal Xc? and that X_L should be equal to one half of R_L.

Suppose we design our amplifier using a 6AC7 tube followed by a 6AG7. These tubes are television pentodes having high transconductances.

First we must calculate the value of the total shunt capacity of the circuit. The tube manual shows the output capacity of the 6AC7 to be 5 $\mu\mu$fd. The input capacity of the 6AG7 is 12.5 $\mu\mu$fd. We can estimate the value of the stray capacity of the wiring to be about 15 $\mu\mu$fd. Since these three capacities are in parallel across the circuit they are additive and their sum is 32.5 $\mu\mu$fd. By employment of the formula for capacitive reactance,

$$X_c = \frac{1}{6.28\, f\, C}$$

we find the reactance at five megacycles to be 980 ohms. Since the desirable condition is that R_L should equal this value of reactance, we know that R_L should be 980 ohms.

The second condition is that the inductive reactance, X_L should equal one half of R_L or 490 ohms. Working back from the formula

$$X_L = 6.28\, f\, L$$
$$490 = 6.28 \cdot 5 \cdot 10^6\, L$$

$$L = \frac{490}{6.28 \cdot 5 \cdot 10^6} = 15.6 \text{ microhenries.}$$

$\therefore$ 15.6 microhenries is the value of inductance required.

The gain of this stage may be calculated from the formula

$$\text{gain} = G_m\, R_L$$

where G_m is the mutual conductance of the tube. In this case 9,000 micromhos.

$$\text{gain} = 9000\ 10^{-6}\ 980 = 8.82$$

The loss of gain in an amplifier at low frequencies is caused by the increased reactance of the coupling condenser. Why not increase the capacity of this condenser then? The answer is that the capacity is limited by the maximum allowable leakage which is inherent in larger condensers.

To compensate for these losses, the value of the load impedance into which the tube works, must be increased at the lower frequencies. The method of doing this is illustrated in Figure 8. The reactance of C_f is increased with a decrease in frequency.

The conditions which must exist in order that the amplifier's response shall be flat to the lowest desired frequency are as follows. The reactance of C_f should be one-tenth or less of the value of R_f. Secondly, the values of the two time constants $R_L C_f$ and $C_c R_g$ should be equal.

To design the amplifier to have a flat response down to 50 cycles, we first decide upon a value for R_f. Assume 5000 ohms. Knowing that the reactance of C_f should be one-tenth of 5000 ohms at 50 cycles, we work back in the formula

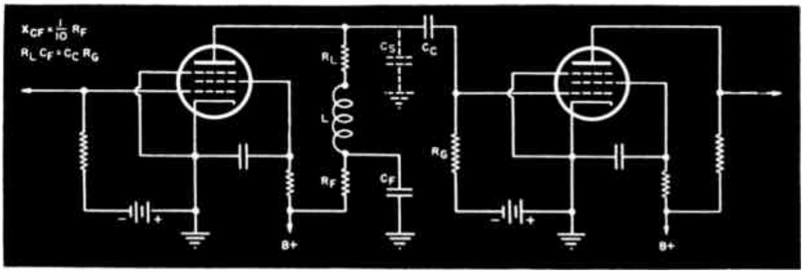

Fig. 8. Circuit diagram of an amplifier compensated for the low-frequency drop.

$$X_c = \frac{1}{6.28\,f\,C}$$

$$500 = \frac{1}{6.28 \cdot 50 \cdot C}$$

$$C = \frac{1}{6.28 \cdot 50 \cdot 500} = 6.37\ \mu fd.$$

6.37 μfd. is the value for C_f to give a flat response down to 50 cycles.

The second condition required is that R_1C_f equal C_cR_g. Knowing all these values but C_c we can calculate its capacity.

$$R_1C_f = C_cR_g$$

$$980 \cdot 6.37 = 500{,}000\ C_c$$

$$C_c = \frac{5800}{500{,}000} = .0116\ \mu fd.$$

The capacity of the coupling condenser should be .0116 μfd.

In practice it is wise to have the reactance of the screen by-pass condenser at the lowest frequency desired

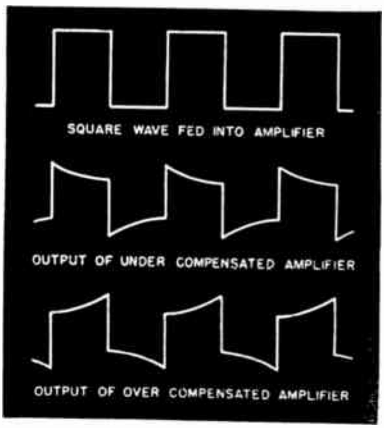

Fig. 9. Wave form for various compensations.

equal to one-tenth or less of the value of the screen voltage dropping resistor.

Having made the low frequency compensation, we can now expect that it will faithfully amplify squares waves (the criterion in judging the quality of amplifiers) with fundamental frequencies as low as 50 cycles per second.

If the low frequency compensation is not carefully calculated, the amplifier may be either over or under compensated as shown in Fig. 9.

Having been compensated for both high and low frequency loss, the amplifier will now have a nearly uniform response extending from 50 cycles to 5 megacycles. The amplification at the two limits being .707 of the amplification at the intermediate frequencies.

THE RADIO TRADING POST

(Continued from page 6)

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