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A New Method of Radio Frequency Amplification

The Theory of Various Arrangements for Neutralizing Tube Capacity in Radio-Frequency Amplifier Circuits and a Discussion of a New Method—An Arrangement for the Measurement of Amplification Constant and Impedance

By C. L. FARRAND

IT IS the purpose of this paper to present a new method of radio frequency amplification, together with the necessary data for the design and construction of the circuits. Tuned radio frequency amplification is not new. See Schloemilch and Von Bronk, United States Patent No. 1,087,982. This method has been used with considerable success, more difficulty being experienced as the number of stages were increased. These difficulties were due to incipient couplings in the amplifier circuits, either between the input and output circuits of a single tube or between the input and output circuits of more than one tube. These couplings are either electro-magnetic or electro-static, as in a good design, resistance couplings are eliminated. The magnetic couplings can best be taken care of by disposing the transformer windings so that their axes are at right angles, and on the same center line, with reasonable distance between windings.

Static couplings between the input and output circuits of the tubes can be eliminated by shielding in all cases excepting the inherent capacity coupling of the tube itself. From general considerations it is apparent, having been brought out before, that there are three capacities in a three-electrode vacuum tube, two of which act in shunt to the input and output circuits respectively, and the third which is the grid to plate capacity, acts as a coupling between the input and output circuits. See Fig. 1. To eliminate this coupling, it is necessary to resort to balancing arrangements or to additonal circuits which will nullify the influence of the coupling current flowing through this capacity. The coupling increases with frequency, and, it is in the broadcasting range and shorter waves that the most difficulty is experienced.

Various methods have been suggested for neutralizing or balancing the tube coupling. Hartley (R. V. L. Hartley, United States Patent No. 1,183,875) has suggested a magnetic balance, which is the equivalent to a reverse tickler coil. See Fig. 2.

By this method, the coupling effect of the grid-to-plate capacity of the tube is balanced by an equal and opposite magnetic coupling between the input and output circuits. This condition holds for only one wavelength. In the Figure shown, the static tube-coupling increases with frequency, while the magnetic coupling remains constant.

THE RICE METHOD

RICE (C. W. Rice, United States Patent No. 1,334,118) has suggested a capacity balance which is in effect Fig. 3. By this method, the coupling effect of the grid-to-plate capacity is balanced by a capacity of equal value connected between the plate and an input coil being opposite potential to the grid.

Hazeltine (L. A. Hazeltine, United States Patent No. 1,450,080) has suggested a

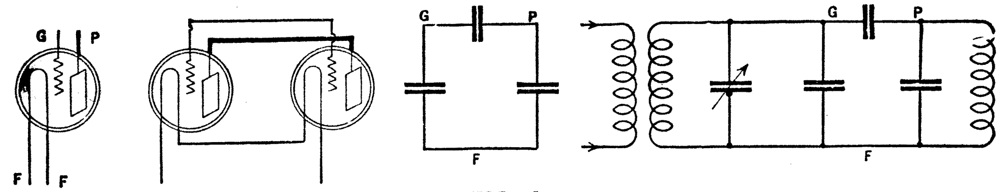


FIG. I

capacity balance wherein the effect of the grid to plate capacity of the tube is balanced by means of an output transformer. Fig. 4.

Here the coupling effect of the grid-to-plate capacity is balanced by a capacity connected between the grid and an output coil having a potential opposite to the plate.

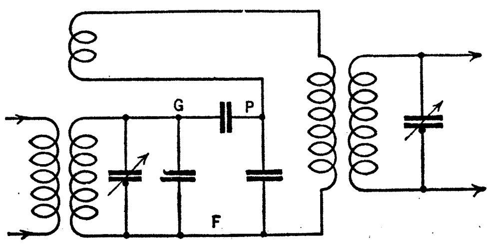


FIG. 2

The output coil is the secondary of the transformer supplying the next tube and has a ratio of turns greater than unity to satisfy the impedance relation, so that it is necessary that the value of the balancing capacity be chosen to equal the grid-to-plate capacity divided by the voltage ratio of the output transformer.

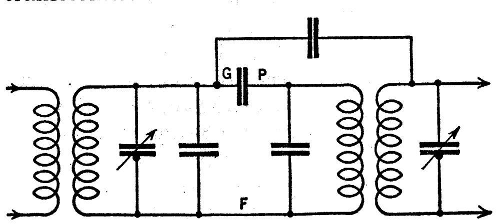


FIG. 3

The disadvantages of the above methods are that, particularly on short wavelengths, it is very difficult to maintain a balance when more than one stage of radio frequency amplification is used. This is due to stray capacities, which tend to upset the balance of the circuit. Oscillations then result. Difficulty of this sort is also brought about by the variation of grid-to-plate capacity of commercial tubes, which vary so much that a balance obtained for one tube may not hold for another.

