SECTION 2

# ADVANCED PRACTICAL RADIO ENGINEERING

TECHNICAL ASSIGNMENT

## RADIO AND AUDIO FREQUENCY CHOKES


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221 E

# - TABLE OF CONTENTS -

## RADIO AND AUDIO FREQUENCY CHOKES

## SCOPE OF ASSIGNMENT

This assignment will cover the various type of inductances, both air-core and iron-core, that are employed in radio-frequency and audio-frequency applications as choke coils, to impede the flow of a-c through them into portions of the circuit where it is not desired to have these currents flow.

Another application is to employ them as reactances so as to develope a voltage across them when a-c is caused to flow through them. This is the case, for example, when so-called impedance coupling is employed in an audio amplifier.

Unfortunately, an inductance or choke coil has inevitably associated with it a certain amount of resistance in the coil windings as well as an equivalent resistance representing the eddy-current and hysteresis losses in the core, and further to complicate matters, a certain amount of capacity between turns and between layers of turns is also unavoidably present. As a result of the distributed capacity effects, the coil may show resonance, and at higher frequencies actually behave like a capacitor!

This assignment deals with these various factors, shows how they may be minimized by proper design, and then discusses the applications of such devices to radio circuits, as well as the use of R-C filters in amplifier stages.

## GENERAL CONSIDERATIONS

In both radio frequency and audio frequency circuit and vacuum tube applications it frequently is necessary to conduct both direct and alternating components of voltages and currents to or from a given point in a circuit without the two mixing except at that point. As an example, it is common practice in high power radio transmitters to feed the d.c. components of voltage and current to the vacuum tube plate through a circuit which will pass *only* direct current, and to take the radio frequency components of voltage and current from the vacuum tube plate to the load circuit by means of a connection which will block the direct current and pass *only* the radio frequency current. Thus the d.c. and R.F. components in this case mix *only* in the tube and not in the circuits; this is called "parallel feed". Many applications of this principle are found in radio apparatus; typical applications will be discussed in this assignment.

The problem of blocking d.c. from the R.F. circuit is simple; the latter is fed through a capacitor which completely blocks the direct current but which, by proper choice of capacity, passes the radio frequency with negligible opposition. By the use of a much larger capacitor, audio frequency components likewise can be passed while blocking the d.c. components.

Passing the direct current while at the same time blocking the radio or audio frequency components is equally simple in principle but not always so simple in practice. Methods of accomplishing this employ series inductance (commonly known as a "choke"), series resistance, and sometimes bypass capacitors in conjunction with L or R. These methods will be discussed.

*GENERAL USE OF THE CHOKE.*—When used to block radio or audio frequency components but to pass direct current, the inductance is called a "radio frequency choke" (RFC) or an "audio frequency choke" (AFC), whichever is appropriate. The operation of the two are similar, but at the higher radio frequencies some characteristics of coils which are not particularly important at the lower audio frequencies become of major importance.

Consider the problem expressed in general terms above. It is desired to apply at a certain point in a circuit a d.c. voltage and at the same time a radio frequency voltage, and it is necessary that the radio frequency current *variations* entering the d.c. supply source be kept to a minimum; it also is necessary that the d.c. voltage be isolated from the radio frequency circuit. The direct current may be kept out of the alternating current circuit by means of a capacitor. (See $C_1$, Figure 1).

It is necessary to keep the A.C. variations out of the circuit of direct current generator G, but at the same time to force the alternating current through R, the load resistor. With switch S open and alternator AC operating, the alternating voltage will force an alternating current through the capacitor and the load circuit. If switch S is now left open and switch $S_1$ closed, there will also be a d.c. voltage forcing a direct current com-

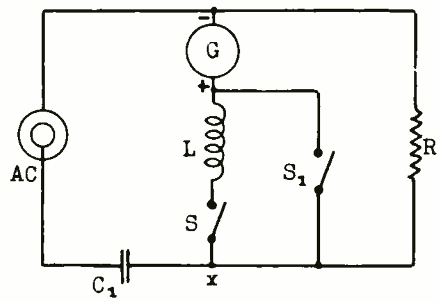


Fig. 1.—Circuit analysis for separating a-c and d-c components.

ponent through the load circuit. Since the d.c. generator is also connected across the alternator it is apparent that there will be an a.c. component flowing through the direct current generator, alternately adding to and subtracting from the direct current through the generator. This condition is very undesirable as the surges will expend power that would otherwise be usefully expended in the load; also there will be a good chance of this additional current damaging the d.c. generator. (In a radio circuit, Load R may represent the plate-filament resistance of a vacuum tube.)

To prevent the a.c. variations from taking place through the d.c. generator, the ideal plan would be to connect a very large value of low-resistance inductance between point x and the generator. If switch $S_1$ is now opened and switch S closed, the inductance will be connected in series with the load and the d.c. generator, but NOT between the alternator and the load. Since the effect of inductance is *to prevent current variations through it,* it would seem that it is only necessary to make the value of L large enough in order to obtain any desired degree of attenuation or choking effect upon the alternating current variations, and therefore keep the a.c. component completely out of the d.c. circuit without opposing the flow of the direct current through the load circuit.

If a perfect inductance or a coil containing *only* inductance and a nominal amount of resistance could be built, that would be true, and the greater the inductance the greater the choking effect would become. Such a condition is not too difficult to obtain practically at frequencies within the audio band, that is, at low frequencies, although even at these frequencies problems arise, as will be explained later in this lesson.

*DISTRIBUTED CAPACITY OF COIL.*— When applying this principle to radio frequencies and inserting a large value of inductance in order to get large a.c. attenuation between the d.c. power supply and the load, it frequently is found that the circuit acts as if no inductance were present; in fact, on test the circuit may act, so far as the radio frequency component is concerned, as if a CAPACITY were connected between point x and the generator. If at this point the inductance is further increased by adding turns to the coil, it will be noted that the condition becomes still more aggravated and instead of greater opposition to the current variations, the current variations through the d.c. circuit are increased. It also will be observed that if the frequency of the alternating current is increased, leaving the same value of inductance in the d.c. circuit, the current variations through the d.c. circuit will increase. This indicates that the coil is not acting as an inductance, but instead *is acting as a capacity.*

From this it will be seen that the principle of increasing the value of inductance almost indefinitely to increase the choking effect, while it may be used successfully (within limits) at audio frequencies, cannot be directly applied to radio frequency circuits. (It should be mentioned here that even at audio frequencies, usually above 5000 cycles, precautions in design must be taken to avoid parallel resonance in audio frequency chokes and transformers).

The failure of the coil to act under all conditions as an inductance is due to the fact that a coil has not only inductance, but ALSO CAPACITY DISTRIBUTED THROUGHOUT THE WINDING BETWEEN ITS TURNS.

The inductance of a coil depends to a large extent upon the shape of the coil. In a similar manner the distributed capacity of a coil also depends to a large extent upon the shape of the coil.

The effect of the distributed capacity is shown in Figure 2. The capacities between the individual turns are in series and the total capacity is ACROSS THE ENTIRE COIL. This in effect forms a parallel circuit, the inductance forming one branch and the distributed capacity of the coil forming the other branch. Thus at frequencies at which the coil distributed capacity is effective, the coil must be treated as a parallel circuit composed of inductance and capacity instead of as a simple inductance.

It is shown in the study of parallel circuits that a given LC circuit may act as a resistance, a capacity, or an inductance, its mode of operation depending entirely upon the frequency at which it is operated. If the parallel circuit is operated at its resonant frequency it acts as a high value of resistance, at frequencies higher than resonance as a capacity, and at frequencies lower than resonance as an inductance.

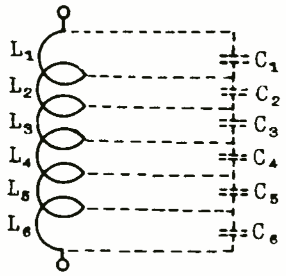


Fig. 2.—Distributed capacity of a coil.

Since every coil possesses both inductance and capacity, then every coil must also have some natural resonant frequency. With the coil thus forming a parallel LC circuit having a resonant frequency, it is apparent that the coil may be placed in the circuit and, by adjusting the frequency, caused to act as either resistance, capacity, or inductance.

