PROCEEDINGS
of the
RADIO CLUB *of* AMERICA

Vol. 2 No. 6 September, 1922

R.C.A. SPECIAL NOTICES

To the Membership:—

The return of the Fall season brings with it the opportunity for renewed activity of the Radio Club of America. During the last year your Lecture Committee observed the great interest in meetings where actual apparatus was exhibited and have provided for an interesting program this Fall.

❁ ❁ ❁ ❁ ❁ ❁ ❁ ❁

When the September meeting notice comes along don't forget to bring your radiofan friend. At the Club he will have a chance to learn about the "works" inside his broadcast receiver. The concert listener may be a new-comer but he will certainly relish the experimental side of the game.

❁ ❁ ❁ ❁ ❁ ❁ ❁ ❁

Walter S. Lemmon—Editor of Proceedings, 342 Madison Ave., New York
Ernest V. Amy
Pierre Boucheron
Lester Spangenberg

Multi-Stage Amplifiers

*By M. C. Batsel**

A Paper Presented before the Radio Club of America, Columbia University, New York

SEVERAL methods of coupling the successive tubes of multi-stage amplifiers will be discussed. The uses of each type including the useful frequency range will be mentioned.

When considering the design of an amplifier the first thing to be determined is the type of tube to use. A complete set of plate-current—grid-voltage and grid-current—grid-voltage curves for different plate voltages should be obtained, also the internal plate-filament circuit impedance vs. plate voltage obtained. From these curves the plate battery voltage and negative grid voltage necessary for the proper operation of the tube as an amplifier can be obtained.

Figure 1 shows some curves of an amplifier tube. The grid must have a sufficient negative D.C. voltage applied to it to insure that the maximum amplitude of A.C. voltage to be applied to the grid will not cause the tube to take grid current. Sufficient plate voltage must be used to produce a fairly straight plate-current—grid-voltage characteristic but must not be so high as to produce saturation.

Resistance Coupling

The resistance type of coupling between tubes will be considered first. Resistance coupling has much to recommend it when amplification absolutely without distortion is necessary. The value of resistance coupling in this connection is due to the fact that the amplification is independent of the frequency. This is true at least for all audio frequencies if the coupling condensers are properly proportioned.

A resistance-coupled amplifier circuit is shown in Fig. 2.

Tubes to be used in resistance-coupled amplifiers should have a reasonably high voltage-amplification factor. A high voltage-amplification factor means a high internal plate-to-filament resistance; this requires a high value of coupling resistance and in turn a higher plate voltage. Due to the number of batteries required the plate voltage that it is practical to use usually determines the amplification factor and impedance of the tubes used in designs for general use. A coupling resistance equal to the resistance of the tube plate-to-filament circuit or possibly as much as 100% higher is satisfactory. The grid resistances are necessary in order to maintain the grid at a fixed D.C. voltage with respect to the filament. The resistance will also tend to relieve the grid of any positive charge that might be accumulated by leakage from the plate battery thru the coupling condenser.

The voltage amplification per stage of resistance coupling is equal to ½ the voltage-amplification constant of the tube when the coupling resistance is equal to the impedance of the tube. The resistance would have to be 10 times the impedance of the tube to give 90% of the voltage amplification factor. It is obvious that the plate circuit battery voltage would be out of reason

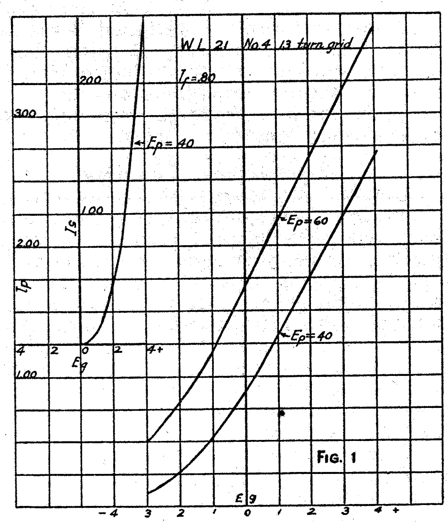


FIG. 1

if such a value of resistance were used.

The plate voltage must be sufficient to produce a linear relation between grid voltage and plate current.

Choke-Coil Coupling

Figure 3 shows a circuit using choke-coils or reactances for coupling between stages. The circuit is the same as shown for the resistance coupling, the resistance being replaced by reactances. The reactance can be so designed that the D.C. resistance is practically negligible and the A.C. impedance very high for even very low frequencies. A choke-coil having an inductance of 50 to 75 henrys can be designed so that the efficiency is not impaired at the high audio frequencies by the capacity of the coil. It is an advantage to use an open-core choke coil in order that the

*Engineer, Westinghouse Elec. & Mfg. Co.

coil can be made small and compact without saturating the iron of the core. By using sectionalized windings it is possible to keep the natural period of the winding entirely above the audible range even when the inductance is as high as 75 henrys.

The amplification is 90% of the voltage-amplification factor of the tube when the reactance is twice the impedance of the tube.