A NEW NEUTRALIZING SCHEME

THE method of nullifying the effect of the grid-to-plate capacity of three-electrode vacuum tubes described in this paper does not depend upon a capacity balance and is free from the disturbing effects described above. The method involves a resistance connected between the grid and plate of the tube as in Fig. 5.

The effect of this arrangement is to change the phase of the coupling current flowing between the input and output circuits, thereby reducing the energy transfer or feed-back between these circuits and causes the remaining energy to be absorbed as quickly as it is transferred or fed back. The value of resistance necessary to nullify the grid-to-plate coupling is dependent upon the design of the tube, as

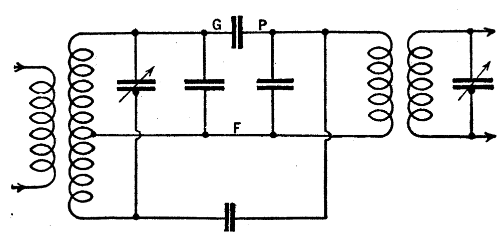


FIG. 4

well as the circuits. This resistance value is not critical. For the storage battery tubes now in commercial production, a resistance ranging between twenty-five and thirty-five thousand ohms gives satisfactory performance for multistage operation. The value for multistage operation is slightly lower as it is possible to take care of the stray overall coupling by a slight reduction of resistance. One hundred thousand ohms is a satisfactory value for the present dry cell tubes and may vary between ninety and one hundred and twenty thousand ohms.

The resistance should preferably be non-inductive and of low capacity. Present forms of conducting coated-paper resistances, and carbon filament wound lavite resistances are satisfactory.

The circuit for a two-stage amplifier is shown in Fig. 6.

It will be noted that a condenser is inserted in series with the resistance between grid and plate to prevent the plate battery from flowing through it to filament. The con-

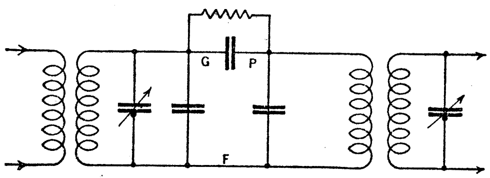


FIG. 5

denser is purely a blocking condenser and may range in value between one microfarad and one one-thousandth of a microfarad, and is only needed to permit the amplifier tubes to be operated from a common plate battery.

The transformer windings should preferably be tightly coupled, although this is not necessary as long as a suitable voltage ratio is maintained between primary and secondary. A suitable design consists of one hundred turns of No. 26 B & S gauge wire on a cylindrical tube, two inches in diameter and about two and three quarter inches in length. This is the secondary winding. The primary should be wound with about twenty-five turns of the same size wire on a concentric cylindrical tube of about one and three quarter inches in diameter. It is preferable to have the primary winding the same length as the secondary winding is when enclosed by the seconary winding. This arrangement gives the tightest coupling, although the same result may be secured by using more primary turns and less coupling. This will be discussed more in detail later. The primary is, in practice, wound opposite to the secondary. That is to say, if the secondary is wound clockwise, the primary is wound counterclockwise, or vice versa. The end of the primary winding directly under the grid end of the secondary should be connected to the plate battery. The other terminals follow as usual. The secondary tuning condenser should have a capacity of approximately two hundred and fifty micro-microfarads. The increase in intensity produced by each stage of radio frequency amplification as outlined above is nearly as much as that produced by each stage of audio frequency amplification. This is a very general statement but holds fairly closely for radio stages up to three or four before the detector when compared one stage at a time with one and two stage of audio after the detector, although the voltage amplification of the radio stages were only about twelve each while the audio amplifiers gave approximately twenty per stage.

This indicates that while the detector characteristic is not linear it is far from a square law.

REGENERATIVE AMPLIFICATION IN THIS CIRCUIT

IN ADDITION to the radio frequency amplification of each stage, it is possible to obtain a regenerative amplification which is equivalent in increased volume to the addition of two audio stages on a signal of average intensity. Fig. 7 shows the circuit of a receiver consisting of three stages of radio frequency amplification, a detector and two audio stages.