*FREQUENCY-IMPEDANCE CHARACTERISTIC.*—In most tuned parallel circuits, as shown in another assignment, a somewhat sharp impedance curve is desired, that is, one which rises to a high value at resonance and falls off sharply at frequencies on both sides of resonance. This condition is obtained by so selecting the circuit constants that both $X_L$ and $X_c$ are reasonably small, that is, by the use of relatively small inductance and large capacity.

In the radio frequency choke very different characteristics are desired. A transmitter usually is designed to operate over a comparatively wide band of frequencies, and even if designed for only one frequency may be tuned over a considerable range of frequencies during the process of calibration. The choke should act as an inductance and be fairly effective over the entire frequency range. This will necessitate a circuit having high impedance over a wide band of frequencies.

In the ordinary tuned circuit, due to the comparatively low value of reactance in each branch, the current in each branch is relatively large, the actual amplitude of course depending upon the applied voltage. At resonance the two currents counteract each other and the total resulting current is almost zero; but as soon as the voltage is applied at a frequency other than the resonant frequency, with the two current amplitudes large, one increasing rapidly, as the other decreases rapidly the difference in current amplitudes results in a large current in the external circuit.

If, however, a parallel circuit is so designed that the reactance of each branch is many thousands of ohms, then the current through each branch will be small. Assume that at resonance both $X_L$ and $X_c$ equal 20,000 ohms. The resistance may be considered negligible in this case and the resulting impedance will be in the order of several hundred thousand ohms. Assume an alternating voltage of 5000 volts. The current in each branch of the circuit will be .25 ampere. The resulting current in the external circuit will be almost zero.

If the frequency is now decreased twenty-five per cent the inductive reactance will become 15,000 ohms and the current through $X_L$ will be $E/X_L$, 5000/15,000 or .333 ampere. The same decrease of frequency will increase the capacity reactance to 26,667 ohms, the current through $X_c$ now equalling $E/X_c$, 5000/26,667 or .188 ampere.

The resulting current in the external circuit is the difference between the two branch currents: $I = I_L - I_c = .333 - .188 = .145$ ampere. The total impedance equals the applied voltage divided by the external circuit current: $Z = E/I = 5000/.145 = 34,483$ ohms *which appears as inductive reactance.*

In contrast with the sharply tuned parallel circuit discussed in the preceding lessons, this parallel circuit, while possessing the same high impedance characteristic at resonance, also has impedance of more than 34,000 ohms as far as twenty-five per cent from the resonant frequency.

*CORRECT OPERATING FREQUENCY.*— If the frequency had been increased the same amount above resonance as it was decreased below resonance, the impedance would still be more than 37,000 ohms *but the circuit would then be acting as a capacity instead of as an inductance.* This condition is usually undesirable but the choke ordinarily may still be used because of its high impedance, if the impedance of the load circuit is well below the impedance of the choke. With such a coil, a considerable frequency variation may be permitted before the choke becomes useless, because of its high impedance over a large frequency range. If the coil were designed for even larger resonant reactances, that is larger inductance and smaller distributed capacity, it would be effective over an even wider range of frequencies. *The most effective operating frequency of a choke, where it will act as a very large inductance, will be at a frequency just slightly below its resonant frequency.*

To be most effective the choke should be designed to have a resonant frequency SLIGHTLY HIGHER THAN THE FREQUENCY AT WHICH IT IS TO BE OPERATED, and should therefore be operated at a frequency just lower than its resonant frequency. For example, a choke coil to be effective at an operating frequency of 500 KC/s might be designed to have a resonant frequency in the order of 525 KC/s or 550 KC/s. This value usually is not critical.

There are circuits in which the R.F. choke *must* be operated at a frequency lower than its resonant frequency, that is, as an inductance. One such circuit is a crystal controlled oscillator in which the plate circuit is untuned, consisting simply of a choke coil. For this type of oscillator to oscillate the plate load must be inductive so that the choke which constitutes the plate load circuit *must* have a natural frequency higher than the crystal frequency. This circuit is shown schematically in Figure 3.

The next point to consider is how to obtain the desired characteristic when constructing a choke coil. With an ordinary tuned circuit a very sharp impedance curve may be obtained by using a small inductance and a large capacity. To obtain a very broad and high impedance curve,

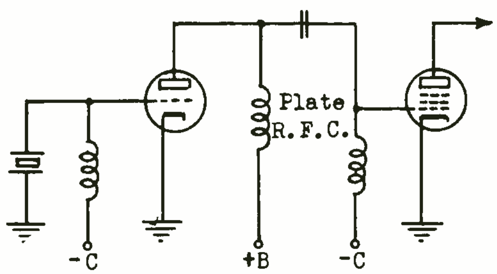


Fig. 3.—Use of an inductive plate load for a crystal oscillator.

the design should be reversed. In order to obtain, at any frequency, a large inductive reactance, the maximum amount of inductance must be used. The limiting factor on how much inductance it is possible to use at any given frequency is the distributed capacity of the coil. As the inductance is increased by increasing the number of turns, the distributed capacity of the coil combines with the inductance to form an LC product which of course results in resonance at some frequency.

To be most effective the choke should act as an inductance, therefore it must have a resonant frequency higher than the frequency at which it is to be operated. But as the inductance is increased, at some point, due to the effect of the distributed capacity, the LC product will be such as to produce a resonant frequency equal to the desired operating frequency. If turns are added beyond that point the coil will assume the characteristics of a capacity, an undesirable condition.

It is evident that in order to be able to use maximum inductance, the coil must be designed to have minimum distributed capacity.

An approach to the situation mathematically is from the viewpoint of an equation for the approximate resonant impedance of a parallel circuit, in which the resistance is practically all in the inductive branch. This is the condition approximated in most choke coils. The equation expressing the resonant impedance is approximately $Z = L/CR$.

With R maintained at a constant or negligible value, it will be seen that an increase of L and a decrease of C will both be in the proper direction to increase Z.

Another feature of the parallel circuit which makes it desirable to use large values of $X_L$ and $X_c$ is the condition existing at resonance if $X_L$ and $X_c$ are small. With the high plate voltages commonly used in transmitters and the comparatively low resistance of the coil, the circulating current at resonance may be large enough to burn up the plate choke. This was a common occurrence in older types of transmitters where the choke design was such that the inductance was comparatively small and the distributed capacity correspondingly large. As the transmitter, during the process of adjustment, was tuned through certain frequencies, chokes frequently were burned out due to the large circulating currents through the windings. This condition is not encountered nearly so often with modern choke coils.

*STANDING WAVES.*—Standing waves represent a phenomenon common to all LC circuits in which the capacity or inductance (or both) is distributed over the linear dimensions of the circuit and not lumped. A common example of such a circuit is an antenna; another is an improperly terminated transmission line over which energy is transferred from one point to another.

Consider first the formation of standing waves on a transmission line. If such a line is terminated by a load having resistance equal to the characteristic impedance $Z_o$ of the line, (to be explained in a later assignment) all the energy reaching the receiving end of the line will be dissipated in the terminating resistance, there will be no reflection and no standing waves. An impulse voltage progressively appearing equally at all points along the line (assuming a line short enough that attenuation may be neglected), and will be completely dissipated in terminating resistance $Z_t$. If a high frequency alternating voltage is applied at the sending end (see Figure 4), each alternation will the receiving end of the line is open-circuited. Start an impulse of energy along the line from the sending end. Such an impulse moving along a line consists of equal parts of magnetic and electric fields, the electric field being due to the voltage, the magnetic field to the current. When the impulse, which is represented by current and voltage in the line, reaches the open end of the line, there is no resistance in which its energy can be dissipated; further, the current at this point must drop to zero because current cannot flow in an open circuit. This results in a sudden collapse of the magnetic field component of the impulse and this collapsing magnetic field, just as a moving field in a generator, creates an additional electric field. This second electric field adds to the original electric field so that the voltage at the open end of the line is greater than the original voltage.