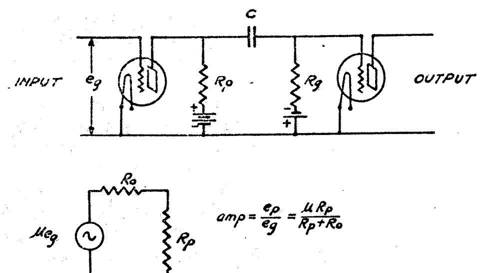


FIG. 2

Choke coils can be designed for use at radio frequencies and by keeping the distributed capacity at a minimum it is possible to obtain amplification over a considerable frequency range even below 1000 meters wave length.

Transformer Coupling

Coupling by means of transformers is desirable in many audio frequency amplifiers and is to be preferred for radio frequency. One advantage is that the voltage can be stepped up in the transformer. It is desirable when using transformers, as will be shown later, to employ tubes having a low impedance. While low-impedance tubes have a relatively low voltage-amplification factor it is possible to realize a greater total amplification per stage using transformers than by any other means.

Figure 4 shows a transformer connected in a circuit and the equivalent circuit of a transformer and tubes. As a transformer is intended to be used to step up the voltage it is necessary to make the step-up ratio as high as possible. If the secondary is first taken into consideration it is obvious that a great many turns are desirable in the secondary winding. The limiting factor is the highest frequency to be amplified. The resonant frequency of the secondary winding may be made the geometric mean of the frequency band to be amplified. If the range is 100 to 10,000 cycles the resonant frequency may be 1000 cycles. The equivalent circuit of the transformer and tube may then be represented by that of a parallel resonant circuit. "*C*" is the combined capacity of the winding and grid-to-filament capacity of the tube multiplied by the square of the ratio of transformation. The reactance of this circuit at the lower frequency is that of the inductance alone. With increasing frequency the reactance increases and reaches a very high value, acting as a resistance at resonance, and then decreases again and finally at higher frequencies its value is practically that of the equivalent capacity. In order to explain the action of a transformer so designed that the secondary is resonant, the variation in the A.C. voltage across a coil having an inductance equal to the inductance of the transformer primary when a constant voltage of varying frequency is impressed upon the grid of the first amplifier tube will be shown. The tube may be considered as a generator having an impedance R. The voltage generated will therefore divide between the resistance R_o and the reactance ωL of the transformer primary. At low frequencies ωL is small and most of the voltage generated is lost as RI drop in R_o, the internal plate-filament resistance. As the frequency is increased ωL increases and when ωL is twice the R_o the RI drop in R_o is less than 10% of the voltage generated. It is obvious then that no matter how great the reactance may be made the voltage across the reactance cannot be greater than μe_g.

The addition of the secondary winding and connections to the tube only affects the impedance of the primary as would the addition of the equivalent capacity C. The reactance then becomes.

$$X_p = \frac{L_p \omega}{1 - L_p C \omega^2}$$

While the capacity causes the reactances of the winding to increase to a great value and then to decrease again as the frequency is increased, the increase above the value for which there is practically no RI

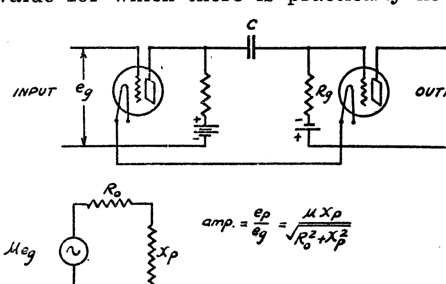


FIG. 3

drop in R_o can not change the voltage across the primary winding. The secondary voltage is equal to the voltage across the primary multiplied by the ratio of turns.

Transformers can be designed to give very little variation in amplification for different frequencies or to be sharply resonant. The secondary winding can be the same in either case. If the primary inductance is sufficiently high to produce little RI drop in R_o at low frequency and the secondary winding is not resonant at a frequency so low that the reactance decreases too rapidly as the frequency is increased, the amplification-against-frequency curve is as shown in Figure 5, Curve 1. The second curve (2) shows the effect of decreasing the number of primary turns.

By decreasing the primary turns still further, the peak is made sharper and the maximum amplification greater because the step-up ratio is increased if the primary

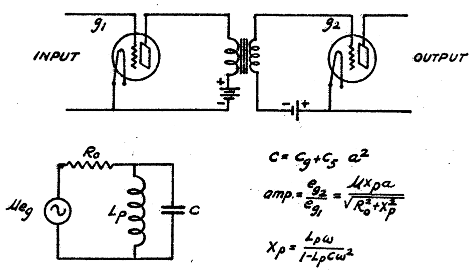
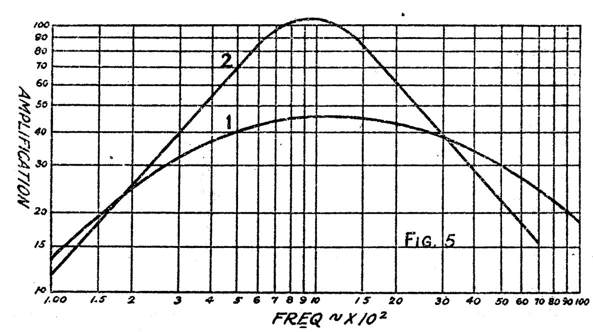


FIG. 4

turns are decreased while the secondary turns remain constant. It is desired to emphasize the fact that the resonance effect is only due to the transformers being connected to a generator having a high internal impedance. If the tube plate-filament resistance could be zero, no peak could be obtained. The only currents supplied to the transformer are the magnetizing current and a load current that is delivered to a capacitive load. If the internal plate-filament impedance of the tube is decreased the effect on the variation of amplification with frequency is the same as the effect of increasing the number of primary turns.

