THE DETECTING EFFICIENCY OF THE ELECTRON TUBE AMPLIFIER.

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SYNOPSIS.

Definition of Detecting Efficiency.—The detecting efficiency of an amplifier is defined as $\lim_{A \doteq 0} \frac{b_0}{A^2}$ where b_0 is the average change in the plate current of the last tube and A is the amplitude of the impressed grid voltage.

Relative Importance of Detecting Efficiency and Input Impedance.—A discussion of the necessity of taking into account both the detecting efficiency and the input impedance is given.

Measurements of Detecting Efficiency for a Transformer-Coupled Radio-Frequency Amplifier.—Measurements of the detecting efficiency of a transformer-coupled radio-frequency amplifier were made by means of a condenser potential divider and a sensitive quadrant electrometer.

Measurements of Amplification.—Measurements of the amplification due to each tube of the above amplifier were made. It was found that the *sound intensity* in the telephones was increased in the ratio of $9 \times 10^3 : 1$ owing to the use of the first two tubes.

1. INTRODUCTORY.

THE multi-stage electron tube amplifier such as is frequently used in radio practice and laboratory experiment is essentially an instrument for giving a relatively strong response, in the form of an electric current or a sound, to a relatively small alternating voltage impressed on its input terminals. It is of basic importance to be able to describe the behavior of an amplifier, or in other words, to be able to predict how a given amplifier will act under given conditions. The behavior of an amplifier depends upon the manner in which it reacts upon the external input circuit and upon the actions which take place inside itself. The general problem, then, of investigating the behavior of an amplifier requires the consideration of two interrelated problems, the first being the determination of the reaction between the amplifier and the external input circuit, the second being the determination of the action of the amplifier itself. The first we term the *problem of input impedance*, the second the *problem of detecting efficiency*.

To emphasize the importance of distinguishing between the two phases of the general problem let us consider a specific example. Suppose it were required to compare two different amplifiers. To do this it would seem sufficient to listen by means of them to a steady signal, connecting each one in turn to the same circuit. Such a procedure, however, would not in general give a fair test. It may happen that the first of these amplifiers, say A, is equivalent to a capacity in series with a large resistance and gives a large change in the output plate current for a small input E.M.F.; while the second, say B, is equivalent to a capacity in series with a small resistance but gives a much smaller change than A in the output plate current for the same input voltage. If then the test were performed on a receiving circuit having a low resistance and capacity B would not influence the antenna current appreciably while A would decrease it on account of a large input resistance. The decrease might be so large that the rectification in the plate circuit might be less with A than with B. Thus the test would be in favor of B. If the same test were performed on a high resistance circuit the amplifiers being connected across a large capacity, then neither amplifier would affect the currents in the receiving circuit appreciably. Hence, since A gives a larger rectification for the same input voltage than B, the test will be in favor of A. It is thus seen that an intelligent choice between the two amplifiers cannot be made unless both phases of the problem have been solved.

2. The Input Impedance Problem.

Let us suppose that the grid and filament of the first tube of an amplifier are connected to a circuit in which high frequency current is flowing. This circuit is known as the input circuit. In general it is not legitimate to assume that the current in the input circuit is the same as it is if the amplifier were absent even though there may be no direct inductive coupling between the input circuit and the various internal circuits of the amplifier. The problem of unravelling the factors which enter into this effect is termed the input impedance problem.

This question has been discussed by H. W. Nichols[1] and by J. M. Miller.[2] They showed that the effect of a single tube, when the grid current is zero, is equivalent to that of an electric circuit having a definite resistance and reactance which was calculated. In a paper[3] by one of us the single electron tube has been dealt with for the cases of positive and negative grid voltage, and the exact formulas have been worked out.

Thus, the problem of the input impedance is considered to have received a complete theoretical solution for the case of a single tube. The more complicated case of the multistep amplifier has as yet not been treated theoretically, although it would appear that the problem offers no fundamental difficulty.

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[1] Phys. Rev., 13, 404, 1919.

[2] Bureau of Standards Scientific Paper, No. 351.

[3] "The Calculation of Detecting and Amplifying Properties of an Electron Tube from its Static Characteristics," G. Breit. (As yet unpublished.)