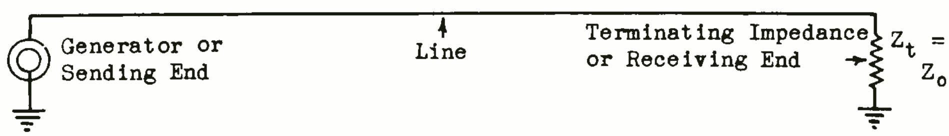


**Fig. 4.—A transmission line terminated in its characteristic impedance exhibits no reflections from the far end.**

travel progressively along the line; a voltage indicating device moved progressively along the line will indicate the same voltage at all points even though the line may be several wavelengths long.

Now consider the conditions existing in such a line if the termination impedance is disconnected and

This increased voltage starts an impulse of energy back along the line in the opposite direction, the phenomenon being called "reflection". Since there is nothing in an open circuit to absorb energy, the reflected impulse, which assumes the form of equal electric and magnetic fields, will have the same amplitude as the original pulse. Thus at the open-circuit end of the line the voltage will be double the original voltage. The voltage of the reflected wave starts out in phase with the original voltage but the current in the reflected wave will be opposite in direction to the original current at the reflecting point.

The result of the failure of the energy to be dissipated at the end of the line and the consequent reflection back along the line, when a continuous source of A.C. energy is applied—as in Figure 4—is a series of "standing waves" of energy along the line as shown in Figure 5.

of given length because the wavelength of the energy will be shorter.

A similar curve could be drawn for the current in the line. Since at the extreme end of the line (open end) the current must be zero while the voltage is maximum, the current curve will be displaced 90° ($\lambda/4$) from the voltage curve all along the line. Thus the current will be maximum at points of zero voltage and zero at points of maximum voltage.

It should be pointed out that for the development of substantial energy in the line in the form of standing waves, the length of the line and the frequency must be such

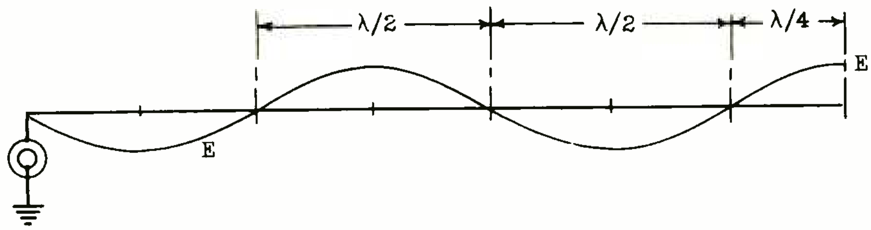


Fig. 5.—Standing-wave phenomena on an unterminated transmission line.

The voltage wave will have maxima at the open end of the line and at all even half-wavelength points from the end along the line. At one-quarter and all odd quarter-wavelength points along the line (from the open end) the voltage will pass through zero and reverse.

It will be seen that for a given frequency the number of voltage maxima or minima will depend on the length of the line. Conversely, *for a given length of line the number of voltage maxima and minima will depend on the frequency.* At a higher frequency a greater number of such points will exist along a line

that the electrical length is an odd number of quarter-wavelengths.

The phenomena would be similar if the extreme end of the line were grounded except that the voltage and current curves would be displaced 90°. Reflection will still occur but at the grounded receiving end the current will be maximum and the voltage zero. Such a line must be an even number of quarter-wavelengths long for the development of substantial standing waves.

Now apply this theory to a coil. If the single wire line of Figure 5. is replaced by a long coil of wire *having equivalent LC product* and the coil is connected at one end to a source of high frequency energy as in Figure 6, the result will be as shown. The transmission line is one example of distributed L and C. In the coil the L and C values per linear unit of length are greater than in the straight wire but in principle the two are identical.

One way of showing this effect is to wind a coil several feet long on a form of small diameter—for example, one inch—and place a section of neon tubing parallel and close to the coil. Energize the coil with an R.F. oscillator whose frequency can be varied over a wide range. As the oscillator is tuned through the frequencies at which the coil represents an odd number of quarter-wavelengths, the neon tube will glow at the points of voltage maxima as shown in Figure 6. If the extreme end of the coil is grounded, the voltage maxima will be displaced 90° and the oscillator must be tuned so that the coil represents an even number of quarter-wavelengths. Just as in the long line, current maxima will occur at the points of zero voltage. If a long section of neon tubing is not available, the voltage maxima and minima may be located by moving a small neon bulb progressively along the coil. Brightest glow will be at points of voltage maxima with no glow at voltage minima.

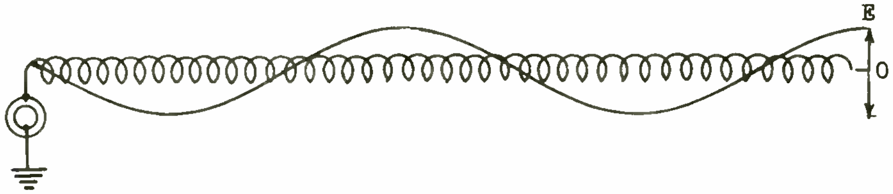


Fig. 6.—Standing-wave phenomena in a coil having distributed inductance.

Now the principle as demonstrated in Figures 5 and 6 does not change as the length of the coil is reduced, its diameter increased, or the shape and dimensions of the coil changed to meet any desired specifications. So long as an alternating voltage is applied to one end of a coil and the frequency made such that the coil is resonant, points of maximum current and voltage will occur in the winding. *The frequency may be that of the resonant frequency of the coil or, as in Figure 6, it may be one of the harmonics of the coil's natural frequency.* In either case the voltage may be such as to break down the insulation or the current may reach sufficiently high peaks to burn out the winding. Fig. 7 illustrates the actual connection of a plate choke for a transmitting vacuum tube. The d.c. component of plate current is fed to the tube from the source (d.c. generator or high voltage rectifier) indicated by +B through the choke coil marked R.F.C. In this case capacitor C, a relatively large bypass capacity, effectively grounds the lower end of the choke for radio frequencies. The alternator of Figure 6 is replaced by the vacuum tube, the high

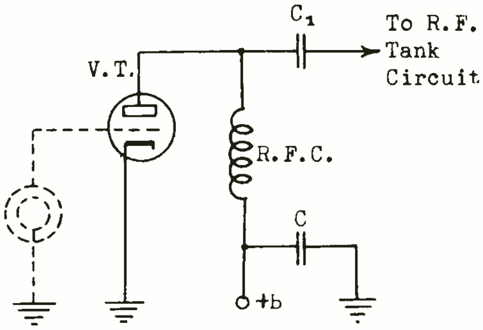


Fig. 7.—Use of r-f choke in parallel plate feed.

R.F. voltage being developed at the tube plate because of the excitation voltage applied to the grid. R.F.C. in Figure 7 will have standing waves set up in it just as in the coil of Figure 6 if the frequency applied to the grid of tube V.T. has the necessary relation with respect to the natural frequency of coil R.F.C.

Figure 8 illustrates another characteristic of the choke coil which must be taken into consideration. Such a coil at resonance and at all ODD harmonic frequencies acts as a *parallel resonant* circuit, that is, as a very large value of resistance. At all EVEN multiples of the resonant frequency of the coil, however, it exhibits the characteristics of a series resonant circuit; that is, it acts as a low value of resistance. This latter condition may have two serious effects: First, the current due to series resonance may be sufficient to damage the choke; second, the choke may offer such low R.F. impedance that it will effectively short-circuit the R.F. tank circuit.

The choke should of course be so designed that at no frequency at which the transmitter is to operate will it approach series resonance. To minimize the possibility of trouble developing from this source during the various processes of tuning the transmitter, the series selectivity of the choke should be made as great as possible. It will be remembered that a series circuit offers maximum selectivity when it is composed of large L and small C. This, as has been shown, is also the desired condition for the large and broad impedance characteristic desired in a choke when operating near parallel resonance. Thus from every point of view the most effective choke coil for a given resonant frequency is one having the greatest possible inductance and the minimum capacity.