The regeneration here shown is provided for by omitting the nullifying resistance of the third radio stage, and controlling the feed-back due to the tube coupling by means of a potentiometer on the grid of this same

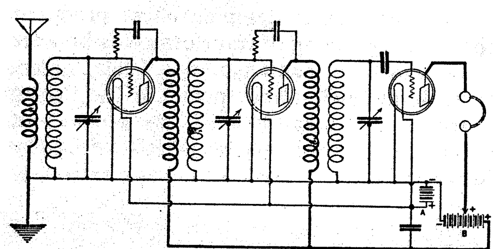


FIG. 6

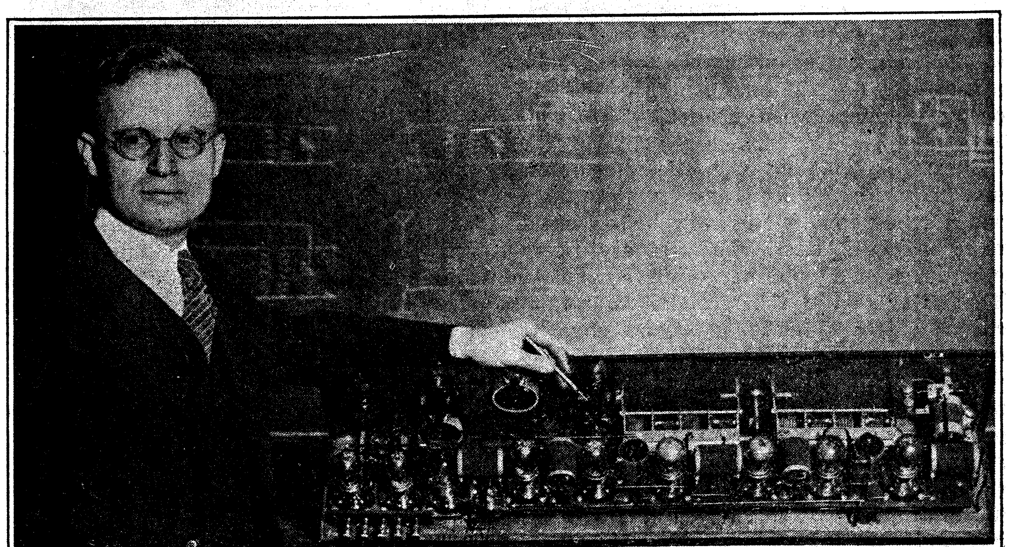
tube. This gives very satisfactory operation. Equally satisfactory operation may be had by the use of a variometer in the plate of the detector tube in the usual manner. In this case the nullifying resistance must be used across the grid and plate of the third tube as well as across the first and second. In the use of three stages of radio frequency amplification without regeneration it is not necessary to take any particular precautions except to dispose the transformer windings at right angles and to use care to provide for short grid leads, and that the grid lead of one tube does not run close to the grid lead of another tube. If such precautions are not taken, the amplifier may regenerate and oscillate at the lower wavelengths. It will be found that when the regenerative feature is added to the amplifier or detector, better control of the regeneration will be obtained if the receiver has first operated satisfactorily without regeneration. This means that the interstage coupling has been reduced to a minimum and that this provides for the localization and better control of the regeneration. In the operation of a receiver as outlined above using two or three stages of radio frequency amplification in addition to regeneration, the local oscillations produced during the adjustment of the regenerative amplifier or detector tube do not radiate from the antenna in any noticeable degree sufficient to cause interference with near-by receivers. As a typical example of this, a receiver has been operated on an outdoor antenna approximately forty feet from an adjacent antenna which is paralleled for approximately twenty feet. Both antennas were approximately forty feet high and had a total length of about one hundred and twenty five feet. The beat produced by the receiver was noticeable on the receiver of the adjacent antenna only on reception from stations nearly one thousand miles distant and then was not particularly objectionable.

Due to the low input impedance of the present commercially produced tubes and the consequently large damping effect produced thereby, the tuning of transformers is broader than would be anticipated. While objectionable in single-stage operation, the tuning sharpens considerably with the addition of several stages until very reasonable selectivity is obtained. It is also possible and extremely practicable to tune the transformers by means of condensers on a common shaft as suggested by Hogan. (J. V. L. Hogan, United States Patent No. 1,014,002). This has been done very successfully with three stages of radio frequency amplification using an aperiodic antenna input by means of four condensers on a common shaft and with six stages of radio frequency amplification by means of eight condensers on a common shaft. In the latter case one condenser was used to tune the antenna separately which was loosely coupled to the amplifier input circuit. The condensers were electro-statically shielded from each other, and the tube coupling capacities were nullified by means of the resistances of values given above.

Additional improvements in selectivity have been made, which, unfortunately cannot be disclosed at the present time and will have to form the subject of a later paper. It might be mentioned that by these means, reception without regeneration of five hundred and nine-meter stations in Philadelphia, through a local four hundred and ninety two-meter station, is entirely practicable.