3. THE DETECTING EFFICIENCY OF THE AMPLIFIER.

The main purpose of the present work was the consideration of the second phase of the general amplifier problem, namely, the detecting efficiency of the amplifier. The detecting efficiency of the amplifier means, in general words, the efficiency of the amplifier to make weak signals intelligible. A precise definition of detecting efficiency is given later on. From general considerations it can be seen that the detecting efficiency depends upon the relation between the input grid voltage change and the resulting change in the output plate current. Therefore this relation must be determined either by theory or experiment before much can be said about the detecting efficiency of the amplifier. To determine this relation from theoretical considerations is, however, a somewhat difficult matter. Let us point out some of the difficulties briefly. Since the relation between the input grid voltage change and the output plate current change depends upon the amplification and rectification taking place in each tube, it is necessary to have an accurate knowledge of the characteristics of the electron tubes. These characteristics must be known with a precision sufficient to enable one to compute the first and second derivatives of the plate current and grid current with respect to plate voltage and grid voltage, respectively. It is further necessary to know the resistance and reactance of all the electrical circuits connected to the tubes for all frequencies. If the tube and circuit constants have been ascertained, then the output plate current can be computed for a given input grid voltage. Since both the measurements of the constants and the computations in the case of the amplifier are somewhat involved it appeared better from an experimental standpoint to measure directly the output plate current as a function of input grid voltage.

4. GENERAL EXPERIMENTAL PROCEDURE.

The type of amplifier chosen for investigation was the three tube high frequency transformer-coupled amplifier. This amplifier, shown schematically in Fig. 1, may be used to receive modulated radio frequency

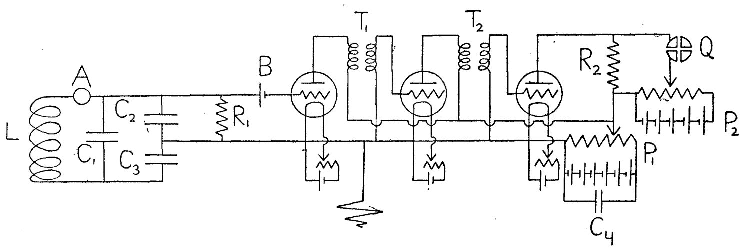

Fig. 1.

signals. Apparatus was arranged to investigate the effect on the rectified component of the plate current of the last tube of impressing in some branch of the input grid circuit a high frequency E.M.F. of the form $A \cos \omega t$, where A is a constant. It is shown in the following paragraph that the results obtained from such a procedure are also true for the case where A is not a constant but varies in a certain manner.

Suppose that the frequency of modulation is so low that the reactances of the plate and grid circuits are negligible for that frequency. Let there be an external E.M.F. impressed in some branch of the circuit between F_1 and G_1 of the form

$$\varphi(\omega' t) \cdot \cos (\omega t - \epsilon),$$

where ω/π is the radio frequency and ω'/π is the frequency of modulation. φ is a periodic function of period 2π, which is supposed to be always positive for real values of the argument. If $\varphi(x)$ is zero for some real value of x the modulation will be said to be *complete*. If there is no real value of x which makes $\varphi(x)$ zero the modulation is said to be *incomplete*. Since the reactances of all the circuits are negligible at the frequency $\omega'/2\pi$, it is legitimate to assume that at any instant of time, t_0, the plate current of the last tube is the same as it would be if an E.M.F. $\varphi(\omega' t_0) \cos (\omega t - \epsilon)$ had been impressed on the amplifier for an infinite time. If such were the case, the plate current would in general be different for different values of $\varphi(\omega' t_0)$. Thus it is sufficient to investigate the effect on the plate circuit of the last tube of impressing in some branch of the input circuit an E.M.F. of the form $A \cos \omega t$ where A is a constant.

5. Experimental Details.

The apparatus consisted of a condenser potential divider, the amplifier, and a quadrant electrometer connected in the plate circuit of the last tube of the amplifier. These will be described in the order named. The arrangement is shown schematically in Fig. 1.

In order to impress on the grid of the amplifier a high frequency voltage of known amplitude of the same order of magnitude as that obtained in the reception of radio signals a condenser potential divider was devised. This consisted of three variable condensers of capacities C_1, C_2, and C_3 connected to a coil L in which high frequency current was induced by a suitable electron tube generating set. A thermo-galvanometer A measured the total current through the combination of condensers. The amplifier was connected across C_2, so that the voltage across C_2 was E_g, the effective grid voltage of the input tube of the amplifier. The high resistance leak R_1 (about 2 megohms) was connected across C_2 to ensure a definite value of E_g during the experiment. The effect of R_1 upon the impedance of C_2 was negligible, because C_2 was large (about 0.05 μF) and the frequency used was of the order of 3×10^5. If the effective value of the current through A is I and the frequency of the current is $\omega/2\pi$, then it may be shown that

$$E_g = \frac{C_3 I}{\omega(C_1C_2 + C_1C_3 + C_2C_3)}.$$

By adjusting C_3 to a small value and C_2 to a large value the coefficient of I in the above equation may be made so small that a readable value of I is obtained when E_g is comparatively small. The absence of stray capacity effects was tested by using different condenser settings and different values of current. In order to eliminate direct action between the generating set and the amplifier, twisted leads about five meters in length were used between L and C_1, and between C_2 and the amplifier. This difficulty increases as the number of stages in the amplifier is increased, but by increasing the distance between the various parts of the apparatus it appears to be possible to reduce any direct action sufficiently for practical purposes.