This condition is shown in Fig. 8, curve $Z_1$ representing the impedance curve for a coil having large distributed capacity and a correspondingly small value of inductance. Curve $Z_2$ represents the impedance curve for a coil having small distributed capacity and correspondingly large inductance. Both coils are assumed to have the same resonant frequency.

In the case of $Z_1$ at $F_2$, $F_4$ and $F_6$ and all *even* multiples of $F_r$, (the resonant frequency), the circuit acts as a very low value of resistance, and as a comparatively low value of reactance for a considerable frequency range on either side of these points. Therefore there will be a fairly wide zone of low impedance on each side of the even multiples of $F_r$ where the choke cannot be used.

be operated over a greater frequency range than can the coil represented by $Z_1$, and the series resonance danger points will cover a much

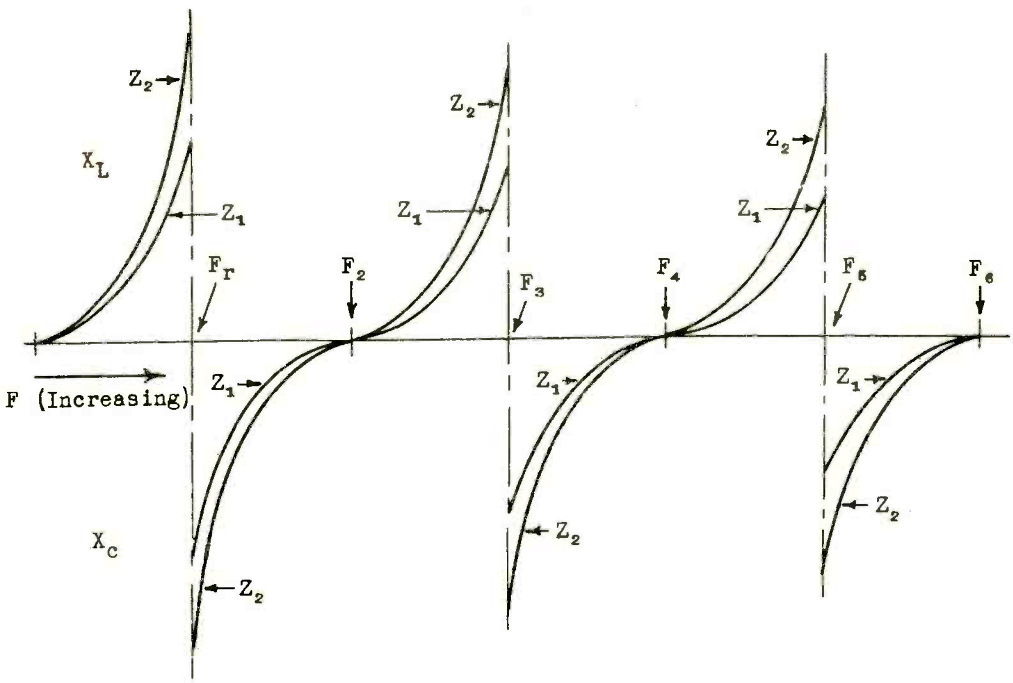


Fig. 8.—Alternate series and parallel resonance phenomena in a distributed circuit, such as a coil.

In the case of $Z_2$ the impedance at the resonant frequency and at ODD multiples of $F_r$ is considerably higher than is the case with $Z_1$. At the even multiples of $F_r$, even though at the exact points of $F_2$, $F_4$ and $F_6$, the series resonant points still exist, the impedance curve rises more steeply than does curve $Z_1$ and the very low impedance zone for that reason is much more narrow.

The coil represented by $Z_2$ can smaller frequency range.

## CONSTRUCTION AND DESIGN FEATURES.

*DESIGN OF EFFECTIVE CHOKE COIL.*—It is apparent that from every viewpoint the really effective choke is one designed to have the lowest possible distributed capacity and the maximum inductance, consistent with the desired resonant frequency. The remaining question is, how to design such a choke coil.

Before it is possible to design a coil having low distributed capacity it is first necessary to understand how the shape and dimensions of the coil enter as factors in the distributed capacity, and what factors determine the distributed capacity of the coil.

In a single layer coil, the distributed capacity is roughly proportional to the radius and practically independent of the number of turns and the length. For a closely wound solenoid the distributed capacity in micro-microfarads is approximately equal to .6 the radius in centimeters.

The capacity of a coil is determined largely by the spacing between turns in which a difference of potential exists. Therefore a single layer coil will have lower capacity for given diameter of winding because the spacing between N number of consecutive turns is greatest, for a given wire size, in a single layer winding.

ted capacity and ease of assembly.

The single layer winding on a form of small diameter has one marked disadvantage, however, when used at any but the higher frequencies. The disadvantage lies in the space occupied by such a coil. With low distributed capacity and large inductance, many turns will be required for a coil that is to have a low resonant frequency. This will mean a long cumbersome coil occupying considerable space, particularly when the current to be carried is large with the necessity for a comparatively large size of wire.

*MULTI-LAYER WINDINGS*.—If the coil is wound in ordinary layer form, from one end to the other end, back again, etc., (See Figure 9) the capacity of the coil becomes excessive. The effective capacity effect is much greater when a high numbered turn is brought back alongside a low numbered turn because the voltage between turns is greater. For example, a coil twenty one turns long and four layers deep wound from one end to the other and back, will have

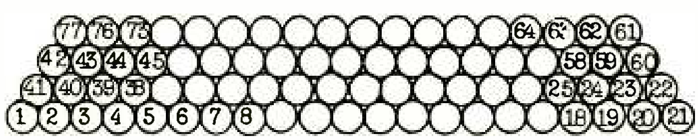

Fig. 9.—Ordinary layer wound coils would have excessive distributed capacity.

From this it would seem that a long coil of small diameter with a single layer winding should form the ideal choke. At the higher frequencies this type of coil is extensively used because of its low distribu-

turn number 41 alongside turn number 1, turn number 60 alongside turn number 22, and turn number 77 alongside turns number 1, 41 and 42. This is shown approximately in Fig.9 which represents a cross-section of a simple layer winding. This type of winding, while producing large inductance, also has extremely large distributed capacity.

A much better compact form of winding for all purposes in which large inductance is required with small distributed capacity, is the bank wound coil. This winding is illustrated in Figure 10. Here the high numbered turns are considerably removed from the low numbered

Second, a coil of large inductance has quite large dimensions due to the space occupied by the form on which it is wound. Hence in recent years such coils have been replaced to a large extent by machine wound self-supporting inductances such as the "Universal Wound" coil.

This coil, shown in Figure 11, is similar in general shape to the coil of Figure 12 except that it is so wound as to be self-supporting.

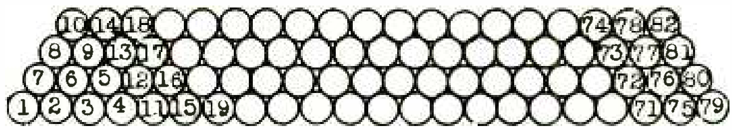


Fig. 10.—A bank wound coil has less distributed capacity because the voltage difference between adjacent turns is lower.

turns. Such a winding produces a coil with as much inductance but much less distributed capacity than in the case of the layer-wound coil of Figure 9.

The bank wound choke coil has been quite extensively used as it provides comparatively large inductance with fairly low distributed capacity for a specified resonant frequency, thereby forming an effective choke. A coil of this type can be kept within smaller dimensions than a single layer coil having the same inductance.

A bank wound coil has certain disadvantages: First, its type of winding is not adaptable to machine production; a coil of large inductance is expensive because of the skilled labor involved, and because of manual production it is difficult to hold production tolerances close.

That is, the turns overlap in such a manner that, when tightly wound by

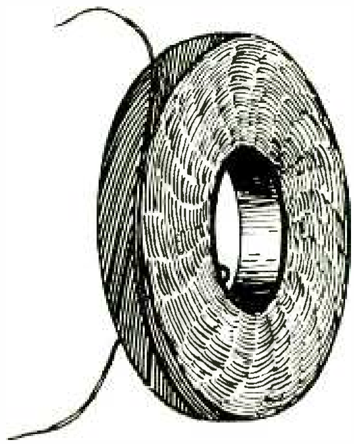

Fig. 11.—A self-supporting universal wound coil.

machine, the entire winding locks together in a compact assembly. The distributed capacity of such a coil is small and is in the order of that shown for the slot-wound coil in the next section. This type of winding is adaptable to a large range of inductance; it is used, because of its small physical dimensions, for compensating coils of a very few microhenries in television video amplifiers, as windings for receiver R.F. and I.F. coils, and for choke coils in the order of hundreds of millihenries in low frequency transmitters.