The secondary voltage is practically equal to the voltage across the primary multiplied by the ratio of transformation. If the transformer is well designed there is no leakage and therefore no chance of series resonance. The resistance of the windings, core losses, and dielectric losses modify the above statements slightly. Transformers afford a practical method of coupling tubes for cascade. It is not practical to use more than two or at most three stages of audio-frequency amplification. The last step may consist of a power tube if a powerful loud-speaker is used. For signals weaker than can be received with audio amplifiers, radio frequency should be used.



Radio Frequency Amplification

The greatest obstacle to be overcome in the design of a radio-frequency amplifier is the self-oscillations set up when a radio-frequency amplifier is connected to a tuned circuit, the oscillations being due to feed-back thru the inter-electrode capacities. Other feed-backs may be effectively eliminated. If a transformer is used the amplifier will tend to oscillate at a frequency at which the transformer behaves as an inductance. The inductance in the plate circuit then gives rise to regeneration as in the well known regenerative tuned-plate circuit. The nature of the feed-back has been explained by Miller, Ballantine and others. Figure 6 shows the equivalent circuit of a tube with its inter-electrode capacities, also a diagram of the phase relations of the plate current and various voltages acting in the circuits.

Starting with I_p we may draw R_oI_p representing the RI drop in the plate circuit. 90° ahead of this voltage we may draw X_pI_p representing the voltage across the reactance X_p. The sum of these voltages is in phase with e_g. e_p is equal and opposite to I_pX_p and causes a current to flow through Cm, the capacity between plate and grid. This current flows to the filament thru the circuit connected between grid and filament when the tube is connected to a tuned loop. At resonance the grid and filament circuit is of the nature of a resistance, being a parallel resonant circuit. Cm is very small and the current thru Cm will be a current leading the voltage e_p in phase by nearly 90° since the impedance of Cm is very great. The voltage drop over the resonant grid circuit, which behaves as an effective resistance, will be in phase with e_g and therefore tend to regenerate or sustain oscillation. Only when the plate circuit reactance is inductive can the feed-back occur in the proper phase to regenerate.

The voltage e_p is 180° out of phase with μe_g when the impedance X_p is replaced by resistance and in that case it is not possible to induce a voltage in the grid circuit thru Cm that would be in phase with the original voltage e_g.

Transformers for wave lengths below 1000 meters must be designed so as to keep the distributed capacity of the windings themselves and between primary and secondary windings at a minimum value. We have found iron cores to be useful even at a wave length of 300 meters. The iron must be thin and the laminations well insulated. The permeability of the iron is

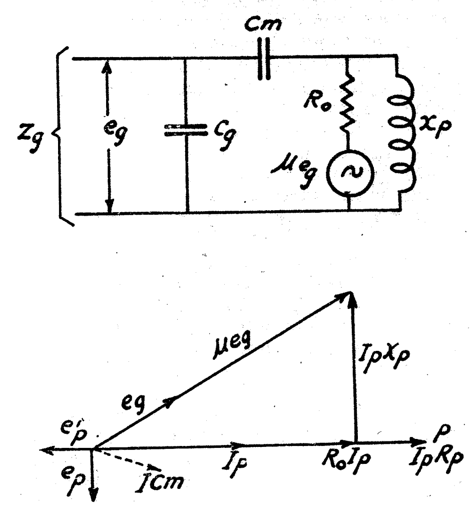


FIG. 6

of some advantage as the primary and secondary windings can be located farther apart than they could be in air for the same coupling or flux linkage. The losses in the iron core are a benefit rather than a loss as the impedance of the transformer primary may be such that the phase of the plate voltage with respect to the grid voltage may never be right for regeneration.

It is interesting to note that the regenerative action can occur only in the tube connected to the tuned loop circuit provided all the transformers are similar. The feedback occurs at a frequency for which the transformer behaves as an inductance and when a resistance or its equivalent is connected between the grid and filament.

Radio-frequency amplification has not been widely used by amateurs because it is very difficult to secure amplification on 200 meters. For wave lengths from 250 meters and upward radio-frequency amplification is entirely practical. For the reception of broadcasted entertainment a loud speaker is usually desired if vacuum tubes are used and audio-frequency amplification is necessary for the operation of a loud-speaker. It is not practical to use more than 3 or 4 vacuum tubes requiring considerable current for filament heating, as the storage battery would be very expensive to purchase and to maintain. For this reason radio-frequency amplification has not come into general use, the regenerative circuit with audio-frequency amplification usually being used instead.

There are many places where the use of a loop or coil aerial is desirable or necessary and then radio-frequency amplification is necessary. This is true in a great many congested districts and apartment houses.