The amplifier was a three-tube high-frequency transformer-coupled amplifier. The tubes were Western Electric Company tubes, Type VT1; they were used with the filament current always 1.10 amperes and the plate voltage always 22.0 volts. Separate storage cells supplied each filament; the plate voltage supply was common to all the tubes. By means of a standard cell B, Fig. 1, the input voltage E_g was kept always at a standard value. The plate battery was shunted by a $2\mu F$ condenser C_4. The transformers T_1 and T_2 were resonance transformers, both tuned to the same radio frequency. They were made of No. 36 silk-covered copper wire wound on paraffined wooden spools 3 cms. in diameter, 200 turns on the primary and 250 turns on the secondary winding.

The change in the value of the rectified component of the output plate current of the amplifier was measured by a Dolezalek quadrant electrometer Q, Fig. 1, connected across a high resistance R_2 placed in the plate circuit. The connections are shown in Fig. 1. The sensibility of the electrometer was 2500 mm. deflection per volt difference of potential between the quadrants. R_2 was 60,000 ohms. Therefore the electrometer deflection in millimeters could be reduced to the plate current change in amperes by dividing by 15×10^7. P_1 *and* P_2 are potential dividers, P_1 serving to keep the plate voltage at a standard value, and P_2 to compensate for the potential drop in the resistance R_2, so that the electrometer rested approximately at zero. When the input grid voltage was changed, a deflection of the electrometer resulted which was proportional to the change in the rectified component of the output plate current.

It was important that the filament voltage of the last tube and the voltages of P_1 and P_2 be constant. Storage cells were found to be sufficiently steady for the purpose. When a slow drift of the electrometer occurred, the error was eliminated by averaging deflections.

6. Experimental Results.

The electrometer deflections, which were proportional to the change in the value of the rectified component of the output plate current, were recorded for a series of values of the amplitude of the radio frequency voltage impressed on the input grid for various frequencies. It was seen that the electrometer deflection was nearly proportional to the square of the amplitude of the grid voltage. This meant that the rectifying action of the last electron tube was represented approximately by the expansion of the plate-current grid-voltage relation, by Taylor's theorem, in which derivatives of higher order than the second were neglected. In Fig. 2 are shown the curves for the electrometer deflection plotted against the square of the grid voltage for the five different frequencies corresponding to the wave-lengths 800, 825, 850, 875, and 900 meters.

7. The Detecting Efficiency.

If A and b_0 denote the amplitude of the change in the input grid potential and in the rectified component of the output plate current, respectively, the detecting efficiency for a given frequency is defined conveniently by the relation

$$\text{detecting efficiency} = \lim_{A \doteq 0} \frac{b_0}{A^2}.$$

The detecting efficiency for a specified wave-length is obtained from the slope at the origin of the curve of Fig. 2 for that wave-length. The slopes at the origin have been computed for each curve of Fig. 2, and are shown in Fig. 3 plotted as ordinates against wave-lengths as abscissas. These slopes are reduced to the detecting efficiency by dividing by 15×10^7 which is the factor of proportionality between electrometer deflection in millimeters and the change in the rectified plate current in amperes. It is seen from Fig. 3 that the detecting efficiency of the amplifier is greatest at wave-length 850 meters. It is to be noted that the results shown in Fig. 3 give a complete solution of the question of the numerical value of the detecting efficiency of the amplifier. They do not, however, give any information as to the various factors upon which the detecting efficiency depends. Nor do they yield information concerning the input impedance of the amplifier.