It may be desired to use some kind of binder to hold the wires in place, particularly in the case of self-supporting windings. Very frequently a binder is used on the top layer of such a coil but the entire winding not impregnated. A binder usually results in some increase of R.F. resistance but in the case of choke coils this is not important. Collodion is one of the best binders from the viewpoint of minimum increase of R.

To summarize the characteristics of a good R.F. choke: The R.F. choke coil must have an impedance of many thousands of ohms over a considerable range of frequencies. It should have a resonant frequency slightly higher than the frequency at which it is to be operated. It must be wound with a size of wire that will safely carry the direct current of the circuit in which it is to be used.

To meet the requirements for a good choke coil *the inductance should be as large as possible and the distributed capacity as small as possible.* The maximum inductance it is possible to use in any coil and still keep within a specified minimum resonant frequency depends directly upon the distributed capacity of the coil. The smaller the distributed capacity the larger the inductance it is possible to use. *The distributed capacity of a coil for any given resonant frequency depends largely upon the shape of the winding.*

*SLOT WINDING.*—Some years ago engineers were confronted with the necessity for designing a coil to have the maximum of inductance for a given resonant frequency and a distributed capacity lower than that of any previously designed types of coils. The result was a coil wound with a small size of wire in a deep slot cut in an insulated form. The form of the winding is shown in Figure 12.

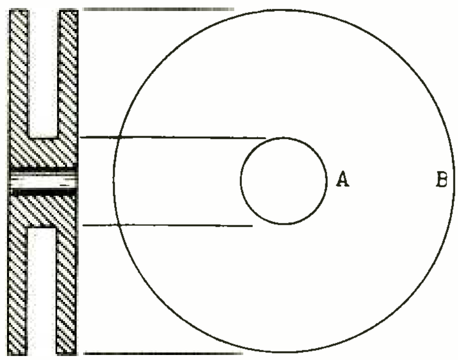


Fig. 12.—Slotted Arm used in slot winding.

Calculation and measurement demonstrated that the distributed capacity of a coil of this design is very nearly equal to the capacity of two rings, one within the other, one ring having a diameter of circle A, the inside of the winding, the other ring having a diameter equal to that of circle B, the outer surface of the winding; both rings have a width equal to the width of the winding in the slot.

It will be seen that with this form of winding, one end coming out from the center and the other end from the outside of the coil, the capacity of the coil will be a function of the diameter of both rings, the width of both rings, and the distance between the two rings.

The capacity of any capacitor having opposing plates of greatly different areas depends largely upon the area of the smaller plate. It is therefore important that the smaller ring, that is, the inside diameter of the coil, be as small as possible. Since the area of the ring depends not only upon its circumference but also upon its width, it is necessary that the coil be as narrow as possible. These requirements are met by making the slot narrow and the inside diameter small.

As the width of the slot is decreased, to obtain the same number of turns it is necessary to wind higher in the slot causing the outer turns to be further from the inner turns, thus decreasing the distributed capacity and allowing more turns to be used, this in turn increasing the inductance. This design of course can only be carried to the point where the LC product does not exceed the allowable maximum for the operating frequency at which the choke is to be used. Since L increases approximately as the square of the increase in turns, this procedure cannot be carried out indefinitely for a given frequency. Also there is a practical limit to the ratio of outside diameter to width that can be used where a quite large inductance is required.

From the above it will be seen that a highly effective choke coil will be one wound in a narrow slot with a small inside diameter. This type of coil is found to have a distributed capacity, for a given amount of inductance, well below that of any earlier type of coil. Such a coil, while not originally designed for use as a radio frequency choke, has proved exceptionally efficient for that purpose. This same principle is applied in the self-supporting universal wound coil shown in Fig. 11.

*SECTIONAL CHOKE COILS.*—When it is desired to use a universal wound choke in the plate circuit of a high power vacuum tube for low and intermediate frequencies, another problem is encountered. The d.c. component carried by the choke is necessarily large. This necessitates the use of comparatively large size wire. For use at intermediate or low frequencies the large LC product, with the low distributed capacity, requires a coil having a large number of turns. This, in conjunction with the large wire, will result in a coil of an impractically large diameter if the thickness of the coil is kept small. If the coil is decreased in diameter and the width of the winding increased, the benefits of the particular type of winding will be reduced.

This difficulty can be overcome by building the coil in sections, the several sections mounted on an insulated rod and connected in series, *the high potential end of one section connecting to the low potential end of the succeeding section.* (The high potential end of a choke is the end where the greatest choking action takes place, i.e., where the inductance per unit length of winding is the greatest. This is in the center of the coil where there are the greatest number of turns per unit length of conductor).

One arrangement of such a choke coil is shown in Figure 14. Figure 13 shows the distribution of inductance and capacity of the entire choke. Each section has its own inductance and its own distributed capacity, the total inductance being the sum of the individual inductances plus the mutual inductance. This causes the inductance of the combination to be large. The capacities $C_a$, $C_b$ and $C_c$ are in series, their total capacity being equal to the reciprocal of $1/C_a$, $1/C_b$, and $1/C_c$.

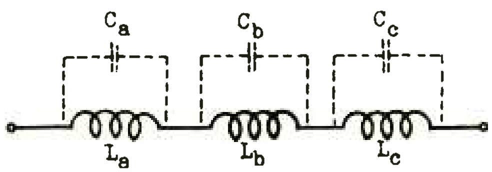


Fig. 13.—Equivalent circuit for a sectionalized coil winding.

This type of winding will have large inductance, small distributed capacity, and therefore large inductive and capacitive reactance, making it an effective choke.

In common with all circuits composed of inductance and distributed capacity, such a coil has series resonant points at the even multiples of the fundamental frequency, i.e., at two, four, six, etc. times the fundamental frequency of the coil. However, as the values of inductive and capacitive reactance are large the series resonant points become narrow and the workable range of the choke is large.

From this type of choke for the intermediate frequencies, a still more effective choke for high frequency operation has been designed.

The principal fault of the coil combination of Figure 14 is the fact that the individual sections of the choke have resonant frequencies of their own entirely separate from the resonant frequency of the entire choke, and in addition to the narrow series resonant points of the entire choke, each section has certain series resonant frequencies of its own. This, however, is compensated for to a large extent by the fact that series resonance of one section ordinarily will not be a series resonant frequency of the other sections so that a certain amount of mutual protection is offered by the several sections of the choke in series.

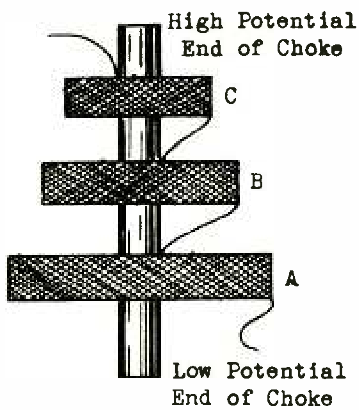


Fig. 14.—Practical arrangement of windings in a sectionalized coil.

For intermediate frequency operation where the choke is operated at one frequency or over one comparatively narrow band of frequencies, it is not difficult to avoid the series resonant points, as the only power applied to the choke coil at such frequencies will be at some high harmonic of the fundamental frequency; the harmonic voltage being undesired ordinarily will be small due to the steps taken to suppress it.

In the case of high frequency crystal controlled transmitters where the high frequencies are obtained by frequency multipliers, the conditions are greatly different. A power amplifier stage may be designed to operate at a specified fundamental frequency, double, and four times the fundamental frequency, the different frequencies being obtained by circuit adjustments. If it is desired to use an amplifier stage to cover such a wide band of frequencies the number of adjustments in shifting from one frequency to another should be kept to a minimum. It certainly is desirable that one set of choke coils be used to cover the entire frequency band of the transmitter.