MEASUREMENTS OF AMPLIFICATION CONSTANT AND IMPEDANCE

A METHOD of measuring the voltage amplification of radio-frequency amplifiers during the writer's experiments became very desirable. After various methods were



MR. FARRAND DEMONSTRATING HIS RECEIVER

Before a meeting of the Radio Club of America in New York. The entire back of the panel is shielded, as can be seen from the photograph. The condensers are all tuned by one knob which controls a gear arrangement. Nine tubes are used in this model

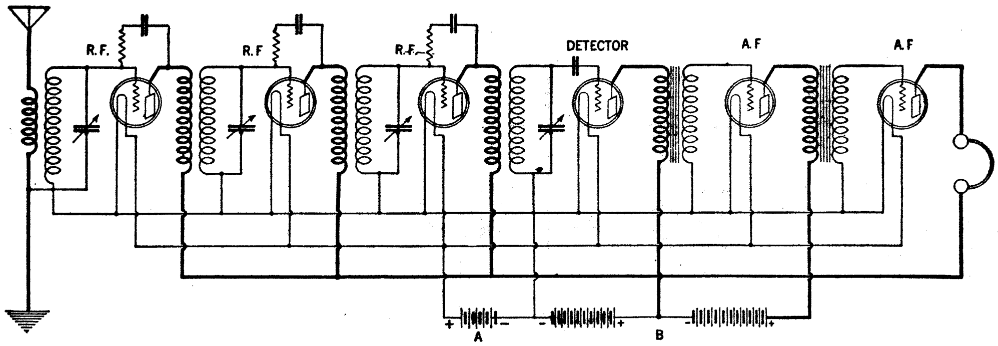


FIG. 7

considered and used, the peak volt-meter was selected as giving most promise. This method consisted in determining the actual voltages of the grids under working conditions by use of a three-electrode vacuum tube. The use of three-electrode tubes as volt meters is well known and has been described before.

The voltmeter was calibrated as follows: A UV-201A tube was used with approximately 67 volts on the plate and about 12 volts negative on the grid. The plate current was then normally about 10 micro-amperes. A known radio frequency voltage was applied to the grid and the grid negative voltage was increased until the plate current reached a known value which was the 10 micro-amperes. The increment of negative grid voltage was recorded. It was found that the tube would always reproduce these conditions with the same voltages. In this manner the voltmeter was calibrated in terms of increments of negative grid voltages vs. applied root mean square values. To save interpolation the measurements of impedance and voltage amplification were made with the same r.m.s. value of voltage applied to the voltmeter. This value was set at .5 volts and the input voltage of the preceding tube changed until this value was produced.

The following is a diagram of the voltmeter and circuit used for these measurements:

The capacity of the voltmeter is very small, since it is only the grid-to-filament capacity of the tube plus small lead capacity which would approximate 10 to 20 micro-micro-farads. This capacity is connected in parallel to the tuning condenser and therefore does not affect the result. The impedance of the voltmeter can be considered as purely resistance in nature and very high, probably several megohms, as the grid has in excess of 10 volts negative applied.

MEASUREMENTS WITH THE VACUUM TUBE VOLTMETER

THE voltage amplification per stage is the voltage of the grid of the second tube divided by the voltage of the first tube. It was necessary to determine that the impedance of the plate circuit of the second tube would not affect the impedance of its grid, as in multistage operation the plate circuit of the second tube would be tuned by a transformer to supply the grid of the succeeding tube, and if this high impedance caused by the plate tuning of the second tube affected its grid to filament impedance, the measurement as outlined would not hold. Non-inductive resistances of 10,000 ohms were inserted in the plate circuit and the plate voltage was maintained constant by adding sufficient battery to take care of the resistance drop, and at radio frequencies this was found to affect the input impedance of the grid very considerably. This corresponded somewhat to the results obtained by Weinberger. (J. Weinberger, *Proc. I. R. E.*, page 584, sec. 1919.) It was thought that this change of impedance might be due solely to capacity coupling of the tube causing feed-back action, therefore the applied frequency was reduced to 1000 cycles and it was found that at this frequency, the grid-to-filament impedance was independent of the plate load impedance. It followed, therefore, that any influence of the plate load on the grid impedance was due to regeneration and would disappear when the regeneration was nullified.

The measurements of voltage ratio by this method would hold and give the true radio frequency amplification without feed-back as long as the amplifier was non-regenerative.