In order to check experimentally the assumptions of section 4 the following test was carried out. With a given current in A, Fig. 1, the electrometer deflection was noted. A 500-cycle interrupter was introduced to chop the exciting current. When the coupling between the generating set and L was increased until the current had its previous

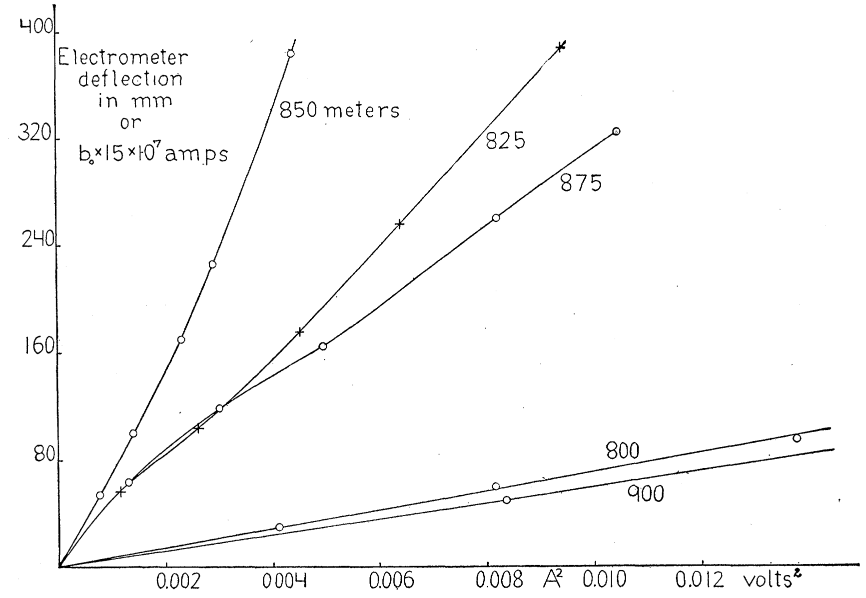

Fig. 2.

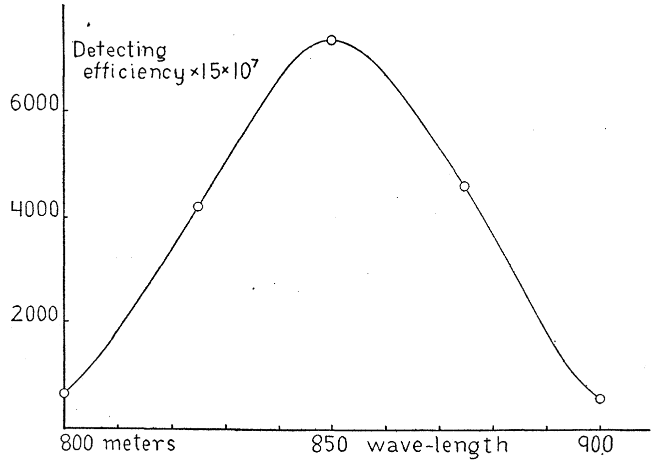

Fig. 3.

value, it was found that the electrometer deflection was the same as before. This test was repeated for various frequencies of the interrupter with the same result. This showed that modulating the exciting wave in the manner described above did not change the detecting efficiency of the amplifier.

8. Amplification of Each Stage.

The degree to which the detecting efficiency depended on each stage of the amplifier was determined by measuring the detecting efficiency of the amplifier for wave-length 850 meters with the first tube disconnected and then with the second tube also disconnected. It was found that the detecting efficiency of the amplifier with all three tubes was proportional to 9710, with two tubes 1020, and with one tube 104. The amplification due to the first tube was, therefore $\frac{9710}{1020} = 9.7$ and that due to the second tube was $\frac{1020}{104} = 9.8$.

This meant that the square of the radio frequency voltage from filament to grid of the second tube was 9.7 times as great as the square of the input grid voltage provided that the voltage was sufficiently small. Any rectifying action which occurred in the successive stages did not influence the result, because the slope of the curve was taken at the origin, and rectification is known to depend on terms in ΔE_g of higher order than the first. For amplitudes which can no longer be considered as infinitesimal the rectification may manifest itself by shifting the operating point on the characteristic of each tube and thus changing the amplification constant and internal resistance of the tube. This may be the explanation of the curious bends in the curves of Fig. 2.

9. Sound Intensity Amplification.

If a modulated radio frequency signal is received by means of the amplifier the kinetic energy of the vibrations of the telephone diaphragm, and also the energy of the sound waves produced thereby, is proportional to the square of the amplitude of the change in the rectified component of the plate current. The amplitude itself is, however, proportional for the same input radio frequency voltage to the square of the detecting efficiency as defined above. Consequently, for weak signals the sound intensity is proportional to the square of the detecting efficiency. In the case of the amplifier cited above the sound intensity was increased in the ratio of $9 \times 10^3 : 1$ owing to the use of the first two tubes.

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