Since the operating frequency band is large, the number of possible series resonant points, if each section of the choke has a different resonant frequency, is large, and the possibility of burning out at least one section of the choke on one of the operating frequencies must not be neglected.

*If, however, all sections have the same fundamental frequency with identical values of inductance and distributed capacity,* all the series resonant points will be the same, and the choke coil then may be designed so that no one of the operating frequencies will hit any one of those points.

In Figure 13 it is shown that in the choke built up of sections, the total inductance is equal to the sum of the individual inductances plus the mutual inductance. If the three coils are sufficiently spaced and are small, the mutual inductance can be made small and can be balanced out by the effect of the capacity between coils. The total effective inductance will then be equal to three times the inductance of one section. (For this condition the three inductances must be exactly equal in value and the mutual inductance must be negligible).

Since all the individual distributed capacities are in series, if they are exactly equal the resulting capacity is equal to one-third the capacity of one coil. The effective capacity between coils can be made such as to balance out the mutual inductance.

With this combination of three coils, all coils being identical, having the same number of turns, the same inductance, the same distributed capacity and the same resonant frequency, connected in series, the total inductance is three times the inductance of one, and the total distributed capacity is one-third the capacity of one.

The resonant frequency of any circuit is determined by its LC product. Two circuits in which the *PRODUCTS* of the inductance times the capacity are equal have the same resonant frequency, even though one has a large inductance and a small capacity while the other has small inductance and a large capacity.

Consider the inductance of one coil as equal to L; the capacity of one coil as equal to C. Then with the three coils in series and properly spaced the total $L_t$ = 3L and the total $C_t$ = C/3.

The product of inductance 3L and capacity C/3, may be written

$$3L \cdot \frac{C}{3} \text{ or } \frac{3LC}{3} .$$

This is seen to equal LC, the numerical values of 3 cancelling. Therefore the total combination has the same LC value and the same resonant frequency as one coil, but it has three times the inductance and only one-third the capacity of a single coil. Aside from the question of a single set of series resonant frequencies, this is exactly the desired design trend for effective R.F. chokes because it results in large values of $X_L$ and $X_c$ and large parallel resonant impedance at the fundamental and odd harmonics.

At any given frequency $X_L$ and $X_c$ will be three times as large as in a single coil, the series resonant points of the combined chokes will be at the same frequencies as the equivalent points for the individual coils, and can be avoided in operation by proper design. It must be remembered, however, that to obtain this condition THE THREE WINDINGS MUST BE IDENTICAL IN EVERY RESPECT. The arrangement of the coils and the mounting is shown in Fig. 15

High Potential End

Low Potential End

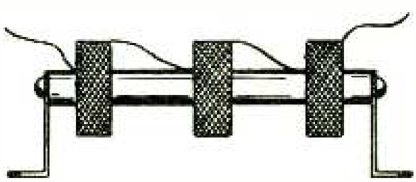

Fig. 15.—Arrangement of coils and mounting in a three-section coil.

The operating conditions of the choke are shown in Figure 16. If the choke is designed to have a fundamental frequency of $F_1$ and is operated at a frequency Y, f amount lower than its fundamental, it will act as an inductive reactance, the reactance being equal to about two-thirds of the total impedance at resonance. With a choke of large inductive and small capacitive values, this will be an impedance of many thousands of ohms.

AT $Y_2$, DOUBLE THE OPERATING FREQUENCY, the choke will be operated at a frequency $f_1$ amount lower than $F_2$, double the fundamental frequency of the choke. The choke is now acting as a capacitive reactance, (see Point $Y_2$), but the reactance will be quite high, at least several thousand ohms, and while not as effective as at the frequency shown at point Y, should still have fair operating characteristics.

Due to the steepness of the reactance curves, the reactance at frequency $Y_2$ which is comparatively close to the series resonance frequency of the choke, is high enough that there is little danger of the choke being damaged and it should be fairly effective in opposing the R.F. component of plate current.

At $Y_3$, triple the operating frequency, the choke will again act as an inductance and will be highly effective.

At $Y_4$, four times the fundamental frequency, the condition is similar to that of point $Y_2$, the double frequency. The choke is again acting as a capacity reactance of several thousand ohms and, is more effective than at point $Y_2$ and is still a comparatively good choke.

This design allows a very wide range of frequencies to be covered with the use of a single set of chokes and is particularly advantageous for high frequency operation where it is desired to operate on several multiples of a given fundamental frequency, especially when the fundamental frequency is crystal controlled so that there is no danger of tuning directly into an even harmonic frequency of the choke fundamental.

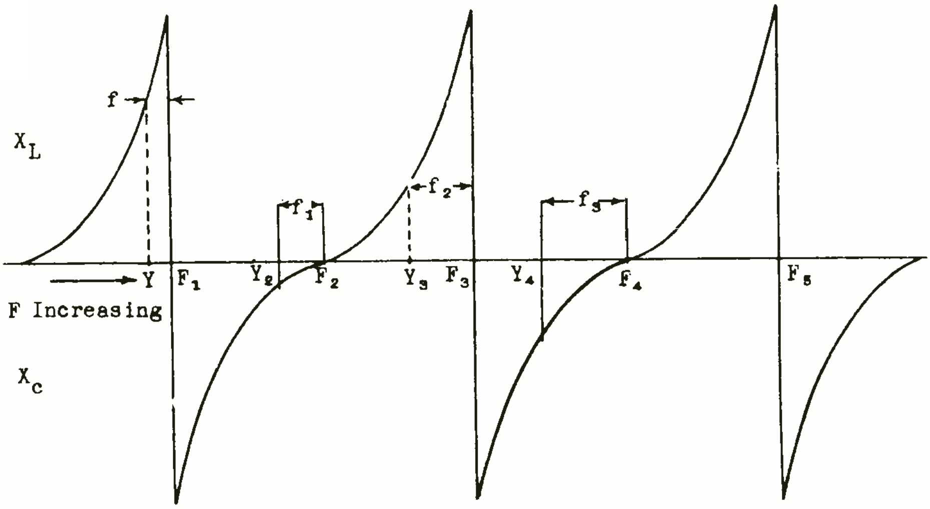


Fig. 16.—Operating conditions of the three-section r-f choke.

Another possible design of choke for such operation, particularly where second and fourth harmonic operation are more important than the fundamental, would be to have the choke fundamental frequency somewhat *lower* than the fundamental transmitter frequency so that the choke operates as a high value of $X_c$ at the fundamental and as $X_L$ at the second and fourth harmonic frequencies. On the other hand, if the R.F. amplifier is to operate at the fundamental and third harmonic frequencies, operation at Y and $Y_3$ (Fig.16) would be as inductive reactance and should be highly effective.

*HIGH FREQUENCY CHOKES.*—Another type of choke is useful for high frequency operation where considerable experimental work is done over a wide band of frequencies. This is the single layer solenoid winding on a long form of small diameter. Every few turns a twist is taken and the insulation removed to form a tap. This results in a tapped choke coil with which, by using a clip and flexible lead, the inductance of the choke may be quickly changed to determine the number of turns that will give the best results. This type of choke is of course used for experimental work and is not recommended for permanent design in a transmitter for use with a single frequency or a fixed band of frequencies.

An improvement of the single layer solenoid choke for high frequency operation is shown in Figure 17. In this design, one end is

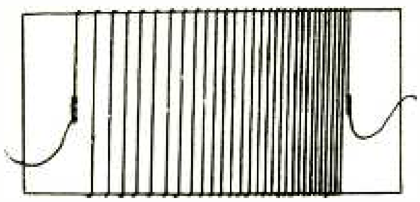

Fig. 17.—Showing how the winding pitch may be tapered to prevent any isolated resonant points in the frequency spectrum.

wound normally with turns close together. Near the middle of the winding the turns are spaced slightly, the spacing being gradually increased as the other end of the coil is approached.