The voltage ratio was determined for a tuned radio-frequency transformer as shown in the Figure and the radio frequency ampli-

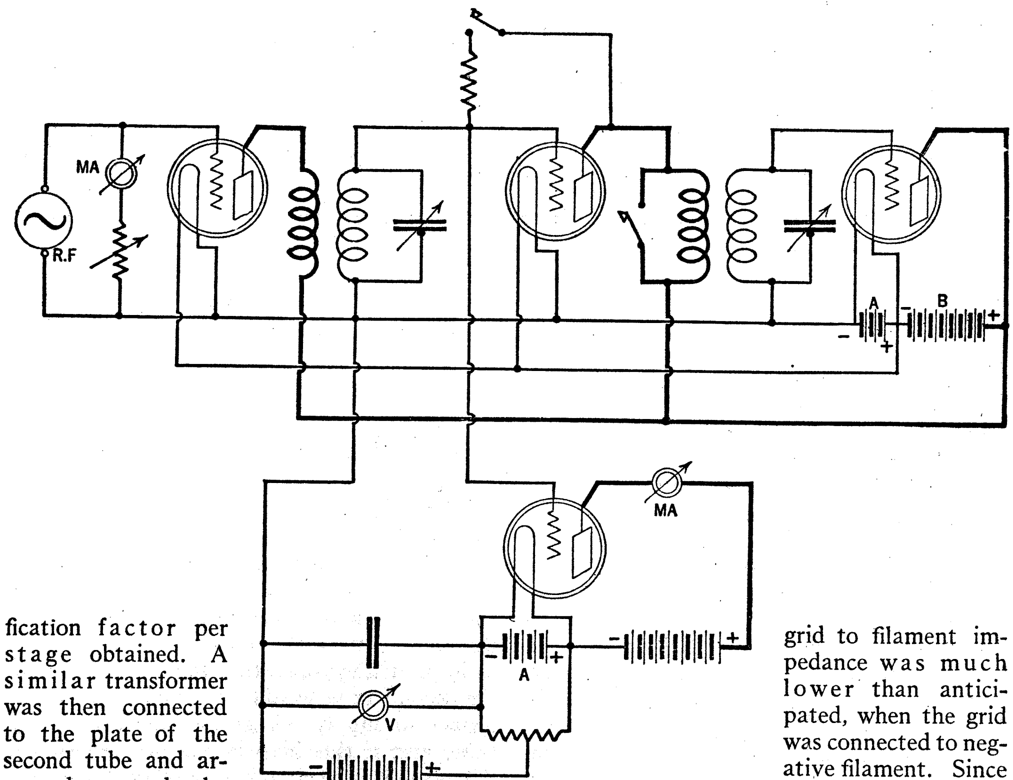


FIG. 8

fication factor per stage obtained. A similar transformer was then connected to the plate of the second tube and arranged to supply the grid-to-filament circuit of a third tube which was connected as the second tube had been in the first case. The voltage on the grid of the second tube was found to be decidedly higher due to feed-back action. A nullifying resistance was then connected from grid to plate of the second tube and adjusted until the voltage of its grid equalled the original voltage as given when the output of the plate was shorted by switch "S." The resistance had then nullified the feed-back action due to the natural capacity between the grid and plate of the tube and the voltage amplification obtained was the original non-regenerative radio frequency amplification. The value of nullifying resistance thus obtained was found to be between 30,000 and 50,000 ohms for UV-201A tubes and between 80,000 and 120,000 ohms for UV-199 and WD-11 tubes The values of resistance approximate the capacity coupling reactance of the tubes, i. e., the grid to plate capacity in ohms at the operating frequency.

IMPEDANCE VALUES OF COMMERCIAL TUBES

THE maximum voltage amplification determined and the turn ratios for maximum amplification lead to the conclusion that the grid to filament impedance was much lower than anticipated, when the grid was connected to negative filament. Since the grid to-filament impedance was always shunted with a secondary tuning condenser, it could be considered as purely resistance in nature. It was decided to determine this impedance value for commercial tubes. The peak voltmeter method was very well suited to this measurement as it was only necessary to substitute a known non-inductive resistance for the tube, retune to compensate for the reduction of capacity of the grid-to-filament and adjust the resistance until the voltage of the grid of the second tube was at its original value. The resistance thus determined was then equal to the resistance of the grid-to-filament path of the tube. These values for UV-201A tubes with grid connected to negative filament were found to be between 120,000 and 150,000 ohms with 130,000 ohms as a fair average. This accounted for the broadness of tuning of non-regenerative radio-frequency amplifiers, as with a circuit using a condenser of 250 micro-microfarads maximum, for the broadcasting range, the condenser reactance at 400 meters is approximately 1800 ohms and the effect of 130,000 ohms in shunt to such a circuit is the same as if approximately 25 ohms had been inserted in series with the condenser and inductance, and consequently produces very large damping.