Such a winding has the effect of two or more chokes in series with no definite frequency characteristic change, one section gradually blending into the other sections. The closely wound section possesses higher inductance is effective at the lower (comparative frequencies); the widely spaced section of the winding is more effective at the higher frequencies. Such coils have been designed with no apparent "holes" over a quite wide band of high frequencies.

## APPLICATIONS

*R-F APPLICATIONS.*—Choke coils are used in the plate circuits of high frequency receivers, particularly in the case of regenerative detectors where resistance or capacity controlled regeneration is used. If the radio frequency choke is not used a large portion of the radio frequency component of plate current will be bypassed to ground by the capacity of the windings of the audio frequency transformer and the receiver will refuse to oscillate. If a radio frequency choke is used, the audio frequency component will pass through the choke with no opposition, while the radio frequency component will be blocked by the choke and forced to the plate feedback coil. This is shown in Figure 18. The choke is connected between

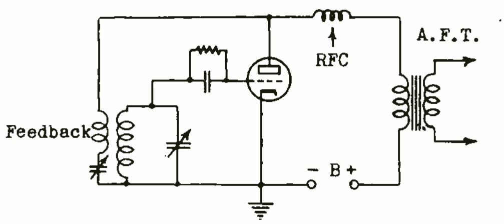


Fig. 18.—Use of r-f choke to block the flow of r-f current, but not audio current.

the plate of the tube and the primary winding of the audio frequency transformer. In connecting be SURE that the feedback winding is connected to the PLATE END OF THE RADIO FREQUENCY CHOKE. If connected to the other end the circuit will not oscillate.

Such a receiver choke is easy to construct. Between sixty and seventy-five turns of silk covered copper wire, size 28 to 32, wound on an insulated form one-quarter inch in diameter will operate satisfactorily over a frequency band in the order of from three thousand to twenty thousand kilocycles. R.F. chokes may be used in broadcast and communication receivers in any part of the circuit where it is required to block R.F. currents.

In transmitters operating at ultra-high frequencies—as from 100 MC to 600 MC—it is still necessary to employ R.F. chokes through which to apply plate and grid d.c. voltages. At such frequencies extremely small chokes must be used. For an oscillator capable of supplying from 4 to 8 watts with input of about 30 watts at frequencies between 300 MC and 600 MC, one manufacturer recommends choke coils having windings 1 1/2 inches long, 1/4 inch diameter, with 15 turns of No. 30 or 32 copper wire. It will be noted that this forms a coil long in respect to its diameter with the turns of small wire well spaced. Such a winding will have small inductance and very small distributed capacity. In spite of the very small L of such a coil, the choke effect at the ultra-high frequencies can be great. $X_L$ at 300 MC/s is 1884 ohms per μ-henry and if advantage is taken of the increase of Z near parallel resonance, the small choke can be very effective.

Signal generators, high frequency receivers and precision R.F. measuring apparatus often is entirely shielded within a metal case. To make the shielding more effective small radio frequency chokes should be inserted in each of the battery or rectifier power supply leads, *immediately inside the shielding.* This will prevent undesirable pickup and interference or radiation through the power supply circuit, and the only radio frequency energy entering or leaving the apparatus will do so by way of the proper terminals where it can be properly controlled. If radio frequency chokes are used in vacuum tube power supply leads it will be necessary to connect a by-pass capacitor between the +B lead and the cathode, between the *plate circuit and the choke* and not between the choke and the power supply. This is to provide a radio frequency path from the plate circuit to cathode. In this way very complete shielding can be obtained. Such R.F. filters are used in the power supply leads of signal generators, R.F. oscillators, etc.

The connection of a choke (R.F. C.) and bypass capacitor (C) in bringing a power supply lead into a shielded compartment, as explained in the preceding paragraph, is shown in Figure 19. Without bypass capacitor C, the tuned plate circuit would be isolated from the cathode by means of R.F.C. To prevent radiation of R.F. energy from currents in the choke coil winding, the coil itself should be shielded as shown.

In the construction of choke coils for transmitters and receivers it is not necessary to take elaborate precautions to ensure low R.F. resistance as is done in the ordinary tuned radio frequency circuit. In a good choke the impedance, due to the high reactance of each branch, is so great that the normal resistance of the coil becomes negligible. So far as the d.c. resistance is concerned, the choke is in series with the resistance of the tube which is always large, usually in the order of several thousand ohms,

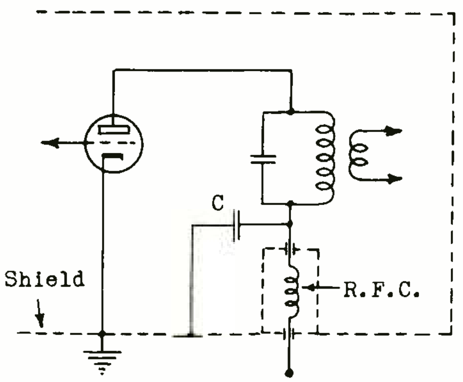


Fig. 19.—Use of an r-f choke to prevent "leakage" of r-f back into the plate power supply.

so that a few extra ohms of resistance in the choke can be neglected. It is only necessary to use sufficiently large wire to carry the required current with an adequate margin of safety.

In a well designed transmitter very little trouble develops in the choke coils, and when trouble does occur it is a simple matter to locate. An open plate choke will be indicated by zero reading of the plate ammeter or milliammeter when the connections in the plate circuit are good and the plate generator or rectifier is developing the proper voltage. A choke may be tested for open circuit by means of a battery and a pair of phones, an ohm-meter, a voltmeter and battery. The possibility of a short-circuit developing in a choke is almost negligible.

A burned out grid choke may be indicated by zero grid current; if no grid milliammeter is used, the open grid circuit will be indicated by the blocked condition of the tube after a few seconds of operation. The grid choke may be tested for open in the same manner as the plate choke.

If a choke burns out and no spare is available, it will have to be rewound unless the open section is near the end and can be cut out without seriously impairing the operation of the transmitter. If the choke is a single layer solenoid type, rewinding will be a simple matter, the principal precaution of course being to use as nearly as possible the same size wire and to replace the proper number of turns on the same length of winding. This can be done by carefully counting the number of turns removed and replacing them with the same number of turns in the same space on the coil.

If the choke is of the bank wound type, rewinding will be somewhat more difficult but if care is taken a satisfactory job can be done. If the same size of wire can be obtained, the same number of turns should be replaced as were removed.

Some high frequency transmitters have been designed with choke coils which can be tuned by means of the inductor principle, that is, by means of a conducting sleeve that is variably inserted within the coil to decrease its inductance due to the eddy-currents set up in the sleeve. This type of coil can be accurately tuned to give the optimum results at any given frequency within its range and is used on transmitters designed to cover a certain limited range of frequencies in continuously variable steps.

*R.C. FILTERS.*—In multistage high-gain radio receivers, it is necessary to supply plate, screen, and grid bias voltages to the several R.F. and I.F. amplifier tubes. These voltages, with the probable exception of the negative grid bias, are supplied from a common source. A variable grid bias voltage usually is supplied from the A.V.C. (automatic volume control) rectifier. Interstage shielding of R.F. and I.F. amplifiers—at least of the coils—is essential for stable operation. Similarly, isolation of the several circuits connecting into a common voltage source is essential to prevent interstage coupling through the impedance of the common voltage source. Circuit isolation is accomplished in a simple, compact and inexpensive manner by the use of resistance-capacity filters as shown in Figure 20.

The most simple filter is in the grid circuit which is negatively biased to the point where no grid current flows; here very small comparatively high resistance components may be used. In Figure 20 these are represented by $R_1$, $R_3$, $R_6$, $R_8$, $R_{11}$ and $R_{13}$, all 100,000 ohm .5 watt resistors. Above each of these resistors, to provide an R.F. circuit back to ground and to the respective cathode, is a bypass capacitor. In the circuit of Figure 20 bypass capacity of .05µF is used with each grid resistor. These are capacitors $C_2$, $C_3$, $C_8$, $C_9$, etc. The values of resistance and capacity are not critical but should be of such values that the resistance is *at least* 10 times greater than the reactance of the accompanying capacitor at the lowest signal frequency. In the broadcast band, the lowest frequency is 550 KC/s and the reactance of a .05µF capacitor at that frequency is negligible compared with R and a high degree of isolation is obtained. The larger R is

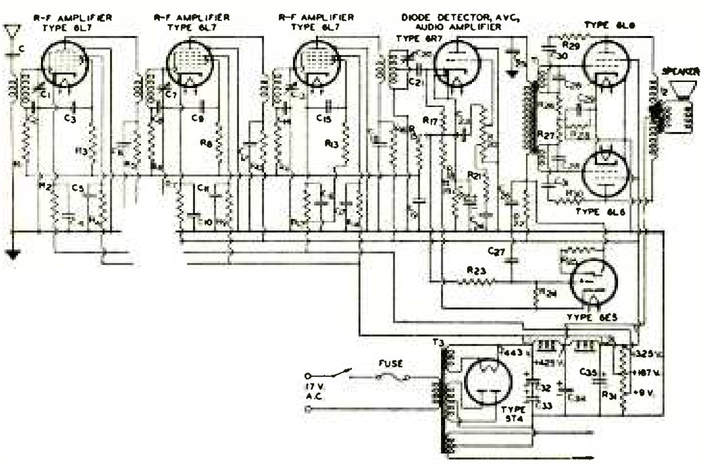


Fig. 20.—Schematic showing use of r-c filters.

made, the smaller C can be for the same degree of isolation. For grid circuit isolation where no current flows and the value of R is not critical, small inexpensive carbon resistors can be used in conjunction with low voltage paper capacitors.

In the circuit of Figure 20 similar filters are used to isolate the plate circuits of the R.F. tubes. Here, however, plate current flows and the filter resistance must not be so large as to produce excessive voltage drop. In this circuit $R_5$, $R_{10}$ and $R_{16}$ are 12,000 ohms and the accompanying capacitors $C_6$, $C_{12}$ and $C_{18}$ have capacity of .1 µF. This still provides a large $R/X_c$ ratio. .5 watt resistors are used with paper capacitors of the proper voltage rating. These resistors also serve to drop the plate voltage at the tubes from the +325 volts at the source to +250 volts as specified by the manufacturer for this tube. In the event of a tube failure, plate current to that tube drops to zero and the voltage above the resistor rises to that of the source, in this case to 325 volts. The plate bypass capacitors should have voltage rating of not less than 400 volts.

Similar isolating filters are used in the screen grid circuits where the resistors $R_4$, $R_9$ and $R_{14}$ (10,000 ohms) also serve as screen voltage dropping resistors. .1µF capacitors of the same voltage rating as used in the plate filters are employed. In the plate circuit filters .5 watt resistors are used but 1 watt resistors are used in the screen filters. The screen current of the 6L7 tube normally is slightly greater than the plate current, but in the event of an open plate circuit the screen current will rise to almost double its normal value and this must be considered in selecting the dissipation rating for the screen resistor.

*AUDIO FREQUENCY CHOKES.*—Audio frequency chokes are used less frequently than R.F. chokes, but when used their design is fully as important as at radio frequencies. Figure 21 illustrates the use of audio

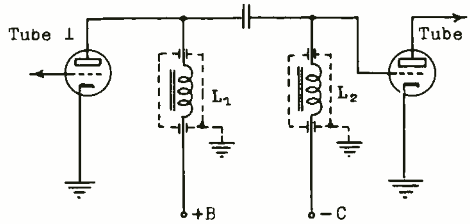


Fig. 21.—Impedance coupled audio amplifier stage.

chokes, in this case usually called "reactors", at audio frequencies. The circuit is that of an impedance coupled audio frequency amplifier. $L_1$ serves as the plate load impedance for Tube 1. It carries the d.c. component of plate current and the a.c. component of plate current flowing through it develops the a.c. component of plate voltage for excitation of the following tube. $L_2$ is the grid choke of Tube 2 through which the negative grid bias is applied without undue loss of a.c. excitation voltage.

The inductance of $L_1$ should be large enough that $X_{L_1}$ is not less than $R_p$ ($R_p$ = tube plate-filament resistance) at the lowest frequency which must be amplified. For example, if $R_p$ is 20,000 ohms and it is desired to amplify at frequencies down to 50 cycles/second, then $X_{L1}$ should be at least 20,000 ohms at 50 cycles/second, $L = X_L/2\pi F = 20,000/(6.28 \times 50) = 63$ henries. At all higher frequencies $X_{L_1}$ is greater than $R_p$. A coil having sufficient turns to produce, even with an iron core, inductance of 63 henries, has large distributed capacity. This imposes the upper limit on the frequency band which can be passed and is the most severe limitation to the use of this type of amplifier for good audio amplification. To reduce C to a minimum, various types of windings and cores have been used. The most successful development along this line is the use of one of the high permeability alloys for the core. For specified inductance, as the permeability of the core is increased the required number of turns is decreased, this in turn reducing the coil capacity and placing the resonant point at a higher frequency.

Another factor is core saturation. $L_1$ must be so designed that magnetic core saturation does not occur within the plate current range of Tube 1. This is particularly important where a high permeability alloy is used because such materials saturate with lower ampere turn magnetizing force than does transformer steel. When high permeability cores are used in audio plate chokes parallel feed should be employed to avoid core saturation.

The inductance of $L_2$ should be as large as possible consistent with keeping the distributed capacity sufficiently low and the high frequency characteristics adequate. In such an amplifier Tube 2 will be operated with sufficient negative bias that no grid current flows. Hence core saturation need not be considered and the use of a high permeability alloy and small wire size permits the construction of a coil of small dimensions and correspondingly small distributed capacity, but having inductance in the order of hundreds of henries.

The use of audio chokes or reactors in modulator circuits of transmitters is discussed in considerable detail in another lesson, as are the filter chokes in transmitter and receiver power supplies.

Very often the R.F. choke is thought of as "just another coil" and the importance of careful design sometimes is neglected. The development engineer who wishes to turn out an efficient trouble-free transmitter will be as careful in the design of the R.F. chokes as he is in the design of any other of the transmitter components.

*RADIO AND AUDIO FREQUENCY CHOKES*

**EXAMINATION**

1. What is the difference in the design of a parallel circuit for high impedance at resonance with a very broad impedance curve, and the design of a parallel circuit which will have high resonant impedance with a very sharply peaked curve. EXPLAIN IN DETAIL the reason for the difference in the shapes of the curves with respect to the relative value of circuit components.

2. (A) What is meant by the distributed capacity of a coil? Explain why a coil has a resonant frequency.

2. (B) What determines the distributed capacity of a choke coil? Explain in detail the type of construction.

3. For what purpose is a choke coil used? Why? Explain fully.

4. What would be a desirable relationship between the fundamental frequency of a choke and the fundamental frequency of a crystal-controlled oscillator if the latter were to operate as an oscillator-doubler. Assume choke to be used in plate B+ supply. Why?

5. Explain the advantages of the slot-wound choke over each of the single layer, the ordinary multilayer, and the bank wound types of chokes.

6. A single choke coil of the universal wound type is to be compared with a sectional choke composed of three pi's, each identical to the single choke coill How should the coils be connected in the sectional choke for maximum L and minimum C? How does $f_r$ compare with that of the single choke coil?

7. (A) Discuss the design of an r-f choke coil for high frequencies and describe the type of choke you would build for such applications.

(B) Explain the operation of an RC filter. What should be the relationship between the constants of the series and shunt elements of an RC filter?

8. At what frequencies do choke coils usually burn out? Why? What precautions can you take in designing a choke to keep the danger of the choke burning out to a minimum? Explain.

9. The complete choke assembly shown in Fig. 15 has a resonant frequency of 5 mc/s. The total distributed capacity is 4 $\mu\mu F$. What is the resonant frequency, inductance, and distributed capacity of each individual winding? Show your work step by step.

10. (A) A choke coil has an inductance of 50 μH, and a capacity of 5.6 μμF. List three *frequency ranges* for which it will act as an inductance, and three *ranges* for which it will act as a capacity.

(B) At approximately what frequency will it operate most satisfactorily as a choke coil? Give a specific frequency value as an answer.